Effect of Saw Tooth Side Clearance on Stability and Cutting Accuracy of Guided Circular Saws

by

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ABSTRACT

This research considers the effect of saw tooth side clearance on stability and cutting accuracy of guided circular saws. The objective of the study is to achieve a better understanding of variables controlling the saw-workpiece interactions and their influence on the cutting accuracy of guided circular saws. This study intended to facilitate the optimum design of guided circular saws. The research work includes investigation of saw-workpiece interaction, identification of controlling variables, development of hypotheses, formulation of a theoretical model and experimental studies.

The investigations identified saw tooth side clearance as a primary variable controlling the saw-workpiece interactions and the behavior of guided circular saws. The hypotheses explaining the significance of tooth side clearance were developed based on earlier sawbody-workpiece interaction models. Based on the hypotheses a 'circular beam model' was developed to represent the effect of tooth side clearance on the cutting characteristics of a guided circular saw. Results of the theoretical model indicated increased sawbody-workpiece interactions and reduced cutting accuracy at very small saw tooth side clearances.

An extensive series of experiments was performed to verify the theoretical observations. The experimental studies analyzed the variation of cutting accuracy and saw-workpiece interactions as a function of saw tooth side clearance, tensioning states and sawing configurations. Experiments were also carried out to simulate the possible errors in the workpiece feed system of sawmills and to study their effect on the cutting accuracy of guided circular saws.

In general, the experimental results supported the theoretical expectations. Experimental results showed a clear relationship between the saw tooth side clearance and the cutting accuracy of guided circular saws. Reduction of saw tooth side clearance increases the saw-workpiece interactions close to the guides and results in inferior sawing performance. Observations also revealed the ability of climb cutting saws to perform even at very small tooth side clearances. Experiments with simulated feed error showed higher sawcut standard deviations for feed errors greater than tooth side clearances.

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NOMENCLATURE

C	constant used to calculate *Total Fiber Loss*
C	gyroscopic matrix in trigonometric domain
C^*	gyroscopic matrix in nodal displacement domain
E	modulus of elasticity of the beam element
EI	flexural rigidity of the beam
F	concentrated force vector acting on the nodes
$f(r)$	displacement profile in radial direction
I	moment of area of the beam element
k	foundation stiffness per unit length;
K	stiffness matrix in trigonometric domain
K^*	stiffness matrix in nodal displacement domain
L	length of the beam element
M	mass matrix in trigonometric domain
m	mass per unit length
M^*	mass matrix in nodal displacement domain
n	number of nodal diameters
$q_i(\theta)$	function of time
r	radial position with in the sawblade
R	radius of the circular beam;
S	inverse of the transformation matrix
T	kinetic energy of a circular beam
T_r	transformation matrix
u	lateral displacement of the beam
V	potential energy of a circular beam
w	displacement of a point on the sawblade
δ	incremental change
ΔT	temperature difference between the inner region and outer edge of a sawblade
θ	angular coordinate
θ	angular position in polar representation

$\Phi_i(\theta)$ function of space

ω natural frequency of the sawblade

Ω rotational speed of the sawblade in radians/seccond

ω_b frequency of a backward traveling wave

ω_f frequency of a forward traveling wave

ω_s frequency of the sawblade relative to the saw based observer

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CHAPTER 1 INTRODUCTION AND OVERVIEW

1.1 Introduction

Circular saws are used extensively in the conversion of logs into solid wood products. The amount of wood processed by saws is enormous. In 1997 alone an estimated 1 billion cubic meters of log volume was processed by solid wood industries [2] by sawing.

Whenever saw cuts wood, an amount of wood equal to the thickness of the saw tooth is wasted as sawdust. The lateral vibration of the sawblade during sawing also results in irregular cut surfaces, which require subsequent planing. The typical recovery of solid wood products is about 55%. Losses are mainly in the form of sawdust, chips and shavings. These byproducts have very low value compared to that of solid wood. As the amount of wood processed is enormous these losses account for wastage of about 100–150 million cubic meters of solid wood every year. This has severe economic implications on the profit margin of a sawmill, as the raw materials constitute about 70-80% of the overall cost [36].

Increase in raw material costs, introduction of sustainable forest management and reduction in the availability of lumber has forced the wood industry to focus on sawing process to reduce the wastage of raw material. As the cost of raw material is high, even small improvements in log processing results in a considerable improvement in the profit margin [9]. Therefore, a major challenge of the industry is to achieve maximum recovery of high value products and minimize losses associated with sawing. However, the performance of sawing depends not only on recovery. Maintaining required production rate and lumber quality is also important to remain profitable [33]. Unfortunately all the three parameters cannot be increased simultaneously as they are not mutually independent. Maximization of one of these parameters can typically be achieved only at the expense of one or both of the other parameters [33]. Therefore the primary objective of the modern sawmills is to achieve optimum recovery and productivity while maintaining the quality of the cut.

The focus on minimizing sawdust production to achieve optimum recovery has resulted in the adoption of thin saws. However, maintaining sawing accuracy becomes more of a challenge as the sawblade becomes increasingly thin. Thin saws have relatively low lateral stiffness. Even small lateral cutting forces can cause excessive sawing variation. This is true especially at 'critical speed' when the saw rotation speed coincides with one of the wave speeds of the blade. Thus, excessive vibration of the thin blade in the critical speed region limits the production rate and cutting accuracy.

The introduction of 'guided saws' in the early 70's partially solved the critical speed limitation of thin saws. Guided saws support the sawblade close to the cutting region. This improved stability of the cutting edge resulted in better sawing performance and superior cutting accuracy. This made guided saws very popular in North American sawmills. Even though guided saws perform better and are widely used, the reasons for their superior behavior especially in the critical speed region is not clear. Some of the recent studies indicated that the contact between the workpiece and sawbody as one of the reasons [37]. However, the contact itself is a function of many variables and the influence of these variables on the stability of the blade is not fully understood. This lack of knowledge impedes further improvement in the optimum design of guided saws.

Optimization of any other sawblade parameter other than the thickness of the sawblade would certainly improve sawing performance without compromising the stability of the blade. This process may also give more insight into the superior behavior of the guided sawblade itself. One among these parameters is 'saw tooth side clearance'. Even though much effort has been expended in studying the effect of tooth geometry variables (tooth angles and clearances) on cutting forces of a single point tool, less attention has been paid to the effect tooth geometry parameters such as tooth side clearance on the sawbody-workpiece interactions, stability and performance of guided sawblades.

The objective of the current research is to identify the significance of tooth side clearance from the point of view of sawbody-workpiece interactions and to find out its influence on the stability and cutting accuracy of guided circular saws. This study also aims to probe more into the mechanics of sawbody-workpiece interactions and associated parameters. The aim is to model guided sawblade behavior based on experimental observations. This study is designed to give further ideas about improving the recovery of sawing and also to focus some light on the behavior of guided saws and help in the optimum design of guided sawblades.

1.2 Terminology

To facilitate subsequent discussions, some explanations and definitions are provided here for different terms and concepts associated with sawing.

1.2.1 Different types of Saws and Configurations

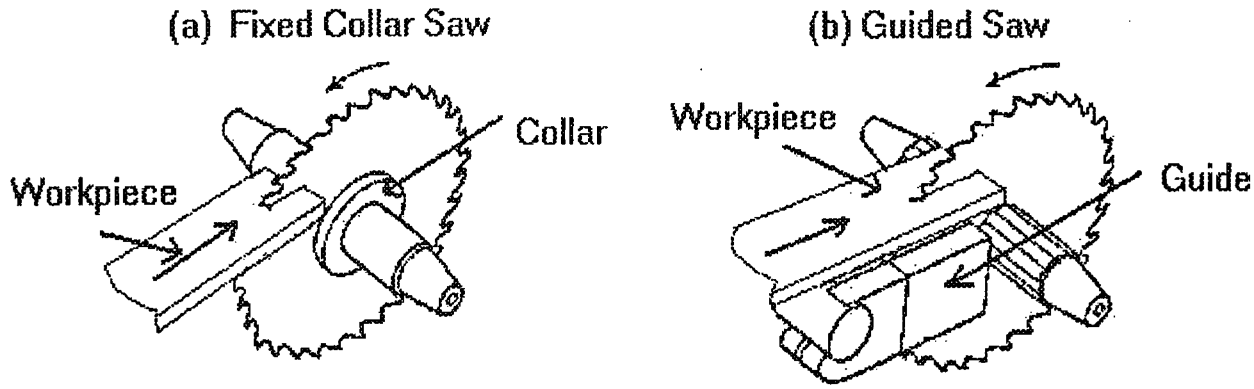


Figure 1-1 Different Types of Saws

Circular saws are classified mainly as fixed collar saws and guided saws. These saws are shown in Figure 1-1. In the case of fixed collar saws, a collar supports the center of the saw. This support is far away from the cutting edge. The stiffness of the saw is maximum near the collar and decreases with distance away from the collar. For guided circular saws, the center of the sawblade is free to move on the arbor. Guides support the rim of the sawblade close to the cutting region. The stiffness of the sawblade is maximum near the cutting region. Increased stiffness of the cutting edge increases the stability of saw during cutting. They are used extensively in North American sawmills because the cut produced by guided saws is more accurate compared to that of fixed collar saws.

Circular saws are used in climb cutting and counter cutting configurations. These are shown in Figure 1-2. For climb cutting, at the cutting edge the horizontal component of velocity of the sawblade and workpiece feed are in the same direction. For counter cutting, they are in opposite directions. Generally climb cutting performs better than counter cutting. However, the difference in their accuracy for stable operating conditions is so small that the argument about their superiority still persists (cited in [38]).

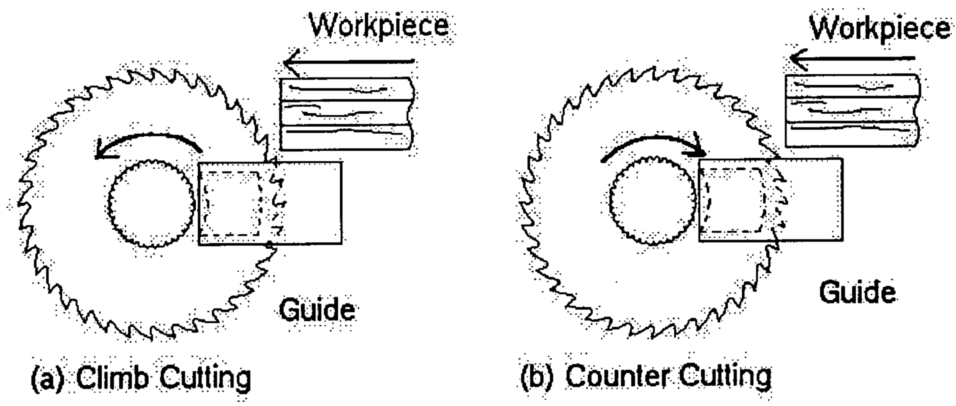


Figure 1-2 Counter and Climb Cutting Configurations

Selection of a particular configuration not only depends on cutting accuracy but also depends on other factors. Previous studies at Forintek and field trials showed that the climb cutting consumes less power than counter cutting (cited in [38]). However, climb cutting requires strong workpiece holding arrangement as any slippage in the workpiece feed system results in the ejection of the workpiece from the out feed end at 'killing speeds' [38]. Consequently there is much favor for counter cutting based on safety.

1.2.2 Terms Associated with Sawing

Kerf: Whenever a saw cuts wood, volume of wood approximately equal to the width of the saw teeth multiplied by area of cut is wasted as sawdust. This is represented in Figure 1-3. For a constant depth of cut, this loss can be represented by the width of the cut and is known as '*kerf loss*'. *Kerf* is approximately equal to the width of the widest tooth of the sawblade. Also, it is approximately equal to the sum of sawblade thickness and the two tooth side clearances.

Side Clearance: Side Clearance is the amount the sawteeth overhang the sawbody.

Sawcut Standard Deviation: The lateral movement of the sawblade is one among the factors responsible for the irregular profile on the workpiece. This is shown in Figure 1-3(a) and Figure 1-3(b). These surface irregularities should be removed by subsequent planning. Usually the amount of inaccuracy present in the cut surface is quantified by measuring the standard deviation of the surface profile along the length of the workpiece. This is known as *Sawcut Standard*

Deviation. A lesser *Sawcut Standard Deviation* corresponds to a better-cut surface. Experiments by *Wang* [37] showed a good correlation between saw vibration state and *Sawcut Standard Deviation* (Refer Appendix II for details).

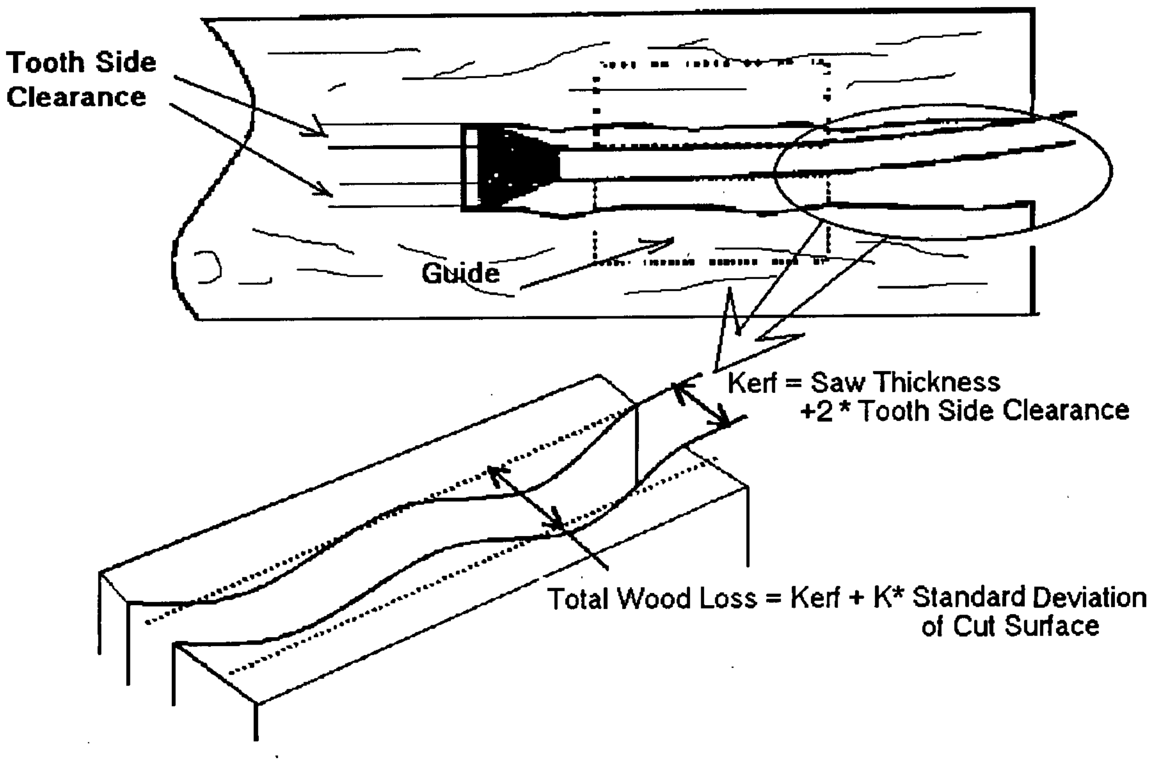


Figure 1-3 Cut Surface Produced by Sawing

Total Fiber Loss due to Sawing and Planing: Total Fiber Loss is used to represent the total loss of solid wood by sawing and subsequent planing operations. It includes both *kerf loss* and the losses associated with planing. However, for a constant depth of cut the losses associated with the planing depends mainly on the surface irregularities or indirectly on the *Sawcut Standard Deviation* of the cut profile. Therefore, *Total Fiber Loss* can be represented as a function of *Kerf* and *Saw Cut Standard Deviation*.

Total Fiber Loss = F (Kerf and Sawcut standard Deviation) 1.1

where, Kerf = f (Sawblade Thickness, Side Clearance) 1.2

$\therefore$ *Total Fiber Loss =F (Sawblade Thickness, Side Clearance and Sawcut Standard Deviation* 1.3

Approximately for a constant depth of cut,

Total Fiber Loss = Saw Thickness + 2 × Side Clearance + C × Sawcut Standard Deviation   1.4

Value of *C* is determined based on a probabilistic model of cut surface profiles of large number of workpieces [4]. For example, when *C*=1.65, about 5% of planed surfaces may show sawing irregularities even after planing.

Critical Speed: At the *Critical Speed* the rotational speed of the saw equals a wave speed. At this speed, any constant lateral force acting on the sawblade can cause excessive vibrations resulting in slow lateral oscillations of the blade. This results in a behavior called '*Snaking*' where the saw cut has an undulating surface. Figure 1-4 shows a snaking sawblade configuration. Critical Speed of the sawblade depends on the diameter and thickness of the sawblade. Thin saws have lower *Critical Speed* compared to that of thick saws. Therefore, a change to thinner saws requires saws to be run at lower rotational speed. Otherwise, the *kerf* gain achieved by the reduced plate thickness will be lost by the reduced cutting accuracy.

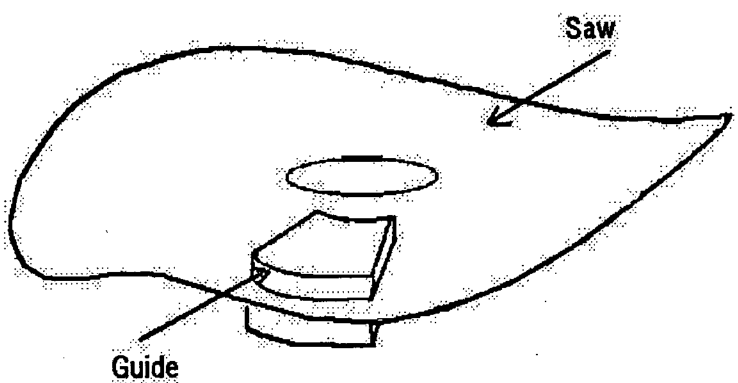


Figure 1-4 Snaking Sawblade

Saw Tensioning: Saw Tensioning is a process by which in-plane stresses are deliberately put into a sawbody by hammering, rolling or non-uniform heating. *Saw Tensioning* is an effective method used to increase the stiffness of the blade and to increase its critical speed. However, over-tensioning can cause compressive radial in-plane stresses and result in sawblade buckling known as '*Dishing*'. A dished sawblade looks like a frustum of a cone with inner and outer edge of the sawblade in different planes. A dished blade produces tapered lumber and results in higher loss of wood.

Feed Speed: Feed Speed is the axial speed of the workpiece. The *Feed Speed* of the workpiece is chosen such that the *Feed per Tooth* of the sawblade is constant at a particular combination of saw rotational speed and carriage feed speed [38].

Feed per Tooth: Feed per Tooth or Bite per Tooth is the depth of cut per tooth. More simply it is the distance the log advances into the saw between successive teeth during cutting. It is represented as,

$$\text{Feed per Tooth} = \frac{\text{Feed Speed}}{\text{Saw Rotation Speed} \times \text{Number of Teeth}} \tag{1.5}$$

1.3 Background

Guided saw stability depends on many factors such as critical speed, tensioning level, feed speed, saw configuration, sawbody-workpiece interaction, guide material, saw tooth geometry and the workpiece itself. Any defect in the form of knots, holes and twisted grain makes it difficult to correlate the behavior of the sawblade with the cut surface accurately. The presence of large number of variables and the uncertainties associated with the workpiece properties resulted in different studies analyzing the effect of different variables, in seclusion. This also resulted in literature being widely spread.

The majority of the studies try to explain the stability of guided saws by extending the critical speed theory of fixed collar saws. However, experimental studies indicated that in case of guided saws, the influence of other variables could not be simply ignored. The current study tries to identify these key variables and find out their influence on the stability of guided saws. At this point it may be of value to give a very brief survey about the research studies already done in the development of circular saws and the present knowledge about guided saws and their cutting behavior.

1.3.1 Previous Research

Vibration of the discs has been an area of research from the early days of the development of science. Earliest reference in this regard can be found in *Platon's* (A.D. 108) report (cited in [6]) that *Hippasos* (a student of *Pythagoras*) tested four bronze disks and found that their natural frequencies were inversely proportional to their thickness. However, this observation was not explored in detail until the end of nineteenth century when there was a rapid progress in building high-speed steam turbines. *Campbell's* [5] research in the 1920's on the subject of turbine disc wheels was one of the first significant contributions to the field of rotating disk vibration. He concluded that a non-uniform axial static pressure around the circumference excited a standing wave at a resonant speed called critical speed, leading to the failure of steam turbine discs. He also explained the variation of the natural frequencies with the rotational speed of the discs and identified the resonant speeds for excitations at different frequencies.

Stability of circular saws near the critical speed also attracted research interest. This was basically motivated by the requirement of running the saws at higher rpm to increase the production rate. *Dugdale* [7] carried out a systematic study about the stiffness variation of a disc clamped at its center with rotational speed. He included the effect of dynamic stiffening and evaluated the critical speeds for different collar diameters under the action of axial loading. *Mote* [23 - 26] applied this theory to the development of analytical models with additional parameters such as bending stiffness, thermal gradients, angular velocity and tensioning stresses to get more exact representation of the circular saw behavior [25]. In 1977, *Mote* and *Szymani* identified factors influencing the stability and performance of sawblades [23 ,24]. They also introduced the idea of interaction of the workpiece with the saw lateral surfaces. However, the interaction was considered as random force causing variations in the sawblade vibration. The critical speed instability was considered most prominent concept and had precedence over other concepts. *Mote* also modeled circular saw tensioning using membrane stresses and examined the stability of the sawblade [25]. Saws showed an improvement of 30-40% increase in their critical speed after tensioning. All these analyses with additional parameters were successful in modeling and predicting the behavior of fixed collar saws very well.

1.3.2 Guided Circular Saw Research

In 1970 *Thrasher* introduced guided circular saws. They quickly became very popular in North American sawmills because of their improved stability and cutting accuracy. Guided circular saws also attracted the attention of lot of researchers. Research studies have been carried out to understand the superiority of guided circular saws and to optimize them to achieve the maximum benefit.

1.3.2.1 Stability of Guided Saws

Schajer [32,28,27] analyzed the stability of guided circular saws and the variables influencing their performance. He addressed a variety of issues including guided saw hunting, critical speed stability and sawblade tensioning. In 1989, based on his experimental work [27] he concluded that guides have very little effect on the critical speed except that the dynamic response of the saw becomes much more complicated by the addition of guides. This was further substantiated in the dynamic model of a guided circular saw developed by *Hutton* [10]. His model indicated that the introduction of one or two guides does not significantly influence the critical speeds of guided sawblades. *Hutton* and *Lehmann* analyzed both theoretically and experimentally, the self-excitation phenomenon in saws that were not perfectly flat [11]. They found that self-excited resonance could occur at certain speeds by the interaction between the guides and sawblade.

Even though all these models represent the frequency characteristics of the guided saws well, they were not fully successful in explaining unusual cutting stability of the guided saws near the critical speed. Operation of guided saws at supercritical speeds was found to be a practical industrial option [18]. Models based on the guide positions and nonlinearly [39] were also not fully successful in explaining the physical observations. This has prompted the researchers to look at the sawing process from a different perspective and to study the effect of other variables on guided saw stability. In 1996 *Lehmann* [15] showed that saw-workpiece interaction is a significant factor for a band saw, influencing its operational behavior. An experimental study [34] conducted by *Schajer* and *Kishimoto* in 1997, showed that the idling behavior of guided saws closely follow the expectations from critical speed theory whereas the cutting behavior differs from theoretical expectations. This made them conclude that the interaction between sawbody and workpieces was a key factor in deciding the cutting characteristics of guided circular saws. However, subsequent studies did not account for sawbody-workpiece interactions because of the difficulty associated with modeling and performing subsequent eigenvalue analysis under realistic conditions.

1.3.2.2 Sawbody – Wokpiece Interaction:

Even though sawbody-workpiece interaction was observed first by *Mote et al* [23-26], it was not explored in detail because of the prominence of critical speed theory, which successfully explained the behavior of fixed collar saws. However, the fact that guided saws have either the same or lower critical speed than a fixed collar saw of same dimensions and still performs better hinted that simply extending the traditional critical theory to the guided saws without physical observation of the phenomenon is not appropriate. The work done by *Schajer* and *Kishimoto* [34] anticipated an increased focus on sawbody-workpiece interactions and called for further investigation. However, this was not tried in mathematical models mainly because of the difficulties associated with the development of eigenvalue analysis with a dynamical model that describes the interaction between the saw and the workpieces realistically. In 1999, *Schajer* and *Wang*, developed a simple theoretical model in time domain to represent sawbody-workpiece interactions [36]. This model was verified by an extensive set of experimental observations. These experiments showed that sawbody-workpiece interactions facilitate guided saws in comparison to fixed collar saws. The analysis also indicated the importance of having increased stiffness only at the cutting edge and flexibility at the other regions for improved cutting accuracy.

Critical speed instability combined with sawbody-workpiece interaction mechanisms gave a fairly good explanation to the behavior of guide saws. However, the important question is what are the variables that control sawbody-workpiece interactions and how to control them to get an optimum performance of guided saws. It is also required to know to what extent sawbody-workpiece interactions influence different sawing configurations and saw tensioning states. These questions if answered not only give insight into the behavior of guided saws during cutting but also act as guidelines for supercritical speed operation of guided circular saws. For these reasons, the current research will mainly concentrate on finding answers to the above questions and develop realistic dynamic model based on the observations.

1.3.3 Effect of Sawing Variables on Stability

Even though the dynamics of the blade plays a major role in the in the determination of recovery and productivity, influence of other variables such as feed speed, guide material, tooth geometry, sawing configurations etc. is also quite substantial in deciding sawing efficiency and quality of cut. Moreover, some of these variables have a direct influence on the dynamic behavior of the blade itself. Therefore, any attempt to optimize the blade design should pay enough attention to the influence of these variables on sawing.

Many research studies have been conducted in the past studying the effect of sawing variables on the cutting accuracy of circular saws. Majority of them concentrate on the effect of tooth geometry variables on cutting forces, chip formation and quality of cut. A study conducted by *Kivimaa* in 1950, on the effect of sawing variables such as rake angle, clearance angle and moisture content of workpieces on cutting forces of a single point cutting tool is one of the earliest references available [14]. It was followed by *Franz*'s (1958) [8] analysis of cutting forces focusing on chip formation and determination of the direction and magnitude of the resultant forces. However, these earlier studies did not focus much light on the stability of a sawblade as a flexible multi-point cutting tool. In 1958, the publication, *A Status Report on the Research in the Circular Sawing of Wood* gave much wider interpretation of earlier findings as applied to a fixed collar circular sawblade. Even though the report discusses in detail about the variation of power and cutting forces with different saw tooth angles, the very idea of reducing of side clearance and its effect on the dynamical behavior of the sawblade was not explored.

Recent studies, especially after the introduction of guided saws, concentrated more on the tooth dimensional tolerances and their effect on the stability and cutting accuracy. Important among them include the research studies of *Bonac* and *Kirbach et al* [3, 13]. *Bonac*'s studies [3] indicated that erroneous grinding of circular saws can result in a non-symmetric saw tooth and can affect the stability of the sawblade and result in inaccurate cuts. In 1985, *Kirbach* reduced the side clearance of band saws systematically and studied their effect on the cutting accuracy of guided saws [13]. His experiments showed the possibility of deciding a critical side clearance for band saws having minimum sawcut standard deviations. He concluded that increased friction on the side surfaces of the tooth and subsequent instability result in inaccurate cuts for very small side clearances. These experiments also indicated a close relationship between saw tooth geometry parameters and the dynamic stability of sawblades. Other research groups involved in the study of cutting force analysis, chip formation and tooth geometry optimization also supported this observation. *McKenzie*, after extensively studying the effect of tooth geometry parameters [20,21], stressed the need for a joint investigation on the effect of tooth geometry variables and the dynamic stability of sawblades.

In 1999, *Lehmann* carried out extensive set of experiments to investigate the effect of tooth side clearance on the cutting stability of small diameter guided circular saws (17" diameter)[16]. His experiments showed very little variation in sawcut standard deviation of guided circular saws with reduced side clearance. The sawblades were able to cut the workpieces with side clearances as small as 0.003". *Williston*, who observed that guided spline arbor saws could run at side clearances as small as 0.002", earlier quoted this kind of behavior [38]. However, these results contradicted the conclusions drawn from earlier band saw experiments of *Kirbach* [13]. This resulted in number of unanswered questions. These include

- What makes a guided circular saw behavior differently than a band saw when the tooth side clearance is reduced?
- How the tooth side clearance influences the sawbody-workpiece interactions and cutting stability of large diameter guided circular saws in counter and climb configurations?
- What exactly is the mechanism of cutting in case of guided saws?

The aim of the current research is to find answers to the above questions by a cumulative approach involving saw tooth side clearance, saw-workpiece interactions and guided saw critical speed theory.

1.4 Current Research

Earlier studies concluded that the stability of the guided saws near the critical speed region could be partly due to sawbody-workpiece interactions. However, the sawbody-workpiece interaction itself is a function of many variables such as saw tooth geometry, saw tensioning state and sawing configuration. Therefore, the focus of the current research is to study the influence of these governing variables on sawbody-workpiece interactions and accuracy of guided circular saws. Here, the saw tooth side clearance has been identified as a primary variable based on its influence in deciding the region of sawbody-workpiece contact.

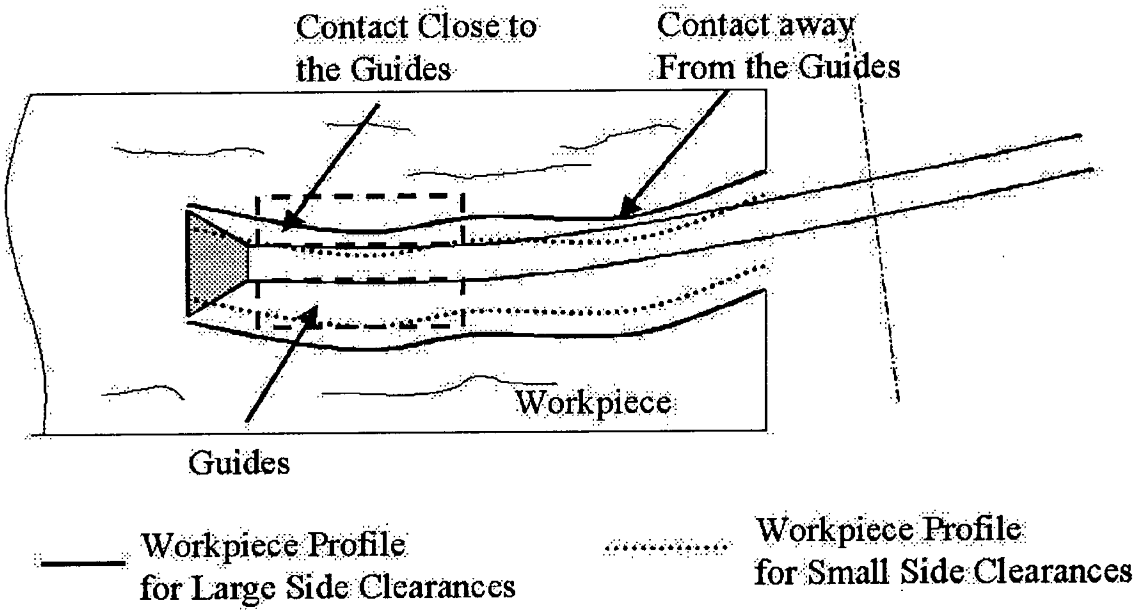


Figure 1-5 Effect of Tooth Side Clearance on Sawbody-Workpiece Interaction

Figure 1-5 shows the sectional view of the contact between sawbody and workpiece at different saw tooth side clearances. It is clear that when the tooth clearance is large, the contact between the sawbody and irregularities on the cut surface takes place in a region of reduced lateral stiffness far away from guides. However, when the side clearance is small the contact would be close to the guides, which is a high stiffness region. These interactions at different regions would certainly have different implications on the stability and cutting accuracy of guided saws for different sawing configurations and tensioning states. Also the presence of the workpiece close to the sawbody restricts the lateral movement of the blade and increases the stiffness locally. Therefore, any mathematical model representing the guided circular saw behavior should include saw tooth side clearance and its influence in deciding the region of contact as variables. For these reasons, this study intends to develop a theoretical model of guided circular saws in time domain to represent their behavior realistically. This work will be complemented by an extensive set of experiments including saw tooth side clearance, saw tensioning states and sawing configurations as variables.

In general, research activities are carried out in an ideal environment where precautions are taken to ensure that the experimental observations are free from systematic errors. However, in an industrial sawing environment, the operating conditions are not as well controlled as laboratory conditions. It is of interest to see how the experimental results stand in the presence of small induced error in one of the parameters governing the behavior of the sawing system. The present research considers this fact by studying the change in sawblade stability and cutting accuracy in the presence of small lateral movement of the workpiece during cutting. This small movement of the workpieces also results in 'forced sawbody-workpiece interactions' when the side clearance is very small and thus gives more insight into the behavior of the saw.

1.4.1 Objectives

The objectives of the present study are summarized as follows

- To study the influence of tooth side clearance on sawbody-workpiece contact mechanism and cutting performance of a guided circular saws.
  This includes a wide range of saw stress conditions and rotational speeds to give a complete representation of the behavior of a guided saw under different operating conditions.
- To understand the effect of tooth side clearance on different cutting configurations of a guided circular saw.
- To study the effect of simulated workpiece feed system errors on the cutting accuracy of guided saws, when the side clearance is being varied.
- To explore the possibility of using two guides to enhance the cutting accuracy.
- To formulate a theoretical model in time domain based on the experimental observation.

1.4.2 Tasks

The objective of the current project is to combine the thoughts from the field of vibrational study of the sawblade, tooth geometry optimization and workpiece contact. To fulfill this objective following tasks are identified and carried out.

- Investigate the theoretical background of sawbody-workpiece interactions.
- Based on the earlier theory develop simple representations of the mechanisms which could possibly explain the significance of side clearance.
- Based on the hypotheses and experimental observations form a theoretical model that simulates the guided saw behavior by taking into consideration number of guides, the change in saw tooth side clearance and sawbody-workpiece contact.
- Identify the parameters to be measured to validate the assumptions and mechanisms.
- Identify the variables that are to be included and effects that are to be removed in the wood cutting test experiments.
- Design experiments based on the combination of variables.
- Design/Modify experimental set up to accommodate new equipment and instruments.
- Conduct experiments for different operating conditions, saw stress states and configurations.
- Analyze the results and derive conclusions to relate different variables.

1.4.3 Scope

The research in its completed form is designed to provide a good understanding of the behavior of guided circular saws as a function of saw tooth side clearance. It also emphasizes the need for combining dynamic analysis with other saw system variables to achieve better understanding of the behavior of guided circular saws. As the experiments cover a large combination of the variables, it is expected that they give valuable information about the interdependency of the variables in deciding the characteristics of guided circular saws. Theoretical model is developed based on the ideas conceived from the experimental studies. Validity of the theoretical model where sawbody-workpiece interactions are included in the form of contact mechanism into a finite element model shows that contact of workpiece with sawbody is indeed important and should not be neglected while modeling guided circular saws. Inclusion of feed error in the experiments and the corresponding results give an idea of the tolerance zone for workpiece lateral movement and its effect on the cutting accuracy.

1.5 Summary

This chapter introduces and gives an overview of the research activities in the development of circular saws. Development of the circular saw research is discussed in detail with relevance to the topic under investigation. Useful contributions made by other scholars in the development of guided circular saws are referred and the new direction in understanding the behavior of guided circular saws has been identified. Interesting questions are raised and the objective of the current research has been formulated with the hope of finding answers.

The concepts of tensioning and critical speed were discussed briefly in the Introduction and Overview chapter. The present chapter analyses these terms and explores their physical meaning from the point of view of vibration of guided circular saws. The implications of the critical speed theory are compared with the earlier experimental observations. Mainly, the approach tries to show the differences in the theoretical expectations and experimental observations for guided circular saws. Simple sawbody-workpiece mechanisms introduced in the recent past and their importance in explaining experimental observations are discussed in detail. These sawbody-workpiece interaction mechanisms are modified and extended to the problem under investigation and hypotheses about the mechanism of sawbody-workpiece interaction under the influence of saw tooth side clearance are developed.

2.1 Guided Saw Critical Speed Theory

Guided saw critical speed theory is an extension of critical speed theory of unguided saws. Even though critical speed theory does not explain the behavior of guided saws completely, it holds good for the majority of observations in case of unguided saws. Therefore, the critical speed theory for thin unguided saws is reviewed briefly to form a basis for further discussion. Present discussion is mainly based on articles [10,18,32,27,31,34,36]

2.1.1 Vibration of Thin Unguided Saws

The vibration of saws during cutting is inevitable because of the unbalanced lateral cutting forces, defects in wood boards, unsymmetrical saw tooth geometry etc. Whenever excited the circular saws vibrate at various natural frequencies, each corresponding to a different vibration mode shape. Figure 2-1 shows the first four nodal diameter modes of an unguided saw. This type of standing wave vibration occurs with a stationary sawblade. This can be represented by the variable separable equation

$$w(r, \theta, t) = f(r) \cos(n\theta) \cos(\omega t) \qquad 2.1$$

where $w(r, \theta, t)$ is the displacement of a point on the sawblade whose polar coordinates in space at time t are r and θ. The function $f(r)$ defines the displacement profile in the radial direction, n is the nodal diameter number and ω is the associated natural frequency.

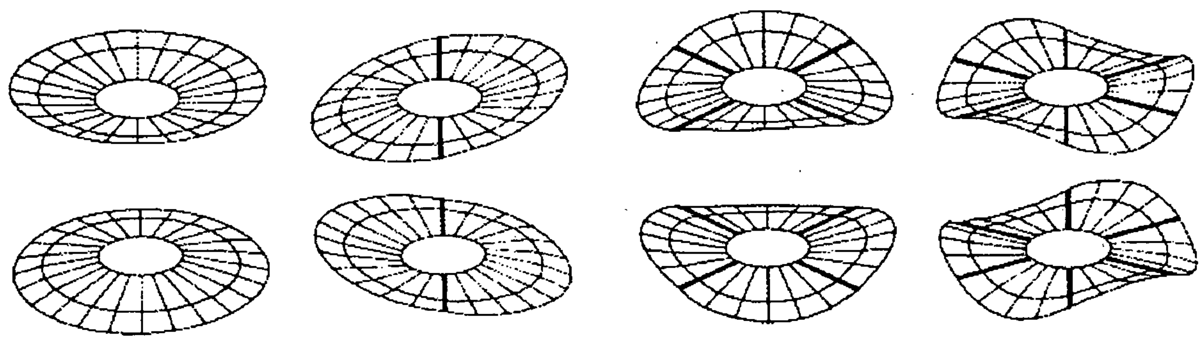


Figure 2-1 Vibration Modes of a Circular Saw from *Schajer* [29]

For $n > 0$, a similar mathematical description of the standing wave vibrations of a circular saw is

$$w(r, \theta, t) = f(r) \sin(n\theta) \sin(\omega t) \tag{2.2}$$

These equations have the same natural frequencies, and differ only in their phase and orientation in space.

An alternative mode shape description can be formed by adding or subtracting standing wave mode shapes to get

$$\begin{aligned} w_f(r, \theta, t) &= f(r) [\cos(n\theta) \cos(\omega t) + \sin(n\theta) \sin(\omega t)] \\ &= f(r) \cos(n\theta - \omega t) \quad \text{and} \end{aligned} \tag{2.3}$$

$$\begin{aligned} w_b(r, \theta, t) &= f(r) [\cos(n\theta) \cos(\omega t) - \sin(n\theta) \sin(\omega t) \\ &= f(r) \cos(n\theta + \omega t) \end{aligned} \tag{2.4}$$

where w_f is known as forward traveling wave and w_b known as backward traveling wave. The two traveling waves move around the sawblade in opposite direction, but with equal speeds. When the sawblade is stationary both standing and traveling wave representations are equally appropriate. However, for a rotating circular saw, the traveling wave descriptions are the only appropriate ones. When the saw rotates, the rotation speed of the saw adds to one traveling wave speed and subtracts from other. The two waves will be having different speeds with reference to a fixed frame. This results in corresponding changes in the observed natural frequencies of a rotating sawblade. A rotation speed Ω will increase the forward traveling wave speed by $n\Omega$ and decrease the backward traveling wave speed by $n\Omega$. The vibration frequencies of a rotating blade are given by the following equations.

Backward traveling wave, $\omega_b = \omega_s - n\Omega$ 2.5

Forward traveling wave, $\omega_f = \omega_s + n\Omega$ 2.6

where ω_s is the vibration frequency relative to a saw based observer, Ω is the circular saw rotation speed , and n is the number of nodal diameters.

Figure 2-2 represents the variation of traveling wave frequencies with saw rotation speed. Above equations of forward and backward traveling waves represent straight lines having opposite slopes. However, the actual variation is slightly curved because of the increase in saw-based frequencies with the rotation due to the stiffening caused by rotation stresses.

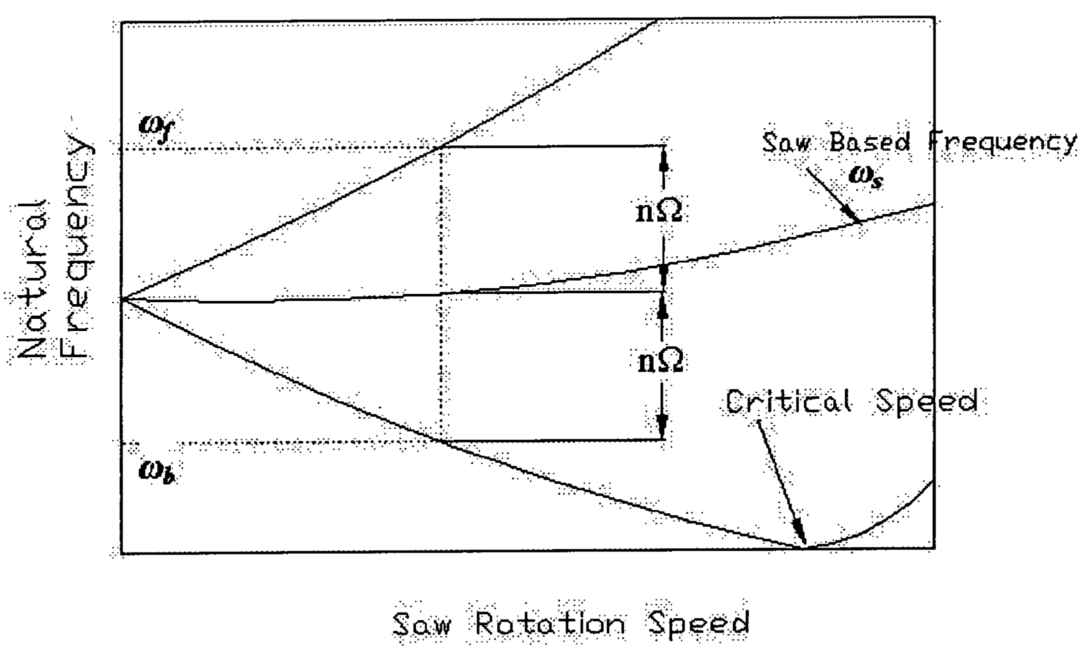


Figure 2-2 Traveling Wave Frequencies of a Circular Saw

Figure 2-3 represents the variation of traveling wave frequencies with saw rotation speed for mode shapes of different nodal diameters. As the sawblade starts rotating each of the mode splits into forward and backward traveling waves. The saw rotation speed at which one of the backward traveling wave frequencies reduces to zero is the critical speed of that mode. At that speed, the saw rotation speed is equal and opposite of the wave speed around the sawblade. The backward traveling speed appears to be stationary in space. Theoretically, the mode shape at the exact critical speed would appear to be a fixed profile. In practical conditions, due to the variation in saw rotation speed, the mode shape seems to move slowly around the sawblade. This results in a snaking sawcut.

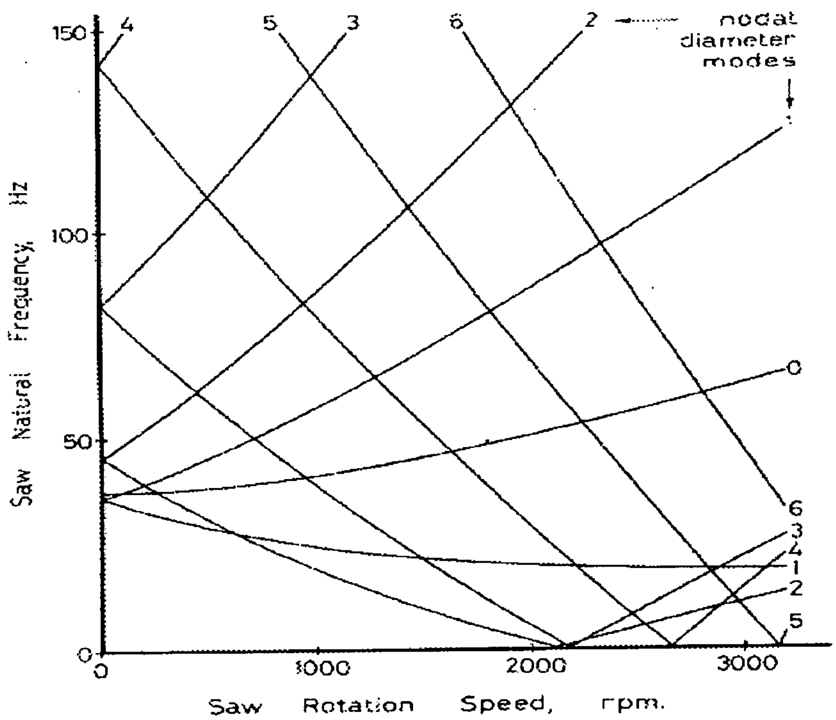


Figure 2-3 Variation of Natural Frequencies of an Unguided Circular Saw with rotation speed, from *Schajer* [29]

Operating conditions of a sawblade should avoid critical speed instability in order to minimize sawcut standard deviation. Most of the vibration modes, except zero nodal diameter vibration mode have their own critical speeds. As the critical speed instability occurs only at the critical speed of an individual mode, theoretically it should be possible to run circular saws in between the critical speed region of different mode shapes. However, in most sawmills the unguided saws run at 50-85% of the lowest critical speed [29]. Once the sawblade reaches its lowest critical speed it becomes so unstable that running the sawblade above that becomes next to impossible. In general, for unguided saws the lowest critical speed decides the performance of sawing. As the thickness of the sawblade decreases the lateral stiffness of the blade also decreases. This results in a lower critical speed and the snaking of the sawblade at operating speeds. Thus any gain in kerf achieved by reducing the saw thickness will be lost due to the impaired quality of a snaking cut.

2.1.2 Saw Tensioning

Early research activities concentrated on improving the critical speed of the circular saws. Saw tensioning is a useful method of increasing critical speed and avoiding snaking saw cuts. Circular saw tensioning purposefully introduces in-plane stresses such that the periphery of the sawblade is pulled into tension and cuts straight. These stresses alter the saw vibration frequencies, and when favorably distributed, they can significantly improve the stability of the sawblade. Usually tensioning increases the frequencies of all the modes except zero and one nodal diameter mode. Increase in the lowest critical speed as much as 40% was observed in experimental observations [35].

There are different saw tensioning methods to obtain required saw characteristics. These include hammering, pressure rolling and non-uniform heating. Hammering and pressure rolling methods produce locked in (residual) stresses in the sawbody and produces small tensile stresses on the periphery. Non-uniform heating involves heating the center of the sawblade to produce thermal stresses due to temperature difference between central area and outer rim. The advantage of this method is that the size of the induced thermal stresses could be easily adjusted by controlling the amount of heating. In the experiments, carried out as a part of this thesis, roll tensioning and additional temporary thermal tensioning has been used extensively. This temporary tensioning disappears as soon as the heating of the sawblade is removed.

Frequency of the zero nodal diameter mode decreases with an increase in sawblade tensioning. Over-tensioning makes the zero nodal diameter frequency become equal to zero. Consequently the saw takes a zero diameter mode shape, producing a phenomenon called '*Dishing*'. Saw dishing corresponds to the buckling of the sawblade. It is produced by compressive radial stresses. When the dishing occurs, the surface profile of the sawblade looks like a shallow bowl. Dishing of the sawblade at operating speed causes the sawblade to produce undesirable tapered lumber. Running the sawblade at speeds higher than the current operating speed often results in rotational tensile stresses that counteract the compressive radial tensioning stresses and make the saw flat. The speed at which a dished sawblade becomes flat is called '*Dishing Speed*'. Thus for an optimum performance the sawblade should be run between the critical speed and dishing speed for a given tensioning.

The relationship between critical speed instability, tensioning and saw dishing is shown in Figure 2-4. The lowest critical speed and dishing speed curves divide the graph into three regions of snaking saw, stable saw and dished saw. When the operating speed of an unguided thin saw is close to the critical speed or above the critical speed, unstable saw vibrations resulting in snaking cut will occur. Typically, the snaking saw region includes many other critical speed curves corresponding to different mode shapes separated by small rotation speeds. However, practical experiences have shown that irrespective of the speed, all cuts performed in regions that are close to the snaking region suffer from high sawcut standard deviation resulting from a snaking sawblade. Therefore, the upper shaded area above the critical speed curve is unfavorable for practical lumber production in case of thin unguided circular saw.

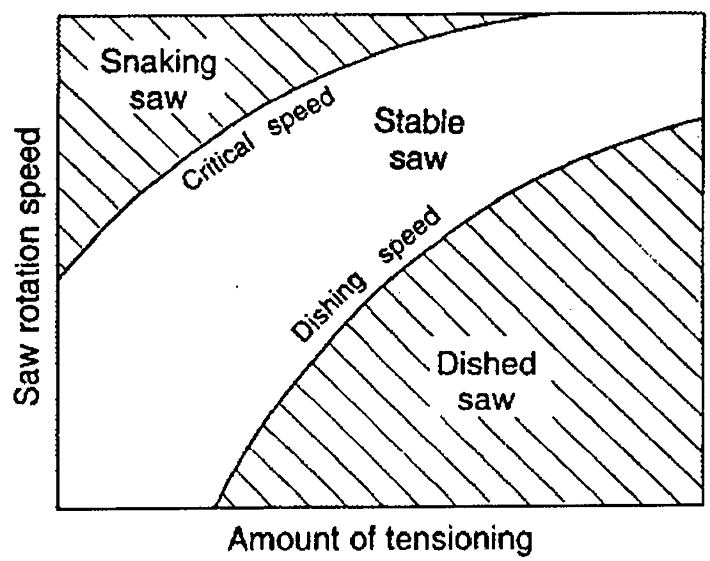


Figure 2-4 Schematic Relationship Between the Critical and Dishing Speeds of a Circular Saw and the Amount of Tensioning from, *Schajer* [34]

The lower bound for the satisfactory performance of the saw is decided by the dishing speed curve. When the saw rotation speed is less than the dishing speed, the radial compressive stress exceeds the rotational stresses and the sawblade dishes resulting in tapered lumber production. As the saw tensioning increases the dishing speed also increases requiring the sawblade to run at higher and higher speeds to counteract the radial compressive stresses. Therefore, for the production of accurate lumber with minimum sawcut standard deviation the saw should operate between the critical speed and the dishing speed curves. This is represented by the unshaded stable saw region.

2.1.3 Cutting Behavior of Thin Unguided Saws

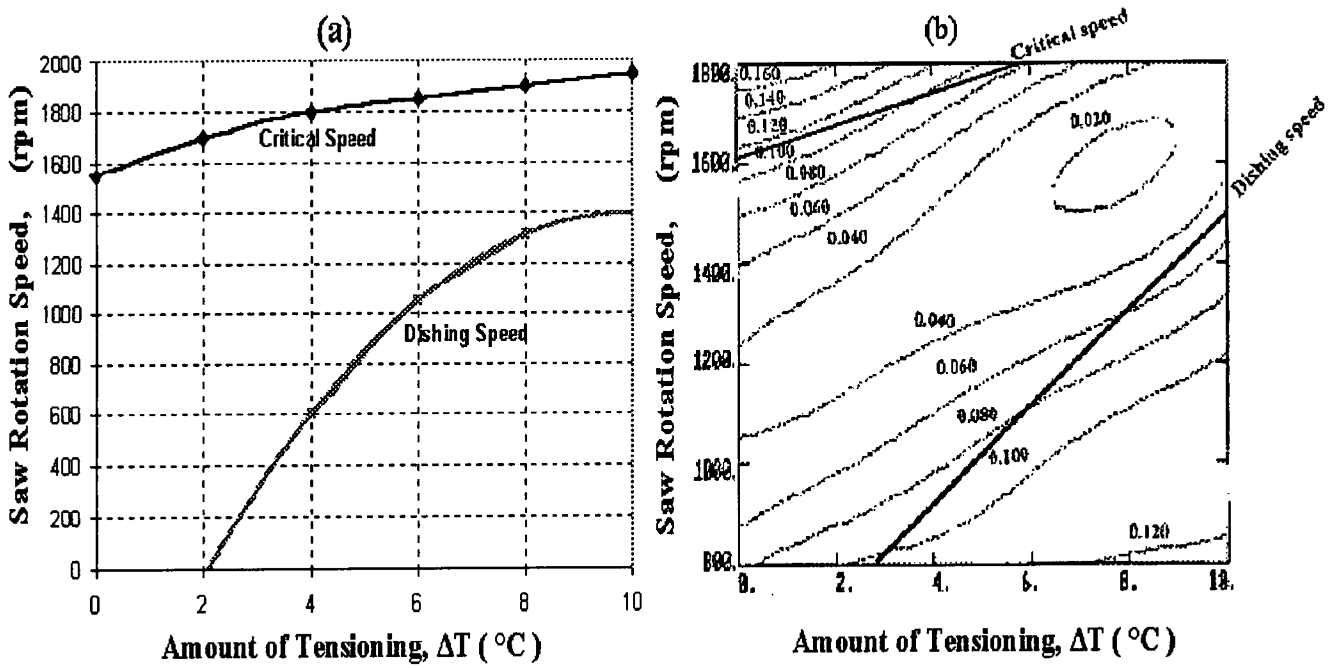


Figure 2-5 (a) Critical and Dishing Speed Variation (b) Sawcut Standard Deviation of a Fixed Collar Saw, from *Schajer* and *Wang* [36]

Figure 2-5 (a) shows the experimental observations of *Schajer* and *Wang* [36] in 1999, regarding the variation of critical speed and dishing speed with saw tensioning of a fixed collar saw. This is supplemented with a contour plot of sawcut standard deviations of extensive laboratory trials in Figure 2-5 (b). The contour plot of sawcut standard deviation shows increasing sawcut standard deviations as high as 700% in the snaking saw region compared to the stable region. The best cutting accuracy occurs between the critical and dishing speed lines and deteriorates with distance away from the stable saw region. Thus these experimental observations strongly supported the expectations from the critical speed theory that cutting accuracy of guided circular saws impairs distance away from stable cutting region.

2.1.4 Vibration of Guided Circular Saws

The introduction of guides considerably complicates the vibrational behavior of guided circular saws. The guides add stiffness to the saw near the cutting edge and distort the mode shapes from the simple trigonometrical forms typical of an unguided sawblade. The representation of guides and their influence on the behavior of saws presents a real challenge to the dynamic modeling of the guided circular saws. In many cases these guides are modeled simply as transverse springs acting on the saw surface. Figure 2-6 shows the variation of saw natural frequencies with saw rotation speed of a saw with transverse springs [7].

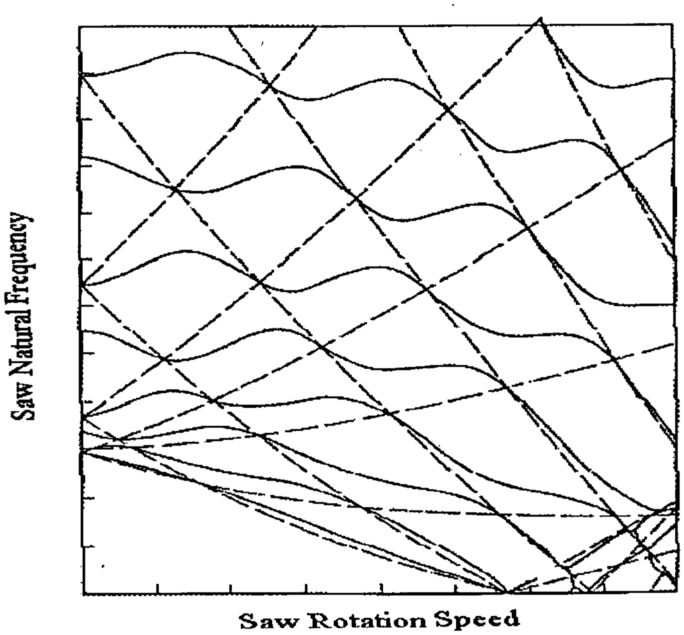


Figure 2-6 Natural Frequencies of a Guided Circular Saw vs. Rotation Speed, from *Hutton* [7]

These frequency curves show an interesting behavior of coupling between the modes. In this case, the natural frequency curves for different mode shapes do not cross each other as in case of an unguided saw. Instead, they approach closely and then turn away, after which each curve follows the direction originally followed by the other. Theoretical studies also revealed that the addition of guides does not cause any significant increase in the critical speed compared to that of an unguided saw. Experiments showed that for guides of practical dimensions the critical speed of guided saws is slightly less than or equal to that of unguided saws [31]. Therefore, improved cutting accuracy of the guided saws is not as a result of a change in critical speed. This contrasts with the behavior of fixed-collar unguided saws, whose cutting accuracy is strongly a function of critical and dishing speeds.

2.1.5 Guided Saw Cutting Behavior

In 1997, *Schajer and Kishimoto* observed the relationship between the critical speed, dishing and tensioning in case of a guided saw [34]. They found that the relationship follows the trend of an unguided saw with critical speeds and dishing speeds less than that of an unguided saw of the same dimensions. This is shown in Figure 2-7(a). However, the cutting tests conducted by *Schajer* and *Wang* in 1999 [36] with the same sawblade showed that first critical speed and dishing speeds have very little effect on guided saw cutting accuracy. The sawblade appeared to cut fairly well even in snaking and dishing regions. This is shown in the Figure 2-7 (b) in terms of a contour graph of sawcut standard deviations.

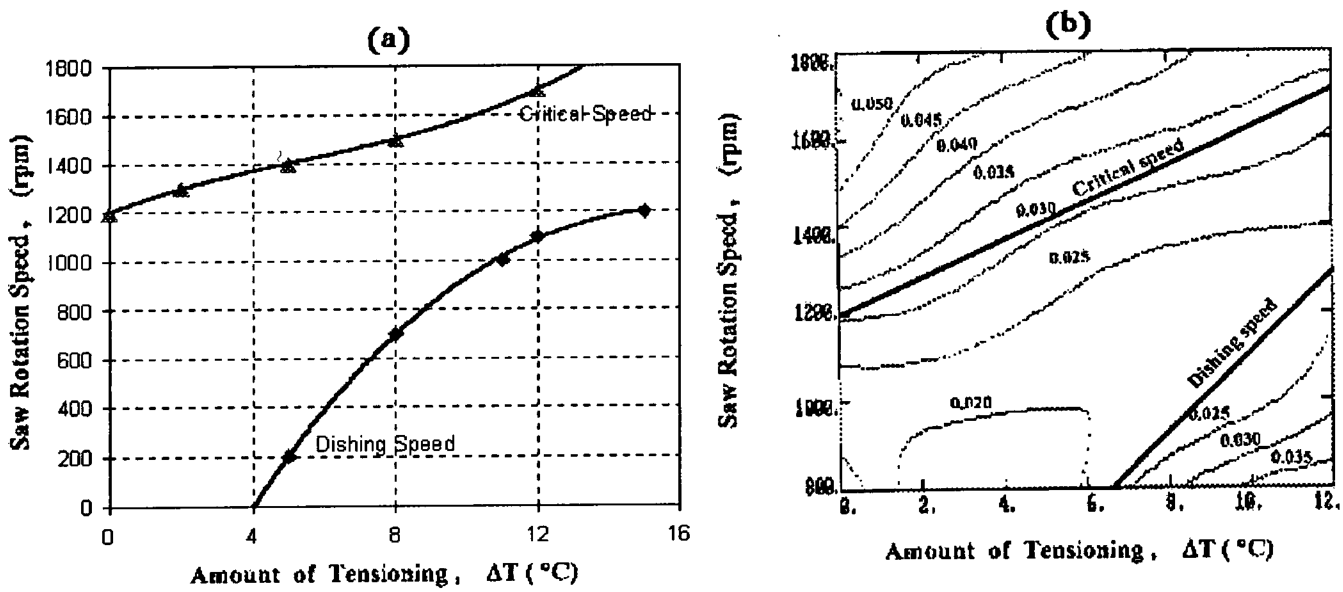


Figure 2-7 (a) Critical and Dishing Speeds of a Guided Circular Saw (b) Sawcut Standard Deviation for a Guided Saw, from *Wang* [37]

These experimental and industrial observations clearly indicated that only the idling behavior of guided saws follows the expectations derived from the theoretical models. The cutting behavior of guided saws does not match the theoretical expectations. Cutting tests also revealed the non-existence of separate snaking saw, stable saw and dished saw regions for guided circular saws. This finding was further substantiated by the experiments on supercritical sawing performance of guided circular saws, in which saws successfully performed at speeds higher than the lowest critical speed [18]. These experimental studies strongly suggested that the presence of workpieces influences the vibration behavior and cutting accuracy of guided circular saws.

2.2 Saw-Workpiece Interaction Models

Some of the recent studies [37] analyzed the cutting behavior of fixed collar saws and guided saws from the point of view of saw-workpiece interaction. These studies concluded that the workpiece interaction deteriorates the cutting accuracy of unguided saws where as it favors the stability of guided circular saws. These studies also developed simple saw-workpiece interaction hypotheses to reason the superior stability of the guided saws. These hypotheses mainly concentrated on sawbody-workpiece interaction and sawtooth-workpiece interaction. Sawbody-workpiece interaction tried to explain the superiority of guided saws compared to fixed collar saws where as sawtooth-workpiece interaction explained the superiority of climb cutting over counter cutting.

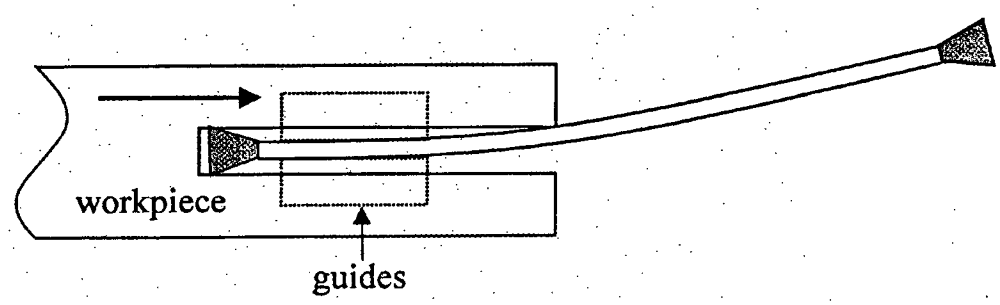


Figure 2-8 Sawbody-Workpiece Interaction of a Guided Saw, from *Wang* [37].

Figure 2.8 shows the plan view of sawbody-workpiece interaction of a guided circular saw. This model assumed that for guided saws the contact between workpiece and the sawbody takes place far away from the guides typically at the out feed end of the sawblade. As this contact takes place at a region of very low stiffness, the teeth at the out feed end run along the previously cut surface pushing the saw back to the line. This idea was supported by the subsequent experimental observation.

The sawtooth-workpiece interaction considered the reaction forces acting on the saw teeth, in both counter and climb cutting. Figure 2-9 shows the plan and side view of both arrangements.

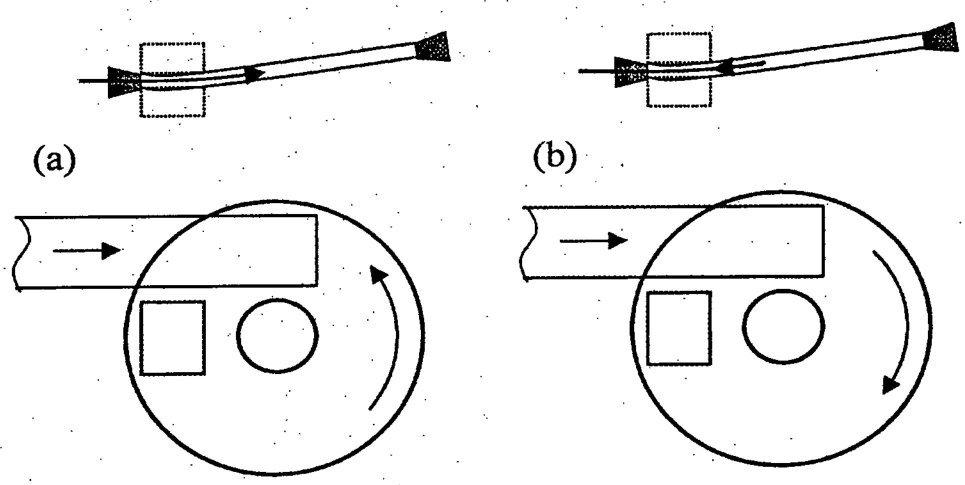


Figure 2-9 Cutting forces on a guided saw. (a) Counter Cutting, (b) Climb Cutting

It was assumed that whenever sawblade is bent slightly to one side, the reaction force exerted by the workpiece on the sawblade follows the slope of the saw. Thus, in counter cutting arrangement, when the saw is bent slightly to one side, the reaction force also turns slightly to that side. The sideways component of the reaction force increases the sideways deflection of the saw, and reduces cutting accuracy. The opposite situation occurs in the climb cutting arrangement. In this case the sideways component of the reaction force reduces the saw deflection from the centerline, and thereby improves sawing accuracy.

The results of the experiments validated the expectations derived from the hypotheses. Even though these models answered some of the fundamental questions related to the stability of guided saws, they do not contain all the needed details to explain the effect of other controlling variables on different sawing configurations. The present hypotheses try to extend the earlier models to identify and evaluate the effect of controlling variables on stability and cutting accuracy of guided circular saws in different sawing configurations.

2.3 *Proposed Saw-Workpiece Interaction Hypotheses*

2.3.1 Identification of Controlling Variables

Observations showed that the behavior of a guided sawblade during cutting is governed by many variables such as sawbody-workpiece contact, sawtooth-workpiece contact, saw tensioning, cutting configuration, friction between workpiece and sawbody, lateral cutting forces, saw tooth side clearances etc. The overall behavior of the sawblade during cutting is a result of the combined effect of all these variables or the one, which dominates rest of the variables. The Present study identifies saw tooth side clearance, added stiffness due to the presence of wood and lateral forces acting on the sawblade as major variables influencing the behavior of guided saws.

Close observations of the earlier models indicate that saw tooth side clearance controls the region of contact of the sawbody with workpiece. This is already shown in Figure 1-5. When the side clearance is greater, contact takes place far away from guides at a region of low lateral stiffness. Decreasing the side clearance results in the shifting of contact regions from low stiffness end to the high stiffness end. Accordingly, if the workpiece contacts the sawblade away from the guides, it results in a movement of the sawblade without excessive reaction forces. However, if the contact takes place at region of higher stiffness, it causes increased reaction forces that could further impair the stability of the blade. This shifting of the contact region is significant in deciding the cutting behavior of guided saws.

In a guided circular saw, in addition to the guides, the presence of wood restricts the lateral movement of the blade during cutting. This increases the stiffness of the sawblade locally. This additional stiffness makes significant contributions in explaining the behavior of guided saws. However, this added stiffness is a function of tooth side clearance. When the side clearance is large, this added stiffness does not assume a very high value, as there is enough gap inside the 'kerf' for the movement of the blade. However, experimental observations showed that the stiffness increases greatly as the side clearance is reduced to a very small value. An important aspect of this added stiffness is that, it increases with time (due to the movement of wood). Thus, saw tooth side clearance not only shifts the region of contact but also controls distribution of stiffness in the guided saw system during cutting.

A sawblade also experiences lateral forces during cutting. These forces exist because of sudden changes in the properties of the wood (change in grain direction, presence of knot etc) and cutting conditions during cutting. As per the observation, these forces are effective only when they act in a region of reduced stiffness. This can result in considerable displacement of the blade in a region away from the guides.

Since saw tooth side clearance controls both the stiffness distribution and sawbody-workpiece contact, it has been identified as a primary variable influencing the behavior of guided saws. Therefore, the following discussions analyze the effect of saw tooth side clearance on counter and climb cutting configurations and develop hypotheses based on the sawbody-workpiece interactions, increased stiffness by the presence of wood and lateral cutting forces.

2.3.2 Effect of Tooth Side Clearance on Climb Cutting

In a guided saw, guides provide support to the cutting edge and restrict the lateral motion of the sawblade irrespective of sawing configurations. The stiffness of the blade is maximum close to the guides and decreases both in horizontal and vertical direction. Part of the sawblade diametrically opposite to the guide is the most flexible region of the guided saw system.

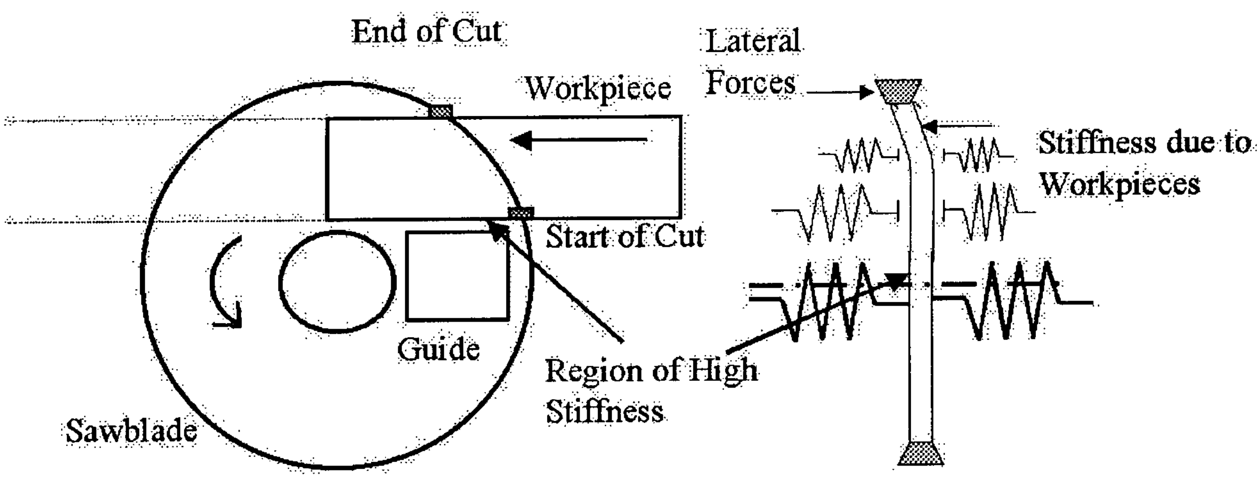


Figure 2-10 Climb Cutting Configuration

Figure 2-10 represents the practical climb cutting configuration during cutting. The side view of the cutting configuration represents dynamical equivalent of the physical system. The thick springs shown in the side view represent the guides. The added stiffness by the presence of workpieces is represented as non-contacting thin springs. The gap between the sawblade and the springs signify the saw tooth side clearance. The presence of the workpiece affects the stiffness distribution only when the lateral vibration of the blade exceeds tooth side clearance or when the side clearance itself becomes very small.

In case of climb cutting, the saw enters the cut just after leaving the guides. Therefore the beginning of the cut is well guided and stable. When the side clearance is large, contact between the saw body and workpiece takes place at the out-feed end of the sawblade. Added stiffness due to the presence of wood does not influence the stiffness distribution much as the gap between the sawbody and workpiece is large. The sawbody-workpiece contact at the out feed end is easily accommodated due to the reduced stiffness and availability of the space between sawbody and the surface profile of the wood. Disturbances of the blade lose its intensity once it passes through the guides before the beginning of cut.

The sawblade leaving the guides starts cutting the workpiece in regions of gradually decreasing stiffness. If present, lateral forces are effective and tend to move the sawblade only towards the end of the cut. However, this lateral movement is in a region of reduced stiffness and does not result in high reaction forces. As discussed in the earlier models, these lateral forces acting on the blade tend to move the blade back to its original position. The cutting region remains free from disturbances and the cut produced is accurate or of low standard deviation. Thus, it can be concluded that at large tooth side clearances, the influence of saw-workpiece interaction on a climb cutting blade is negligible.

When the side clearance is small, the gap between the sawbody and workpieces greatly decreases. This results in a bind between the sawblade and workpiece and additional lateral stiffness. This additional stiffness is present at the beginning of the cut and increases with time. The sawblade leaving the guides passes though a region of considerable stiffness. In the meantime as the side clearance is small, contact between sawbody and workpiece shifts closer to the guides. This results in a lateral movement of the blade in a region of high stiffness (due to the guides and due to the additional stiffness by wood) and results in high reaction forces and oscillation of the cutting edge. As the 'added stiffness' moves with the wood, reactions at the out feed end of the sawblade also gradually increase with time and may further reduce the cutting accuracy.

This hypothesis may also give possible explanation why single guided sawing configurations produce more accurate results than the configurations having guides both at the in feed and out feed end. From the critical speed theory, it can be expected that the additional stiffness provided by the second guide should limit the lateral movement of the blade and improve the cutting accuracy. However, this is not the case. The increased body stiffness may inhibit the self-centering behavior of guided saws. In the presence of a large added stiffness, the presence of a second guide may result in multiple regions having a very high lateral stiffness. Any misalignment in this environment could be catastrophic and may result in an unstable sawblade. Also, the sawbody-workpiece interactions in the stiff exit region may cause further reaction forces resulting in an oscillatory cutting edge.

In summary, it can be expected that the effect of tooth side clearance on climb cutting is not very influential at very large tooth side clearances. However, the cutting accuracy of climb cutting configuration is expected to deteriorate at smaller tooth side clearances. Also, it can be concluded that single guided configuration perform better than two-guided configurations at least at small tooth side clearances.

2.3.3 Effect of Tooth Side Clearance on Counter Cutting

In case of a counter cutting saw, the part of the sawblade leaving the cut passes thorough the guides. The cutting edge is stabilized only near the end of the cut. Figure 2-11 shows a counter cutting configuration. As shown in the figure, the sawblade begins the cut in a region of reduced stiffness away from the saw guides. Any lateral force acting on the blade in this region could disturb the blade significantly and result in an inaccurate cut. Therefore, the accuracy of the cut for counter cutting saws is governed mainly by the condition of the sawblade at the beginning of the cut.

When the side clearance is very large, the contact between the sawblade and workpiece takes place away from the guides, near the out feed end of the sawblade. As this is a region of very low stiffness any contact between the sawblade and workpiece produces considerable movement of the sawblade. As long as the displacement of the blade is small, the part of the blade entering the guide remains unaffected. However, if the saw operates above the critical speed, the high disturbances caused by the lateral movement of the blade and by the sawbody-workpiece interaction may cause an oscillating cutting edge entering the cut and thus reduced cutting accuracy.

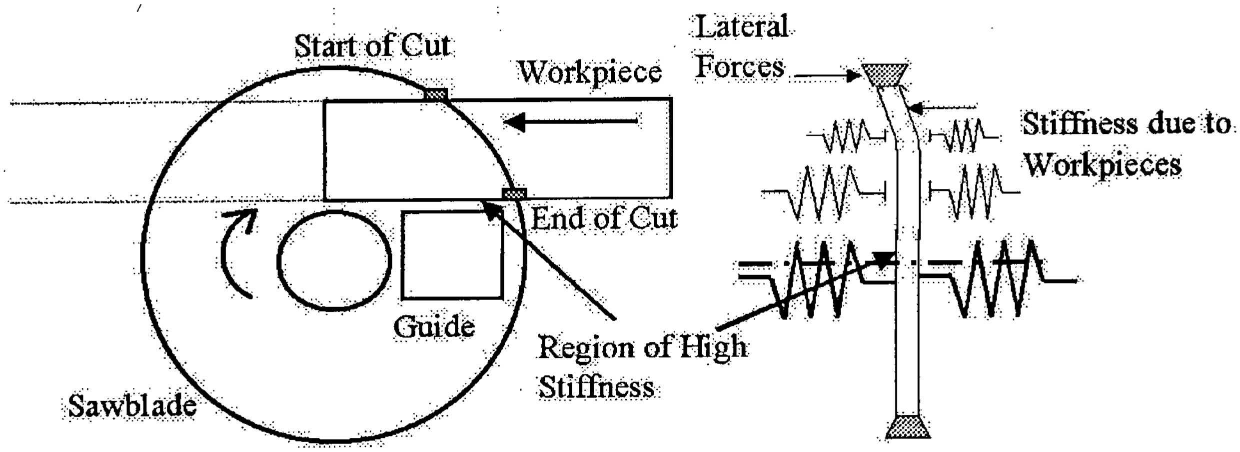


Figure 2-11 Counter Cutting Configuration

A sawblade entering the cut starts cutting the workpiece in regions of gradually increasing stiffness. If present, lateral forces are effective and tend to move the sawblade at the beginning of the cut. When the side clearance is large, this may not result in highly oscillating cutting edge. However, when the side clearance is small, the presence of lateral forces at the beginning of the cut in the form of sawbody-workpiece contacts assumes higher significance and may affect the cutting edge directly.

When the side clearance reduces to a small value, counter cutting has everything opposing the performance of a sawblade. As the saw tooth side clearance decreases the contact between the sawbody and workpiece become closer to the beginning of cut. The presence of wood also results in a region of considerable stiffness close to the beginning of cut. Any disturbance of the blade by sawbody-workpiece interaction or by lateral forces acting on the blade may result in high reaction forces at the beginning of the cut and result in an oscillating cutting edge entering the cut. This further damages the cutting accuracy. As the gap between the workpiece and the sawbody becomes very small, the oscillation of the cutting edge may result in severe sawbody-workpiece interactions and frictional heating of the sawblade.

The presence of second guide at the out feed end may have a different effect on the performance of a counter cutting saw. The additional guide stabilizes the sawblade considerably before it enters into the cut. This could be advantageous to the performance of a sawblade especially at large side clearances. The performance at smaller side clearances cannot be predicted clearly as it depends on many variables. In general, it can be expected that the reduction in side clearance does not favor the cutting accuracy of two-guided counter cutting configuration.

Based on the above arguments, it can be concluded that tooth side clearance influences the cutting stabilities of both climb and counter cutting configurations. It can be expected that increased saw-workpiece reactions and shift in the contact region deteriorate the cutting accuracy at smaller tooth side clearances. By comparison, it can be concluded that climb cutting performs better than counter cutting even at small side clearances, because of the stable cutting edge. Table 2.1 summarizes these points and compares different configurations.

		Climb Cutting		**Counter Cutting**	
		Single Guided	Two-Guided	Single Guided	Two-Guided
Saw-Workpiece Interactions	Large Side Clearance	Good	Bad	Bad	Good
	Small Side Clearance	Bad	Worse	Worse	Not Clear

Table 2-1 Comparison of the Cutting Stabilities of Different Sawing Configurations based on the Hypotheses

The analysis presented here rank the configurations qualitatively based on the hypotheses. The conclusions drawn here could be verified either by the formulating a theoretical model or subsequently by conducting the experiments. The theoretical model presented in the

Chapter 3 and experimental studies carried out as a part of this thesis are designed to give further insight into the hypotheses presented here.

CHAPTER 3 THEORETICAL MODEL

This chapter explains the formulation of a theoretical model simulating the sawing behavior of a guided circular saw. The development of the model is based on the hypotheses developed in the Chapter 2. The first phase of this chapter explains the model development and formulation. This is followed by the results derived from the model and analysis of the results. The purpose of the model is to verify the hypotheses made earlier regarding the influence of tooth side clearance as a controlling variable in deciding the cutting behavior of guided circular saws.

3.1 Development of the Model

A simplified theoretical model which models and simulates the dynamic behavior of guided saws is required to understand the influence of controlling parameters on the characteristics of guided saws. As discussed in the Introduction and Overview Chapter, some of the effort has been already done in developing the models based on eigenvalue analysis. These models typically modeled the frequency characteristics of the guided saws. However, they generally ignored the sawbody and workpiece interactions mainly because of their non-linearity and the difficulty involved in modeling them realistically.

The complication associated in representing the guided saw behavior could be reduced substantially if a time-domain based analysis is used instead of a frequency-based eigenvalue analysis. Even though this approach does not reveal the variation of the frequencies of the guided saw system in the presence of saw-workpiece interactions, it does characterize the system behavior at different distinct points of time. This method has an additional advantage of easily including the nonlinear sawbody-workpiece interactions of guided circular saws. The earlier model developed by *Wang and Schajer*[36] used this idea. They modeled the portion of the sawblade contacting the workpiece as a straight beam resting on an elastic foundation. Values of the foundation springs were varied to simulate guided and fixed collar sawblades.

Even though the earlier model was able to represent the behavior of guided saws, it was not complete in representing the circular configuration of the sawblade and the effect of traveling disturbances. The aim of the present model is to extend the idea of time based analysis to model and represent the circular configuration and dynamic behavior of guided circular saws.

The development of the current model is based on following guidelines.

- The dynamic model should represent and simulate the effect of tooth side clearance on saw-workpiece interaction and cutting accuracy of guided saws in different guide configurations.
- The model should realistically represent the frequency characteristics of an idling saw.
- It should be as simple as possible to avoid mathematical complexity and computational time.

Instead of modeling guided saw as a circular plate, the sawblade can be modeled as a chain of elements connected together in a circular form. This reduces the mathematical complexity and computational time required for the simulation. Earlier model developed by *Schajer* [30] represented guided circular saw as a rotating string subjected to a fixed elastic restraint and was successful in explaining most of the characteristics associated with the guided saw system. The present model follows the earlier formulation. However, the present formulation represents the guided sawblade as a chain of beam elements to get more realistic dynamic characteristics.

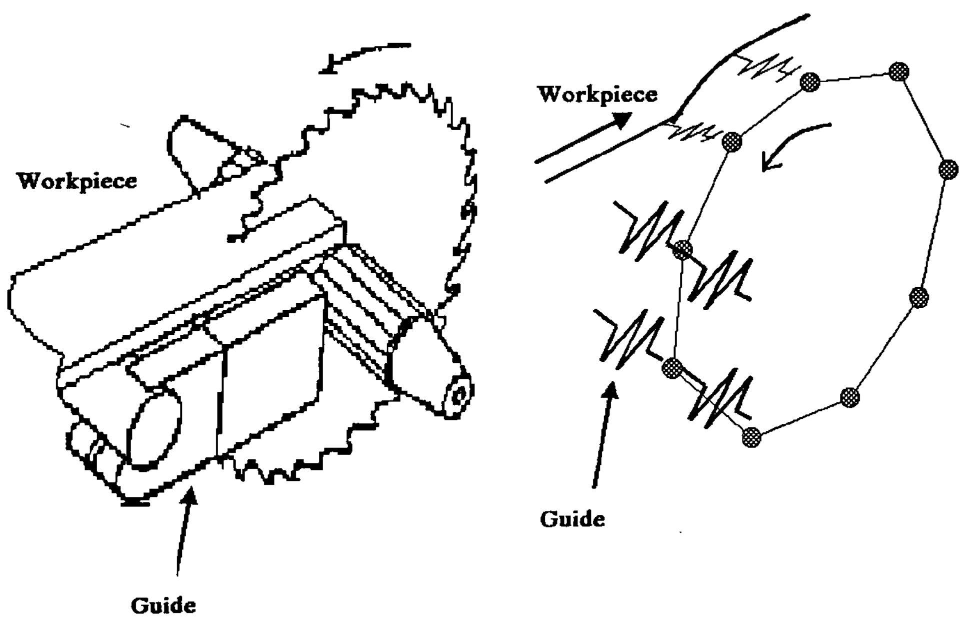


Figure 3-1: (a) Guided Circular Saw Cutting Wood, (b) Simplified Model of the Sawblade as a chain of Beam Elements on an Elastic Foundation

Figure 3-1 shows a guided circular saw and its equivalent finite element representation as a circular chain of beam elements on an elastic foundation. Figure 3-1(a) shows a guided saw cutting wood. In the case of guided saws, guides support the cutting edge during cutting. The stiffness of the blade decreases distance away from the guides. The presence of guides is represented in the model by foundation springs attached to the beam elements. The effect of saw rotation speed influencing the stiffness of the blade could be modeled by following Eulerian approach where the nodes are fixed in space and the ring rotates through the nodes.

During cutting, the workpiece moves forward and the area of the sawblade along the path of the workpiece experiences saw-workpiece interactions when the saw lateral vibration exceeds tooth side clearance. Realistic simulation of this requires a complete circular plate model of the sawblade. However, a similar effect could be achieved if it is assumed that the workpiece moves along the periphery of the circular ring of beam elements. In that case, the workpiece enters the ring at a particular node, moves along the periphery of the ring and exits at a different node. However, special attention should be given while selecting the nodes where the workpiece flows into and out of the model.

In reality, the presence of wood adds additional stiffness to the lateral movement of the blade. As described earlier in the hypotheses, this additional stiffness becomes effective only when the lateral vibration of the blade exceeds tooth side clearance. Therefore, this additional stiffness is represented in terms of springs attached to the workpiece surface. These springs are not attached to the circular ring. There is a small gap between the springs and the blade surface equal to the tooth side clearance. These springs restrict the lateral movement of the blade only if it exceeds the gap or when the gap itself becomes very small. This arrangement realistically represents the non-linear sawbody-workpiece interaction. For clarity only one workpiece surface has been shown in Figure 3-1 (b).

The comparison between a guided saw performing cutting and the corresponding simplified finite element model is shown in the Figure 3.2. As shown in the figure the portion of the blade inside the wood performs cutting. The sawbody-workpiece interactions take place along the path of workpiece and continue till the workpiece crosses the out feed end of the blade. The phenomenon of cutting and saw-workpiece interaction could be simulated together in the circular beam model if it is assumed that only the node at which workpiece enters the ring performs cutting and generates the surface profile. The surface generated by this node decides the position of the gap between the blade and the surface. All other nodes in between the entry node and the exit node simulate saw-workpiece interaction based on the gap between the surface profile and node position. As the workpiece moves forward, the profile of the surface passes from node to node. The sawbody-workpiece interactions continue till the out feed end of the sawblade. Exit node is at a region diametrically opposite to the guides to include possible saw-workpiece interactions.

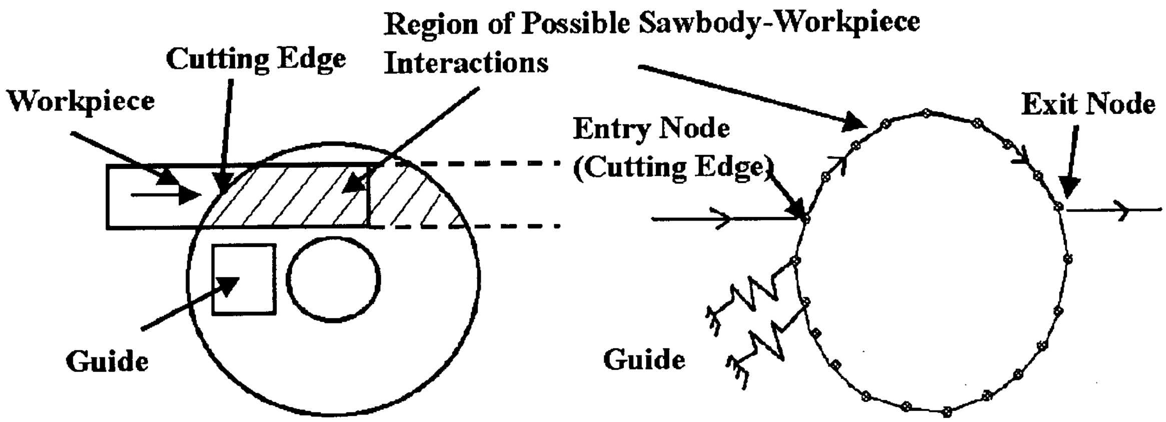


Figure 3-2 Comparison of a Guided Saw Cutting wood and the Corresponding Model Parameters

Beam elements are connected to each other at nodes. All the calculations are done based on the nodal values of displacement. Spatial representation of the nodes of a circular ring requires a two-dimensional representation. However, the circular ring can conceptually be "unrolled" into a straight line to simplify the spatial representation of nodes. This is represented in Figure 3-3. However, the stiffness calculation of the circular ring considers circular arrangement of beam elements.

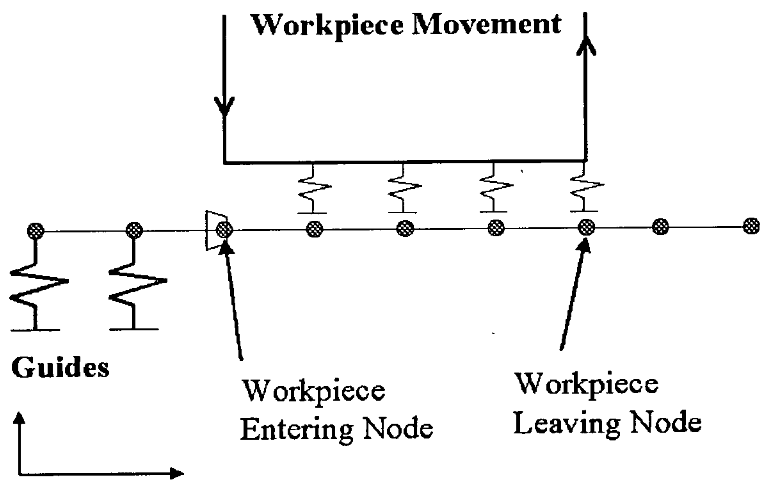


Figure 3-3 Spatial Representation of nodes and the workpiece movement

3.2 *Formulation of Theoretical Model*

3.2.1 Vibration of a Circular Beam

Formulation of the model is based on the vibration of a circular beam. The energy method is used to derive the equation of motion of the system. The *Rayleigh-Ritz* method is used to discretize the system and to get an approximate numerical solution.

A simple circular beam is assumed to have a uniform cross section with flexural rigidity *EI*. The radius of the beam is *R*. The beam is assumed to have foundation stiffness per unit length as *k*. *m* is the mass per unit length of the beam. Circular beam is assumed to rotate at *Ω* radians/sec. *u* is the lateral displacement of the beam at an angle *θ* with respect to the coordinate system fixed in space. The beam is analyzed in its linear elastic range.

For this configuration, the potential energy *V* associated with the beam is

$$V = \int_0^{2\pi} \frac{EI}{2}\left(\frac{1}{R^2}\frac{\partial^2 u}{\partial \theta^2}\right)^2 R d\theta + \int_0^{2\pi} \frac{1}{2} k u^2 R d\theta \qquad 3.1$$

Similarly, the kinetic energy associated with the circular beam is

$$T = \int_0^{2\pi} \frac{m}{2}\left(R^2\Omega^2 + \left(\frac{\partial u}{\partial t} + \Omega\frac{\partial u}{\partial \theta}\right)^2\right) R d\theta \qquad 3.2$$

where,

EI	Flexural rigidity of the beam:
R	Radius of the Circular beam;
k	Foundation stiffness per unit length;
m	mass per unit length;
Ω	rotation frequency radians/sec;
u	Lateral displacement of the beam;
θ	Angular coordinate with respect to fixed coordinate system

According to Hamilton's principle, the motion of the system from time t_1 to time t_2 is such that the integral

$$\delta\int_{t_1}^{t_2}(V-T)dt=0 \qquad 3.3$$

Applying Hamilton's principle to Equations *3.1* and *3.2* results in,

$$\delta\int_{t_1}^{t_2}\int_0^{2\pi}\left[\frac{EI}{2}\left(\frac{1}{R^2}\frac{\partial^2 u}{\partial\theta^2}\right)+\frac{k}{2}u^2-\frac{m}{2}\left(R^2\Omega^2+\left(\frac{\partial u}{\partial t}+\Omega\frac{\partial u}{\partial\theta}\right)^2\right)\right]Rd\theta=0 \qquad 3.4$$

$$i.e.\ \int_{t_1}^{t_2}\int_0^{2\pi}\left[\frac{EI}{R^4}\left(\frac{\partial^2 u}{\partial\theta^2}\frac{\partial^2 \delta u}{\partial\theta^2}\right)+\frac{k}{}u\delta u\ -\frac{m}{2}\left(\frac{\partial u}{\partial t}+\Omega\frac{\partial u}{\partial t}\right)\left(\frac{\partial\delta u}{\partial t}+\Omega\frac{\partial\delta u}{\partial\theta}\right)\right]Rd\theta dt=0 \qquad 3.5$$

Rearranging the terms results in equation,

$$\int_{t_1}^{t2}\int_0^{2\pi}\left[\frac{EI}{R^4}\frac{\partial^2 u}{\partial\theta^2}\right]\frac{\partial^2\delta u}{\partial\theta^2}Rd\theta dt-\int_{t_1}^{t_2}\int_0^{2\pi}\left[m\Omega\frac{\partial u}{\partial t}+m\Omega^2\frac{\partial u}{\partial\theta}\right]\frac{\partial\delta u}{\partial\theta}Rd\theta dt$$
$$+\int_{t_1}^{t_2}\int_0^{2\pi}ku\delta uRd\theta dt-\int_{t_1}^{t_2}\int_0^{2\pi}[m\frac{\partial u}{\partial t}+m\Omega\frac{\partial u}{\partial\theta}]\frac{\partial\delta u}{\partial t}dtRd\theta=0 \qquad 3.6$$

Numerical solution of the above equation could be obtained using the *Rayleigh-Ritz* method to discretize the system. Assume the displacement of the beam at any point in the space and time $u(\theta,t)$ as

$$u(\theta,t)=\sum_{i=1}^{n}\phi_i(\theta)q_i(t) \qquad 3.7$$

where $\Phi_i(\theta)$ is a trial function of space and $q_i(t)$ is a function of time.

Substituting the approximate variable separable solution into Equation *3.6* and applying domain and boundary conditions for circular arrangement results in

$$\int_{t_1}^{t_2}\int_{0}^{2\pi}\left[\left(\frac{EI}{R^4}\sum_i\frac{\partial^2\phi_i}{\partial\theta^2}q_i\right)\sum_j\frac{\partial^2\phi_j}{\partial\theta^2}\delta q_j+\left(k\sum_i\phi_i q_i\right)\sum_j\phi_j\delta q_j-\left(m\Omega\sum_i\phi_i\dot{q}_i+m\Omega^2\sum_i\frac{\partial\phi_i}{\partial\theta}q_i\right)\sum_j\frac{\partial\phi_j}{\partial\theta}\delta q_j\right]Rd\theta dt$$
$$+\int_{t_1}^{t_2}\int_{0}^{2\pi}\left[m\sum_i\phi_i\ddot{q}_i+m\Omega\sum_i\frac{\partial\phi_i}{\partial\theta}\dot{q}_i\right]\sum_j\phi_j\delta q_j Rd\theta dt=0$$

3.8

The variation of δq_j is arbitrary for all values of j. and t_1 and t_2 are also arbitrary. Therefore the equation *3.8* could be written in the form

$$\int_0^{2\pi}\sum_i\left[m\phi_i\phi_j\ddot{q}_i+m\Omega\left(\frac{\partial\phi_i}{\partial\theta}\phi_j-\phi_i\frac{\partial\phi_j}{\partial\theta}\right)\dot{q}_i+\left(\frac{EI}{R^4}\frac{\partial^2\phi_i}{\partial\theta^2}\frac{\partial^2\phi_j}{\partial\theta^2}+k\phi_i\phi_j+m\Omega^2\frac{\partial\phi_i}{\partial\theta}\frac{\partial\phi_j}{\partial\theta}\right)q_i\right]Rd\theta=0$$

i.e. $\sum_i\left[m_{ji}\ddot{q}_i+c_{ji}\dot{q}_i+k_{ji}q_i\right]=0$ *3.9*

where ,
$$m_{ij}=Rm\int_0^{2\pi}\phi_i\phi_j d\theta \qquad c_{ij}=m\Omega\int_0^{2\pi}\left(\phi_i\frac{\partial\phi_j}{\partial\theta}-\phi_j\frac{\partial\phi_i}{\partial\theta}\right)Rd\theta$$
$$k_{ij}=\int_0^{2\pi}\left(\frac{EI}{R^4}\frac{\partial^2\phi_i}{\partial\theta^2}+k\phi_i\phi_j+m\Omega^2\frac{\partial\phi_i}{\partial\theta}\frac{\partial\phi_j}{\partial\theta}\right)Rd\theta$$

Rearranging the terms results in the equation of motion of the system.

i.e. $\tilde{\tilde{M}}\ddot{q}+\tilde{\tilde{C}}\dot{q}+\tilde{\tilde{K}}q=0$ *3.10*

where $\tilde{\tilde{M}}$ is the mass matrix, $\tilde{\tilde{C}}$ is the gyroscopic matrix and $\tilde{\tilde{K}}$ is the stiffness matrix. Here the mass matrix $\tilde{\tilde{M}}$ and the stiffness matrix $\tilde{\tilde{K}}$ are symmetric whereas the gyroscopic matrix $\tilde{\tilde{C}}$ is skew symmetric.

Equation *3.10* represents a polynomial eigenvalue problem. The imaginary parts of the roots of equation *3.10* represents the natural frequencies associated with different mode shapes. A computer program was developed to calculate the mass, stiffness and gyroscopic matrices for number of beam elements connected in a circular form. This program was tested by comparing the calculated natural frequency results with an analytical solution. For a circular beam on an elastic foundation the analytical solution for calculating the natural frequency is given by

$$f_n = \frac{1}{2\pi}\sqrt{\frac{16\pi^4 n^4}{L^4}\frac{EI}{m}} + \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad 3.11$$

where n = number of nodal diameters (*0,1,2* ....)

and L =length of the beam element,

k = foundation stiffness per unit length and m = mass per unit length

The model was tested for $L = 2\pi$, $EI = 1$, k=1 and m=$1/4\pi^2$ and with 7 beam elements and at zero saw rotation speed. The natural frequencies for this configuration equal to 1.00, 1.4142, 4.123, 9.055 for n=0,1,2 and 3 respectively. The values calculated obtained from the model were in close agreement with these values.

For a rotating beam, at rotation speed Ω rad/sec > 0., the natural frequency splits into forward and backward traveling waves and is given by

$$f_t = f_n \pm n\Omega \qquad 3.12$$

This analytical solution was tested for different rotation speeds of the sawblade and found to be in good agreement with the calculated values. This also confirmed the correct functioning of the circular beam formulation. Figure 3.4 shows the variation of natural frequencies of different mode shapes with saw rotation speed for a guided configuration. Attaching foundation springs to the nodes represents guides. The variation of the natural frequencies is similar and follows the same trend as obtained from the theoretical plate model of guided saws shown in Figure 2.6. The difference is that plate model variations are slightly curved due to the presence of rotational stresses. The rotation speed at which the backward traveling wave frequency of a mode shape becomes zero represents the critical speed associated with that mode shape.

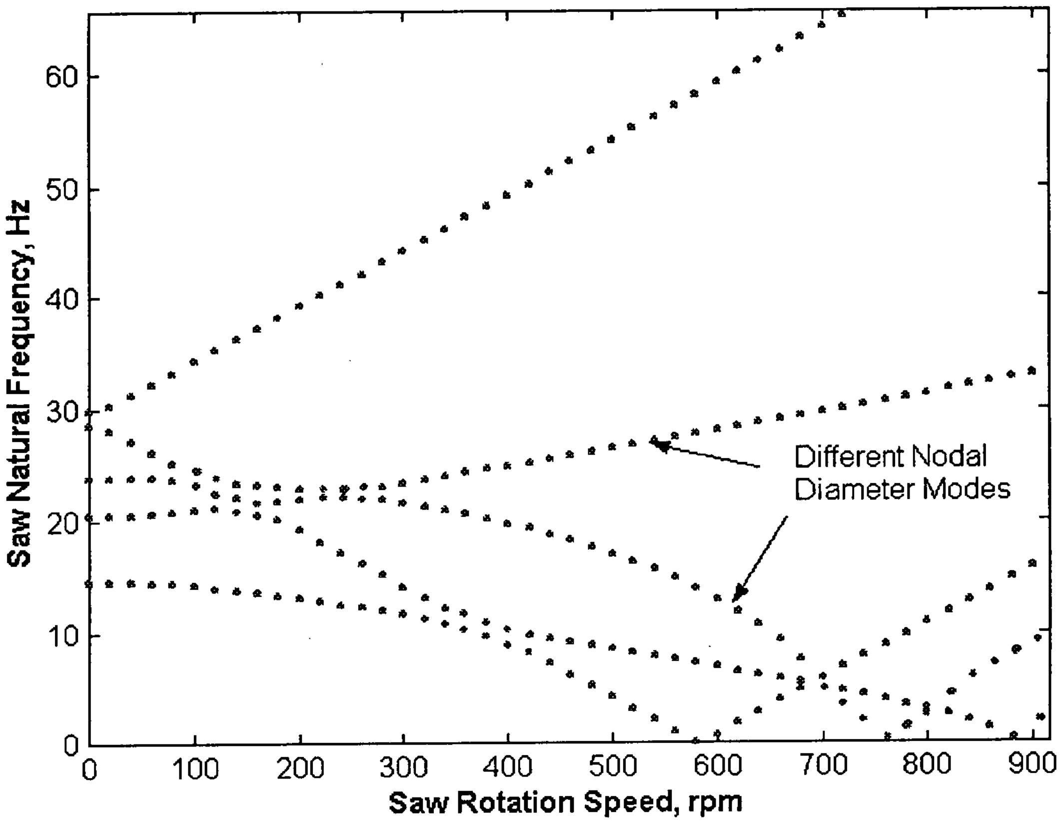


Figure 3-4 Natural Frequencies of a Rotating Circular Ring of Beam Elements with Foundation Stiffness Representing Guides

The presence of a forcing function acting on the circular beam results in an additional term in the potential energy function and modifies equation *3.11*. For concentrated forces acting on the nodes, the equation *3.11* can be modified as

$$\tilde{\tilde{M}} \ddot{q} + \tilde{\tilde{C}} \dot{q} + \tilde{\tilde{K}} q = \tilde{\tilde{F}} \qquad 3.13$$

where, $F_i = \sum_j F_j \phi_i(\theta_j)$ and F_j is the concentrated force acting on the nodes.

3.2.2 Coordinate Transformation

Equation *3.7* defines the lateral movement of the sawblade as a function of time t and angular coordinate θ fixed in space. For any arbitrary value of the foundation stiffness k, the mode shapes corresponding to the beams can be used as trial functions of space. Therefore, the displacement of the beam can be represented as

$$u(\theta,t)=\sum_i \phi_i(\theta)q_i(t) \qquad 3.14$$

where, with $i=0,1,2,\ldots..,$

for even i, $\Phi i(\theta)=\cos n\theta$, $\quad n=i/2$, $\qquad$ 3.15

for odd i, $\Phi i(\theta)=\sin n\theta$, $\quad n=(i+1)/2$, $\qquad$ 3.16

However, the discretization of the model requires the deformed configuration of the circular ring in terms of nodal displacements rather in terms of trigonometric coefficients of q_i. Substituting the equations *3.14* and *3.15* into *3.13* gives transformation of the coordinates in terms of nodal displacements as

$$u_j=\sum_i \phi_i(\theta_j)q_i(t)$$ where θ_j is the angular location of nodes.

$$\text{i.e.} \quad \begin{bmatrix} u_1 \\ u \\ u_3 \\ u_4 \\ u_5 \\ . \\ . \end{bmatrix} = \begin{bmatrix} 1 & \sin\theta_1 & \cos\theta_1 & \sin 2\theta_1 & \cos 2\theta_1 & . & . \\ 1 & \sin\theta_2 & \cos\theta_2 & \sin 2\theta_2 & \cos 2\theta_2 & . & . \\ 1 & \sin\theta_3 & \cos\theta_3 & \sin 2\theta_3 & \cos 2\theta_3 & . & . \\ 1 & \sin\theta_4 & \cos\theta_4 & \sin 2\theta_4 & \cos 2\theta_4 & . & . \\ 1 & \sin\theta_5 & \cos\theta_5 & \sin 2\theta_5 & \cos 2\theta_5 & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \\ . \\ . \end{bmatrix}$$

This can be represented as $\tilde{u}=\approx{T}_r\tilde{q}$ or $\tilde{q}=\approx{S}\tilde{y}$ where $\approx{S}=\approx{T}_r^{-1}$

T_r is called the transformation matrix, which maps the blade movement in terms of nodal displacement values. Substituting equation *3.15* into *3.12* results in following equation.

$$\tilde{\tilde{S}}^T \tilde{\tilde{M}}\tilde{\tilde{S}}\ddot{u}+\tilde{\tilde{S}}^T \tilde{\tilde{C}}\tilde{\tilde{S}}\dot{u}+\tilde{\tilde{S}}^T \tilde{\tilde{K}}\tilde{\tilde{S}}u=\tilde{\tilde{S}}^T \tilde{F} \quad 3.17$$

$$=M^*\ddot{u}+C^*\dot{u}+K^*u=F^*$$

where, $M^* = S^T M S$ $\quad C^*=S^T C S$ $\quad K^*= S^T K S$

Equation *3.17* represents the equation of motion for the finite element model. The calculation of blade displacement as a function of time is based on the mass, stiffness and gyroscopic matrices of equation *3.17*.

3.3 Saw Cut Simulations

The numerical model previously described was used to create a simulation of the behavior of the saw in time domain during woodcutting. This simulation was achieved by modifying the program so that it simulated a workpiece passing along a beam model. This was done by considering a series of small time increments and advancing the workpiece pass the sawblade in corresponding steps.

Figure 3.5 shows the plan view of ring of beam elements performing cutting. The workpiece moves from left to right causing cutting to take place at the left end of the beam. The side clearance of the teeth present at the nodes results in a kerf width greater than the beam width. As the cutting proceeds, the part of the circular beam becomes entirely contained with in the 'kerf'. Lateral cutting forces applied at the cutting tooth can move the tooth sideways. The saw cut surface represent the history of this sideways motion.

Integrating the equation *3.16* over a series of small time intervals, calculates the corresponding displacement and velocity of the nodes as a function of time. Thus, corresponding beam deformations could be computed. Whenever the workpiece starts to touch the beam surface, additional force representing the saw-workpiece interaction is introduced to contain part of the beam with in 'kerf'. The displacement of the beam is then locally constrained to match the sawn surface at contact points. This also results in pushing of the sawblade back to its line of cut. This iterative calculation can be computed for every time interval and the cut surface can be generated sequentially.

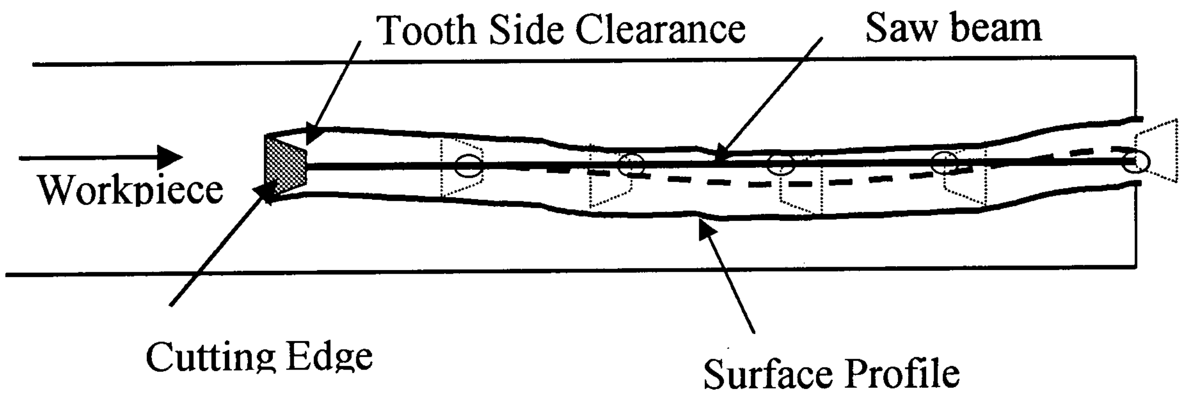


Figure 3-5 Beam Model Cutting the Workpiece

Based on the dimensions used for the test saw following quantities were chosen for the circular beam model. The foundation stiffness was interpolated for nodes between the stiff end and flexible end.

Parameter	Value Used
Outer Diameter of the ring	0.750 m
Inner Diameter	0.140 m
Thickness	0.002 m
Flexural rigidity, EI	23.54 Pa. m^4
Foundation stiffness near Guides	2.5 MN/m
Mass per unit length	3.1 Kg/m
Feed speed	0.5 m/sec
Workpiece length	1.2 m

Table 3-1 Dimensions and Parameters used for the Model

Calculations were done for a guided circular in climb cutting configuration at different tooth side clearances and guide configurations. All the calculations had the same dimensions and were modeled by the same circular beam arrangement. The only difference was that the circular beam for the single guided configuration had foundation stiffness only near the node performing as a cutting tooth. The two-guided configuration had foundation stiffness both at the in feed end as well as at the out feed end. The sizes of the foundation stiffness used were chosen based on the earlier beam model.

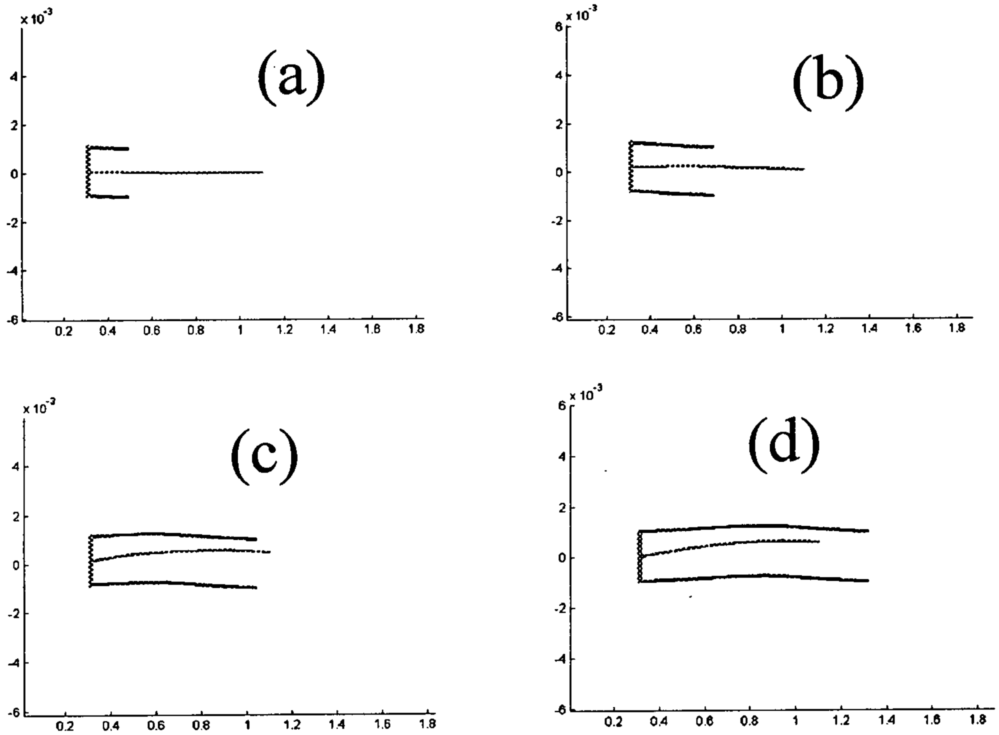


Figure 3-6 Snapshots of a Beam Representing a Guided Climb Cutting Saw during Wood Cutting Operating in a Stable Rregion. Tooth Side Clearance 0.001 m (approximately 0.038")
X-axis: Workpiece Length (in m.)   Y-axis: Sideways Displacement (in m.)

Figure 3.6 shows a sequence of snap shots of the side ways displacement of the part of the circular beam in contact with the workpiece (segment of the beam in between entry node and exit node). A constant side ways force of 1.5 N acts at the cutting edge of the beam. In each of the component diagrams, the upper and the lower curve represents the surface generated whereas the middle curve represents the part of the beam in engagement with the workpiece. The proportions of the beam and tooth dimensions are exaggerated to allow a clear viewing of the cut surface. However, the calculation used considers the dimensions in correct proportions. The cutting force applied was in the same direction through out the cut. However, the cutting edge starts moving in the opposite direction after the first sawbody-workpiece contact. This shows that saw-workpiece contact control the cutting edge oscillation.

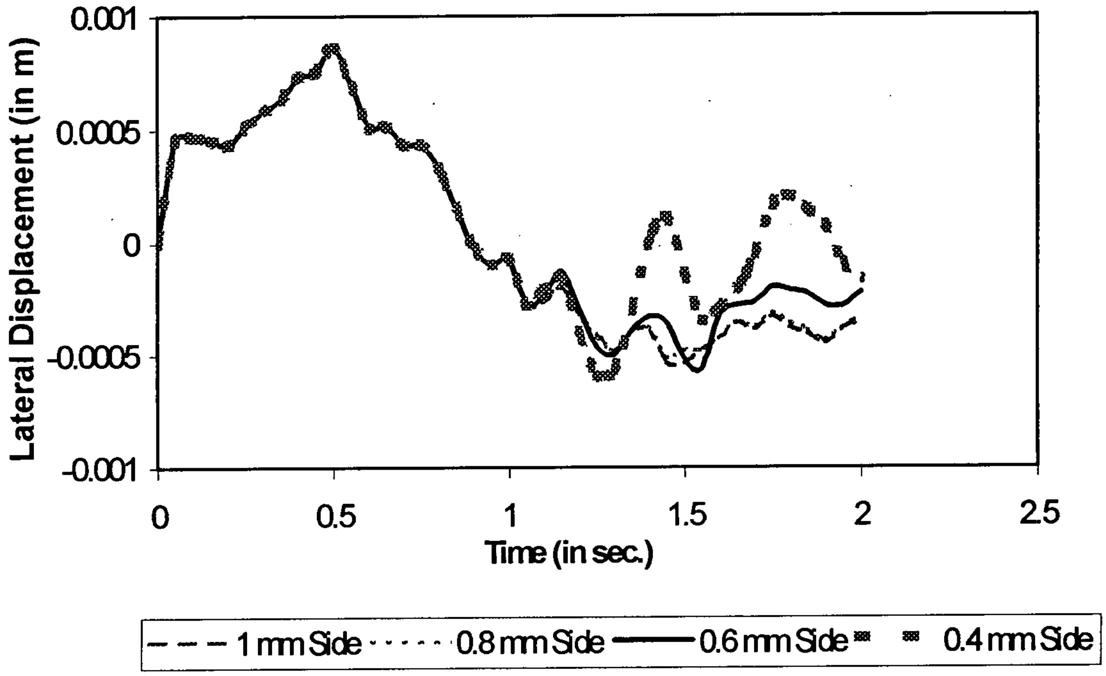


Figure 3-7 Calculated Sideways Displacement of a Circular Beam Model in Climb Cutting at different Tooth Side Clearances

Figure 3.7 compares the calculated lateral deflections of the cutting edge vs. time for a climb cutting saw for four different tooth side clearances. A constant lateral force of 1.5 N was applied at the cutting tooth for all the cases. For all the configurations, the beginning of the cut results is same. However, as the cut progresses, the effect of sawblade-workpiece contact could be clearly noticed. At large side clearances the blade deflection is gradual. This gradual movement continues till the end of the cut. However, when the side clearance becomes very small, this gradual movement transforms into rapid oscillations especially when the blade is fully contained with in the sawcut.

Results of the simulation clearly demonstrate the importance of tooth side clearance as a primary variable controlling the cutting accuracy of guided saws. The deflection of the cutting also showed the ability of guided circular saws to come back to the line of cut even in the presence of a cutting forces. The snapshots of the simulation showed increased saw-workpiece contact at small side clearances. Usually this type of contacts result in frictional heating and unstable cutting edge. The present model does not include this effect. Therefore, it can be expected that the cutting experiments with a reduced side clearance are bound to indicate a highly unstable cutting edge.

Figure 3.8 compares the simulation results of a climb cutting saw in single-guided and two-guided configuration at 0.001 and 0.0008 m side clearance. The results complement the expectations drawn from the hypotheses. Two-guided configuration results in highly oscillatory cutting edge once the beam get contained with in the sawcut. At very low side clearances, two-guided configuration posed computation difficulty and hence the cutting edge deflection was not calculated.

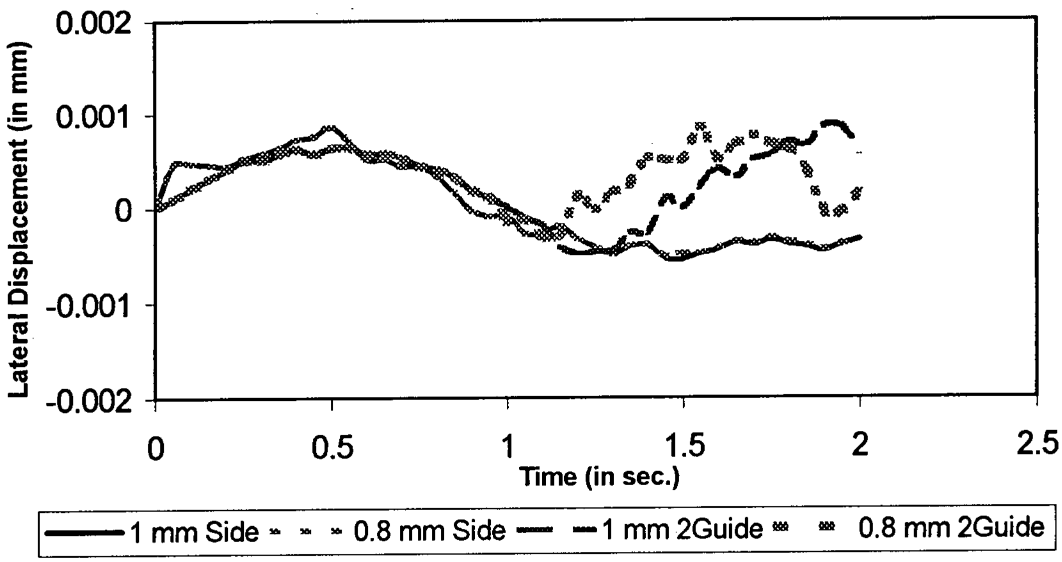


Figure 3-8 Calculated Sideways Displacements of a Beam Model for Single and Two-Guided Configurations

The simple circular beam model presented here simulates the behavior of the sawblade closely. The sawblade behaviors illustrated in figure 3.7 and 3.8 are in good agreement with the conclusions drawn from the hypotheses. Other configurations such as counter cutting and cutting with simulated workpiece feed error are not simulated because of the difficulty in modeling them realistically. However, the simulated results of climb cutting strongly suggest the need for experiments to determine the effect of tooth side clearance on the cutting accuracy of guided saws.

CHAPTER 4 EXPERIMENTAL DESIGN

The objective of the experimental work is to understand the cutting mechanism of guided circular saws in different sawing configurations. As discussed in the Introduction, earlier research studies identified saw-workpiece interaction as one of the reasons for the stability of guided circular systems near the critical speed region. Even though subsequent experimental studies based on sawcut standard deviation corroborate the hypotheses they did not focus on variables controlling saw-workpiece interaction. The present experiment examines the effect of saw tooth side clearance as a variable influencing the saw-workpiece interaction and cutting accuracy of guided circular saws. The result of these experiments will be used to verify the conclusions drawn from the hypotheses and the theoretical model discussed earlier.

This chapter introduces the experimental equipments and measuring systems used for the experiments followed by some preliminary experimental tests. Experimental preparation is introduced first, followed by a discussion on the variables selected for the experiments. Guided saw cutting experiments are described in which the saw-workpiece interaction mechanisms previously described are examined.

4.1 Experimental Equipment and Measurement System

4.1.1 Experimental Equipment

All experiments were conducted at Wood Machining Research Laboratory of the Department of Mechanical Engineering at The University of British Columbia. The experimental equipment and measurement system consist of many subsystems such as a circular saw, hydraulic systems, workpiece feed system, thermal tensioning system, water supply system, laser measurement system, online workpiece lateral displacement system and saw displacement measurement system. Figure 4-1 shows the actual experimental equipment and measurement systems.

Figure 4-2 shows the schematic of the circular saw used for the experiment and the different angles and tooth geometry variables associated with it. Except the tooth side clearance, all other angles assume values typically used for a similar industrial sawblade. Table 4-1 lists the specifications of the sawblade and the values used for different geometric variables.

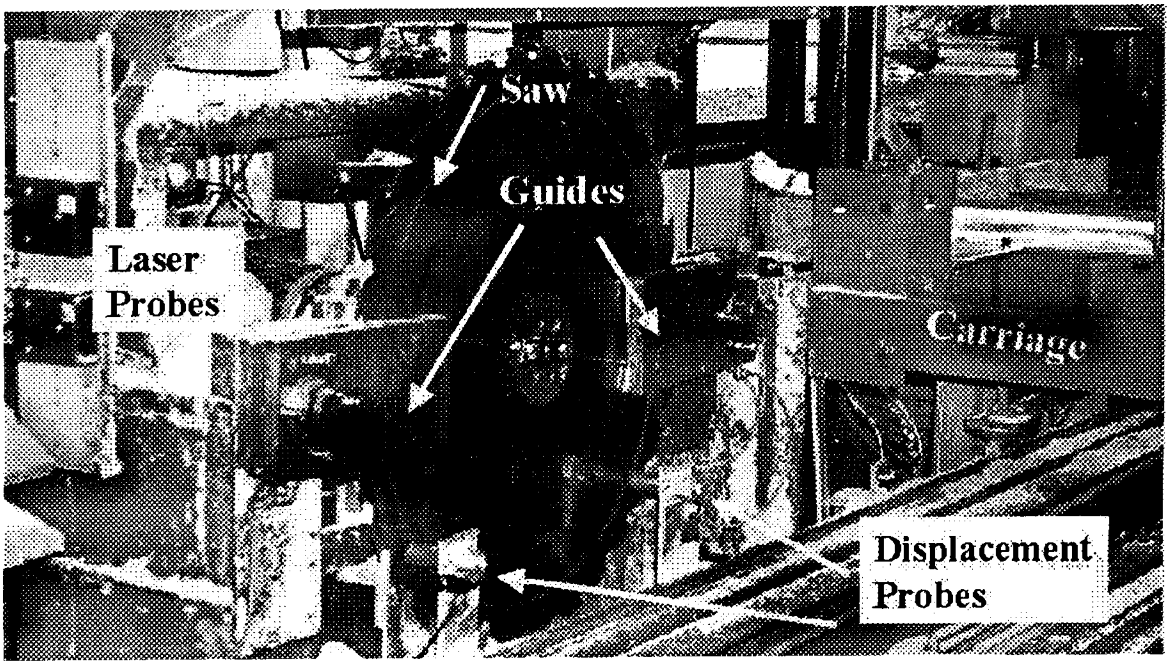


Figure 4-1 Experimental Equipment and Measurement System

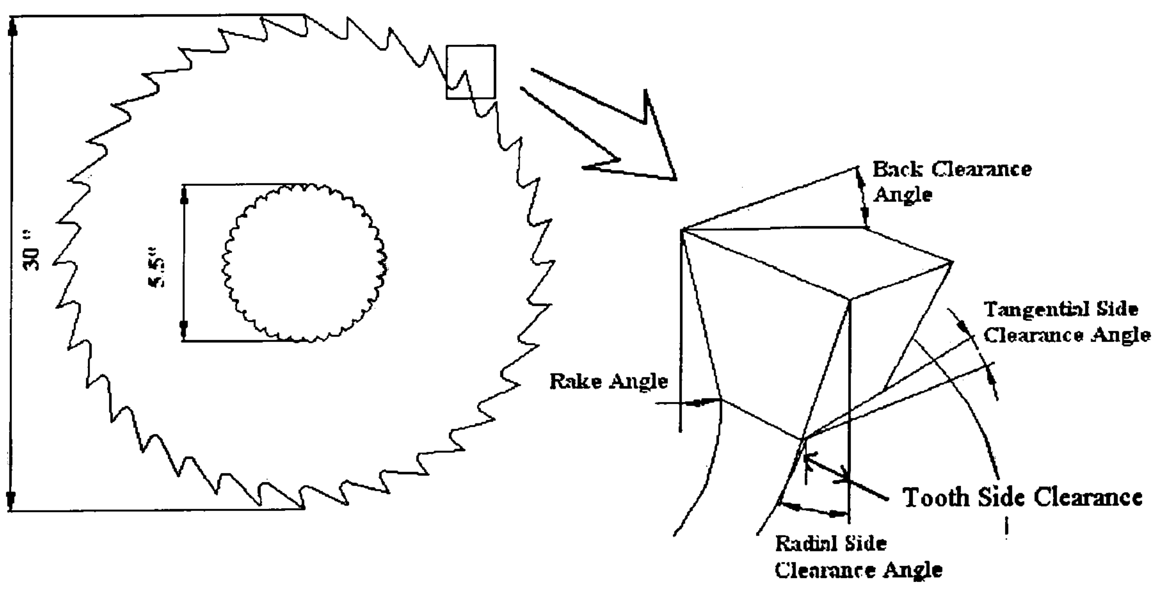


Figure 4-2 Schematic of the Circular Saw and Tooth Geometry Angles

Parameter	Values
Type of Saw	Stellite Tipped
Outer Diameter	30 inches
Inner Diameter	5.5 inches
Thickness	0.075 inches
Number of Teeth	32
Gullet Area	0.089 sq. inches
Radial Clearance Angle	1^0
Tangential Clearance Angle	1^0
Back Clearance Angle	20^0
Rake Angle	8^0

Table 4-1 Specifications of Test Saw

Hydraulic systems are used to drive the arbor of the circular saw and the carriage, carrying workpieces. The speed of the arbor can be adjusted to run in the range of 0-4000 rpm. The carriage holds the workpieces and feeds the wood at the required linear feed speed. It is driven by a 250 hp motor and has a feed speed range of 0-480 fpm. A main control panel controls the rotation speed of the saw, feed direction and feed speed of the carriage. Selection of the feed speed is based on the rotation speed of the saw, saw parameters and gullet feed index (see Appendix I for detailed calculations).

Figure 4-3 schematically represents the experimental apparatus arrangement and measurement system. In addition to the roll tensioning, temporary thermal tensioning induced by non-uniform heating was used to achieve the required level of tensioning. It was provided by a Jajod 'Thermostress' unit. The thermostress system included an induction heater for heating the central zone of the saw. The temperature of the inner area and the outer rim of the sawblade, T_1 and T_2, were detected by two infrared sensors. The intended temperature difference to maintain the required level of tensioning was maintained by a control device. The maximum temperature difference that could be achieved was dependent on saw rotation speed, amount of water used in the coolant system and the configuration of the sawblade. Maintaining a large temperature difference becomes difficult because of large convective heat loss from a rapidly rotating sawblade. In this experiment, temperature differences ΔT in the range of 4°C – 12°C were used. The maximum temperature at the inner area of the saw was 43°C-46°C, which is well below the temperature that causes any permanent effects.

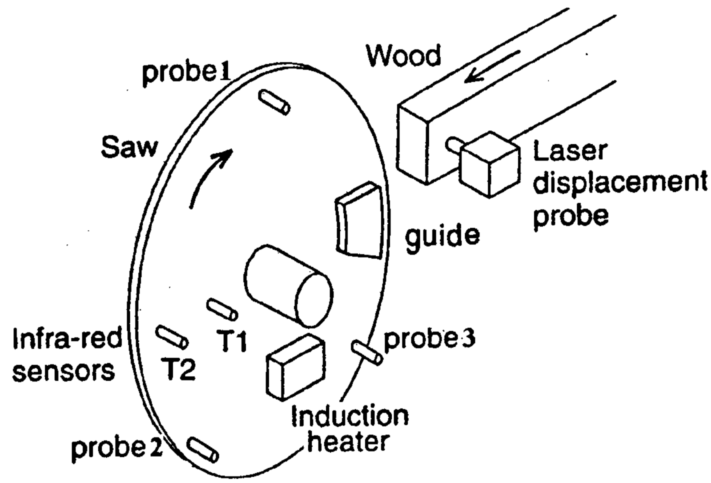


Figure 4-3 Schematic Representation Counter Cutting with Measurement Systems

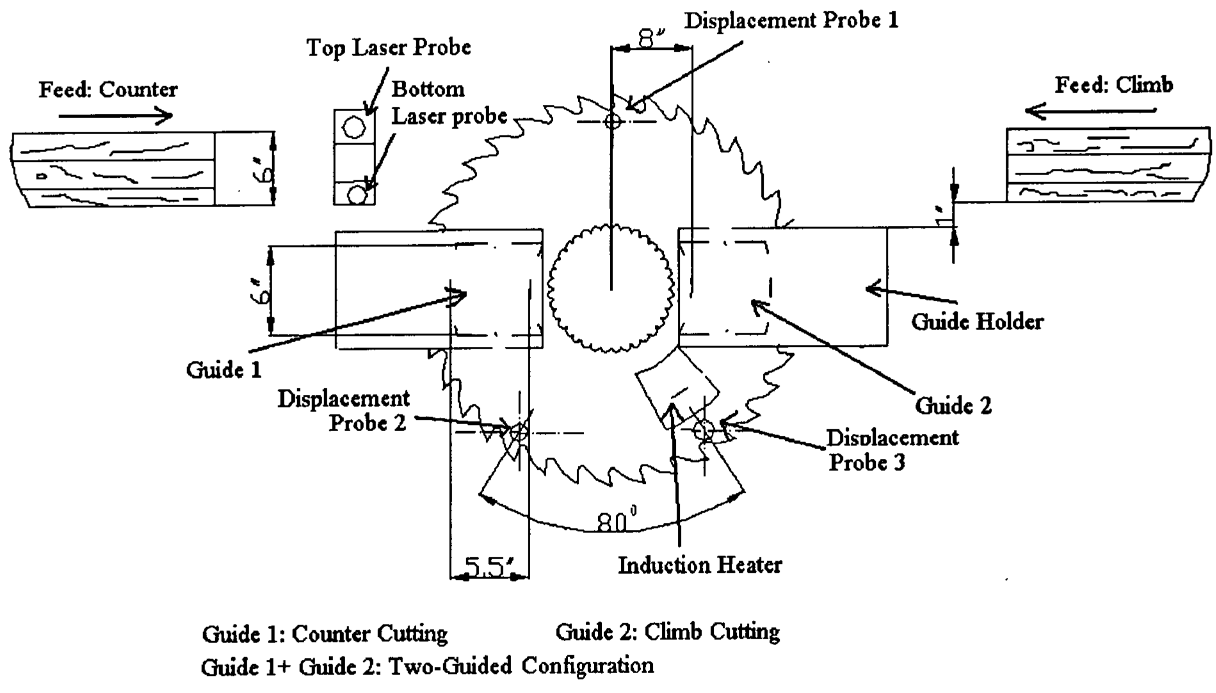


Figure 4-4 Guide and Workpiece Positions for Different Sawing Configuration

As shown in Figure 4-4, varying the guide positions and changing the direction of workpiece movement can achieve counter, climb and two-guided configurations. A water supply system provides water for the guides and the sawblade to serve as lubricant and coolant.

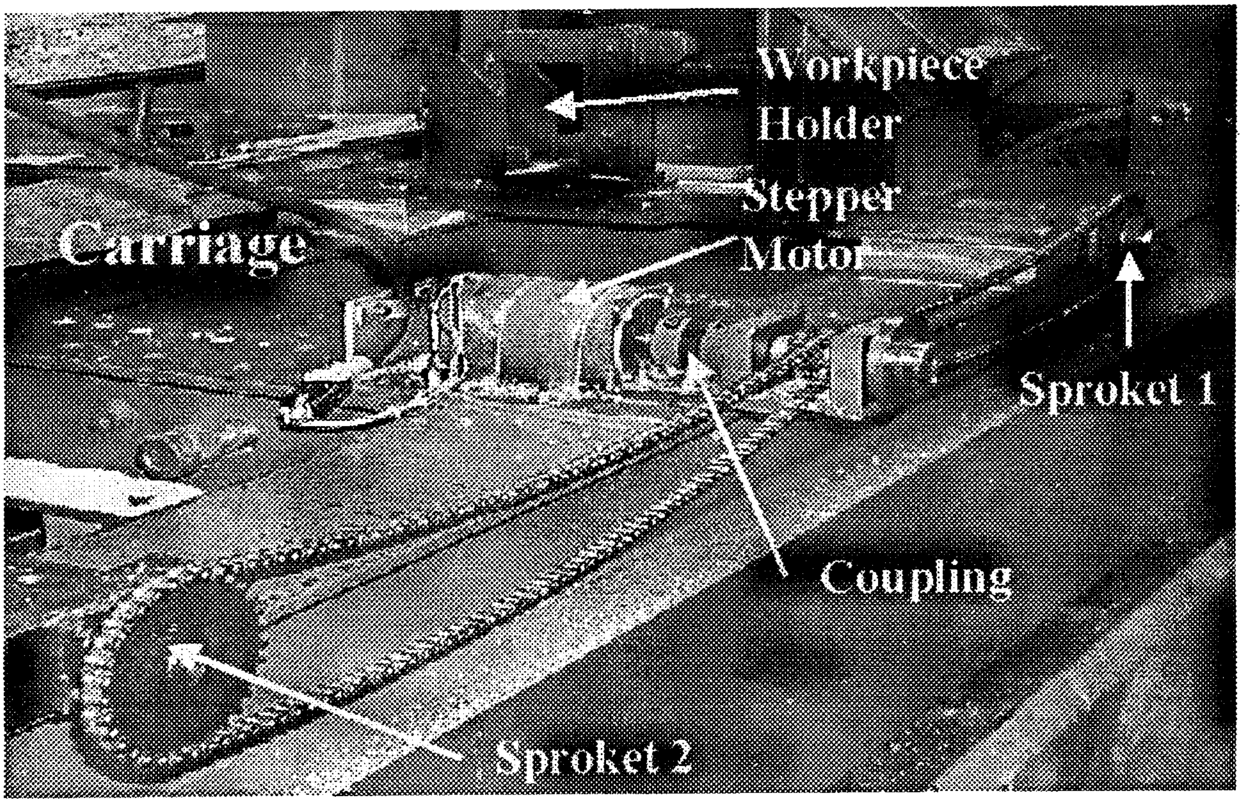


Figure 4-5 Arrangement for Lateral Shifting of Wood

One of the objectives of the experiments was to evaluate the stability of guided saw configurations as a function saw tooth side clearance and feed system error. A small lateral movement of the workpiece simulates an error in the in feed system during cutting. The arrangement for this lateral shifting is shown in Figure 4-5. Proximity switches present on the track of the carriage trigger the signal to be sent to the stepper motor. The signal sent to the stepper motor during cutting moves the workpieces by given amount during cutting. This simulates the lateral movement of large logs while moving on a conveyor. However, this lateral movement of the workpiece was not instantaneous. Maximum available acceleration for the stepper motor was used to minimize duration of wood movement.

Green Hemlock boards measuring 8 feet long × 10 inches wide × 2 inches thick were used in the cutting tests. These boards were weighed individually and the average weight of all available pieces was determined. Three boards were stacked together to get a total depth of cut of 6 inches and approximately three times the average weight. Wood pieces around 0.5 inch thick were cut during each cutting stroke. Total 10-12 cuts were made with each stack.

4.1.2 Measurement System

The current research in part employs the instrumentation and measurement techniques used by *Schajer* and *Wang* [36].

Three induction type displacement sensors measured the lateral movement of the sawblade during cutting. Probes were positioned as shown in the Figure 4-4. These probes have a measurement range of 0.5 inch. Probe 1 is mounted at a mid point between the counter and climb cutting guides and just above the path of the workpiece movement. Earlier experiments of *Schajer* and *Wang* [36] in 1999, showed that mounting the probe in this arrangement gives a good representation of the movement of the blade at the upper edge of the of the workpiece. Other two probes were mounted close to the periphery of the blade, equidistant from probe 1. This typical arrangement not only gives the vibration of the blade during cutting, but also detects any disturbances traveling away or towards the cutting region. With a 12-bit card used for the data acquisition system, these probes could resolve a lateral movement of the blade as small as 0.00012 inch.

Cutting accuracy of the cut was measured by the sawcut standard deviation of the surface profile of the workpiece. After cutting, the workpiece was returned to its initial position and then moved forward with the same feed speed. Two laser probes captured the surface profile. The upper laser probe measured the workpiece surface profile along the upper edge, corresponding to the rim of the saw away from guides. The lower probe detected the workpiece profile along the lower edge corresponding to the sawblade close to the guides. With a 12 bit card used in the data acquisition system, these probes could detect surface variation as small as 0.20 thousandth of an inch. A taco generator attached to the arbor of the circular saw measured the rotation speed of the sawblade.

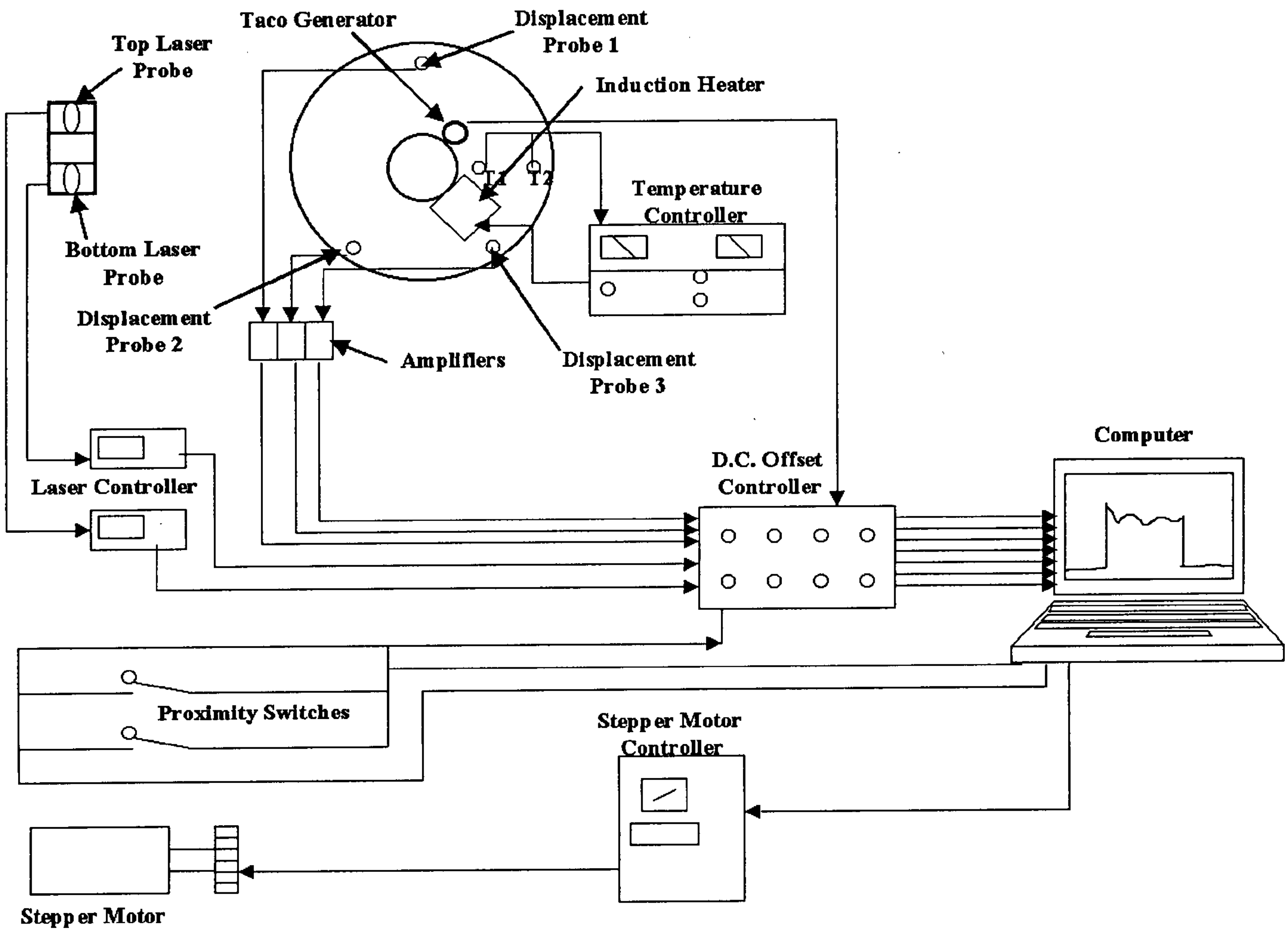


Figure 4-6 Schematic of the Data Acquisition System used in the Experiment

Figure 4-6 schematically shows the Data Acquisition System used to acquire the measured signals and record them in a computer. All the instruments were calibrated to read the output in linear sense. As the output signals of displacement probes contained high frequency noise, simple R-C analog filters were used to condition the signal and were tuned using a trial and error method. These conditioned signals were then read using data acquisition card and further analysis was done using a program written in Fortran. Proximity switches installed on the track of the carriage triggered data acquisition system. All the data files were stored in binary format and could be analyzed even after the cut to perform the statistical analysis.

4.1.3 Preparation of the Equipment

The natural frequencies of the stationary sawblade were measured using a microphone and frequency spectrum analyzer. Prominent frequencies were recorded. These were used as a reference to restore the sawblade back to its original state, after changes caused by tipping or by tensioning and leveling. The initial side clearance of the sawblade after tipping was 0.032 inch.

Displacement probes, Laser probes, Taco Generator were calibrated to read linear output. The carriage speed was calibrated based on an 'average velocity' measurement. The guide surfaces were prepared by grinding. The guide surfaces were adjusted on the guide holders to achieve a flatness error within ± 0.001 inch.

4.2 *Selection of Parameters*

4.2.1 Side Clearance

Side clearance is the primary variable of interest here. After tipping the sawblade with new stellite teeth had a side clearance of 0.032. During the experiments, the side clearance was successfully reduced to 0.024", 0.016", 0.010' and 0.004".

4.2.2 Rotation Speed and Tensioning

As explained earlier, the objective of the experiments was to determine the stability of guided saws as a function of side clearance in different configurations. Even though the stability of guided saws operating in the stable region is of primary interest, ability of the guided saws to work well in the critical and dishing speed region has motivated the extension of side clearance tests in these regions. Ideally, the most detailed information about the cutting accuracy would be given by measuring the influence of saw tooth side clearance for every combination of rotational speed and tensioning. However, as this is extremely time consuming task and one that is not practical considering the other variables involved, only one rotation speed and temperature combination in critical, stable and dishing speed region is considered.

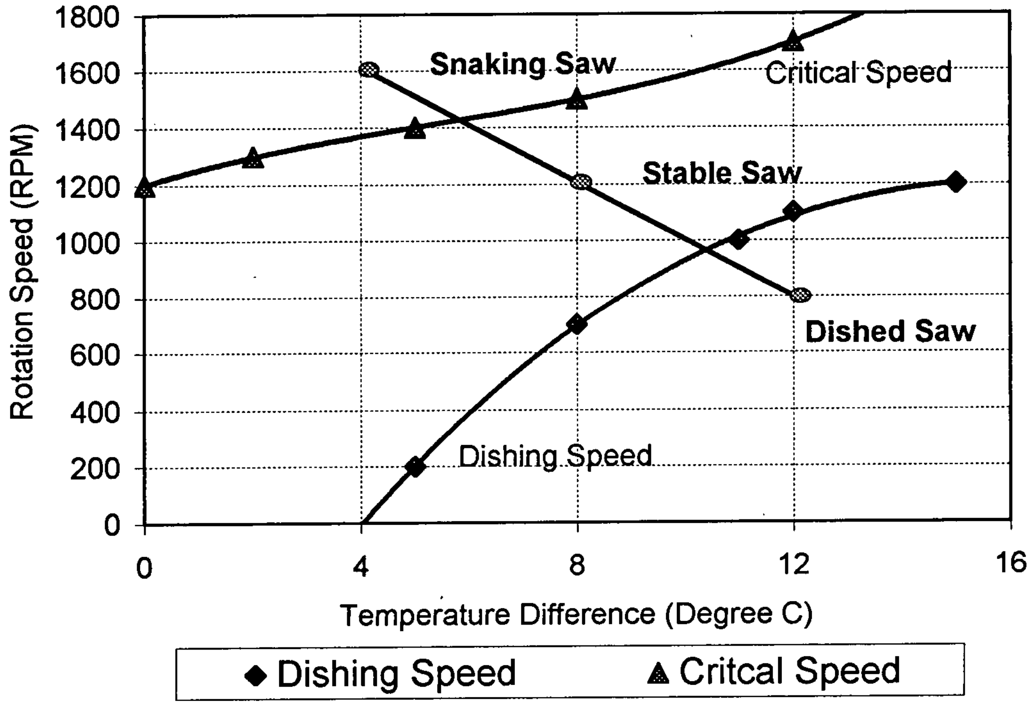


Figure 4-7 Relationship Between the Critical, Dishing Speeds and Tensioning of a guided Saw (Reproduced from the Data Points of *Wang* [27])

Figure 4.7 shows the variation of critical and dishing speeds of the guided saw used for the experiments as a function of tensioning. The present experiments concentrated on three points showed along the diagonal solid line. One of the points is well inside the critical speed region and characterized by a speed, 1600 rpm a and 4°C temperature difference for thermal tensioning. The second point having coordinates of 1200 rpm and 8°C of tensioning is in the stable working region. The third point 800 and 12°C tensioning is well with in dishing speed region. These points were chosen because it spans the saw operating conditions from dishing to critical speed instability. Each of these points represents a sawing condition for a specified sawing configuration and side clearance.

4.2.3 Effect of Two-Guides

Earlier observations of *Wang* [37], studying the effect of guide sizes on the saw-workpiece interaction concluded that for an optimum performance of guided saws, stiffness is required only near the cutting edge and flexibility at other places, especially while operating in the critical speed region. The experiments with two-guided configurations showed higher standard deviations in counter and climb sawing while operating in the snaking saw region. However, it is of interest to see whether similar behavior continues when there is a variation in the side clearance of the saw teeth. Therefore, it has been decided to include the point represented by 1600 rpm and 4°C in Figure 4.7 for two-guided configuration in both counter and climb sawing.

4.2.4 Feed Speed

Feed speed of the workpieces for a particular saw rotation is based on the Gullet Feed Index. Gullet Feed Index is a measure of the cutting capacity of the sawblade. Theoretically, Gullet Feed Index as high as 0.3 could be used with guided saws. However, for the current experiment Gullet Feed Index of 0.28 was used because the laboratory arbor did not have sufficient power to operate reliably at higher values of gullet feed index. This value was used to calculate Feed per Tooth. Following formulae represent the relationship of the cutting parameters.

$$\text{Gullet Feed Index} = \frac{\text{Feed per Tooth} \times \text{Depth of Cut}}{\text{Tooth Gullet Area}} \qquad 4.1$$

$$\text{Feed Speed} = \text{Feed per Tooth} \times \text{Saw Rotation Speed} \times \text{Number of Teeth} \qquad 4.2$$

Feed per Tooth was maintained at a constant value for all the rotation speed and configurations. Before tests, all the feed speeds corresponding to different rotation speeds were calculated. Calibration of the carriage was made for these calculated feed speed values. Appendix I gives the numerical values for the variables in Equation 4.1 and 4.2 and lists the feed speed values for the saw rotation speeds used.

4.2.5 Amount of Shifting

Lateral shifting of the wood during cutting increases the saw-workpiece interaction and influences the cutting accuracy of guided saws. However, as indicated earlier, shifting is effective only when it is more than the side clearance of the saw tooth. Current experiments verify this for various sawing configurations and operating speeds. The amount of shifting was held at a constant value of 0.020 inch. As the side clearance varies from 0.032 inch to 0.004 inch, saw-workpiece interaction increases gradually as the side clearance is reduced. This value was chosen to differentiate the effect of shifting in large side clearance region and small side clearance region clearly.

4.3 Preliminary Tests

Some initial idling tests were conducted to assess the effect of guide clearance and thermal tensioning on the idling behavior of counter and climb cutting configurations. Observations made during these initial idling tests were used to determine value for the clearance between sawblade and guides. This was followed by sample cutting tests to verify the relation between the saw lateral vibration during the cutting as measured by the displacement transducers and surface profile on the workpiece. Some tests were also conducted to determine the effect of width of the wood cut on the cutting accuracy of climb and counter cutting guided saws.

4.3.1 Effect of Clearance between Sawbody and Guide Surfaces

Even though industrial observations require the clearance between the saw guides and sawblade to be as small as possible, observations during the preliminary idling tests indicated a definite relationship between guide clearance and the dynamic behavior of the sawblade. Initial idling tests were conducted to find out the variation in the dynamic behavior of the guided circular saw as a function of clearance between the saw guides sawblade in climb and counter cutting configurations.

Three levels of clearance i.e. tight (0.0025"), medium (0.012") and loose (0.020") were used. The following procedure was repeated for both counter and climb cutting to evaluate the effect of guide clearance.

1. The saw guides were adjusted to achieve the required clearance level between the saw body and the guides. The saw was run at 1200 rpm with $\Delta T=8°$ C to achieve the required tensioning.

2. Once the temperature difference reached a steady state, the vibration of the saw body was measured using displacement probes. The temperature of the inner edge of the sawblade was measured using thermal sensor.

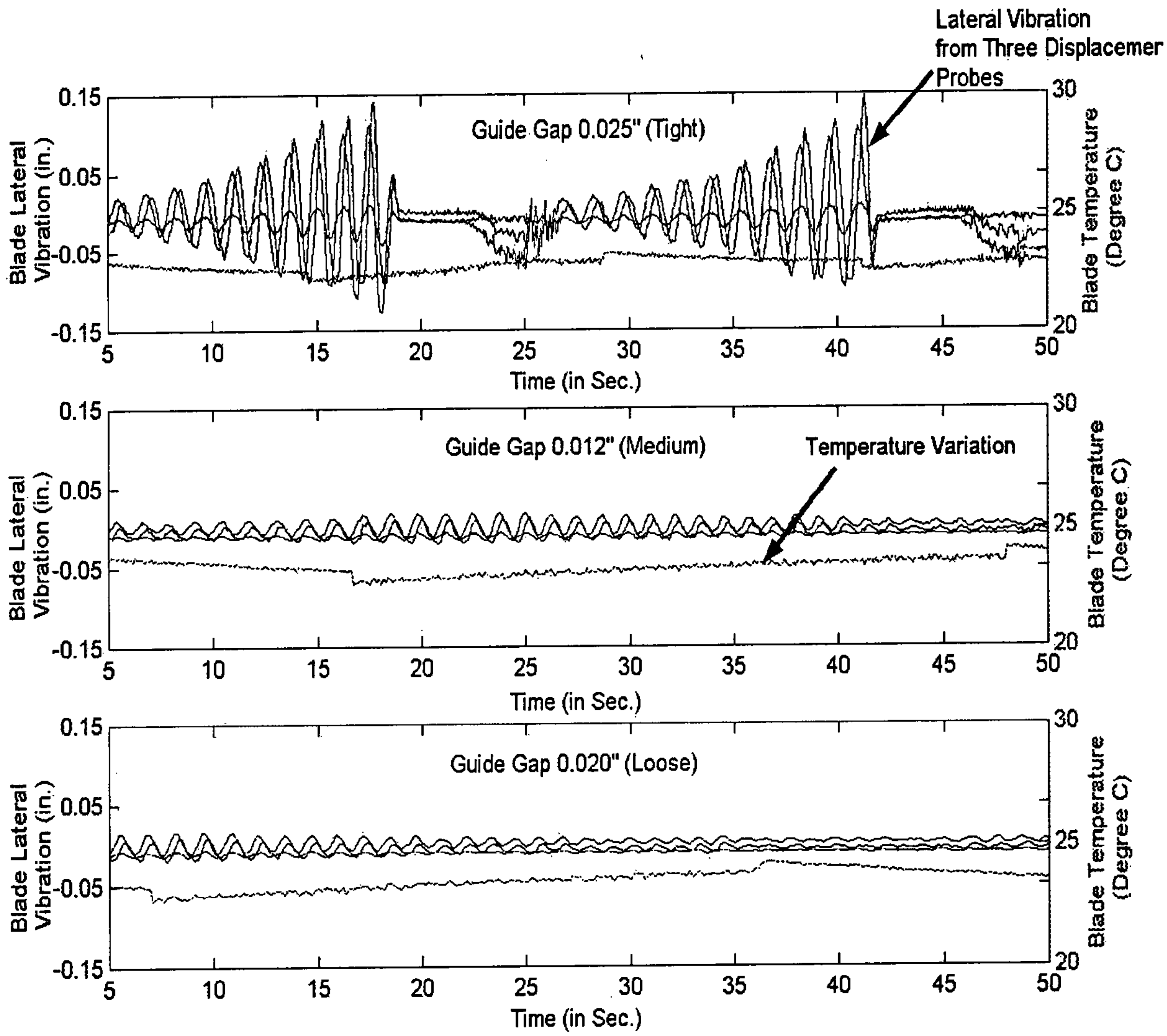


Figure 4-8 Variation in the Saw Lateral Vibration with Guide Clearance

Figure 4.8 shows the observations made for climb cutting with three different gap conditions. Figure shows the variation of saw lateral vibration and temperature of the center region of the sawblade as a function of time as sensed by displacement probes. Contrary to the industrial experience, the trend for climb cutting showed that too much tightening causes the blade to be unstable. This phenomenon is particularly noticeable for the tight configuration, when the 'snaking' of the sawblade continued, irrespective of tensioning state of the saw. When the guide clearance was increased at the same RPM, the unstable condition not only changed to a stable one, but also clearly indicated the periodic nature of the variation of sawblade vibration. The saw appears to become stabilized when the temperature reaches desired temperature level (i.e. when the thermostress unit is on) and to deviate from stable position when the thermo-stress unit is off.

Repetition of the tests indicated that, for a loose condition, snaking of the saw occurs at a much higher speed than that of a tight saw. In the case of counter cutting, the stability of the saw as a function of guide clearance showed similar trend with different amplitude for vibrations.

Based on these observations, it can be concluded that the clearance between the sawbody and the guide is an important factor in determining the dynamic behavior of the sawblade. Experiments clearly showed that too tight guides impair the stability of the guided saws. Hence it has been decided to use medium gap (0.007"-0.010" inch) for the subsequent cutting tests. The variation in sawblade vibration with temperature indicates the importance of maintaining constant temperature while using thermal tensioning. This observation also helped in deciding the moment at which wood must be fed into the saw so as to minimize the effect of deviation produced by temperature variation.

4.3.2 Preliminary Cutting Test Results

Figure 4-9 (a) shows an example measurement of saw lateral vibration displacements as sensed by three displacement probes with time. The temperature difference was 8° C and the rotation speed was 1200 rpm. The saw was operating in the stable region. Figure 4-9(c) depicts the sawn surface profiles along the length of the board measured at the same feed speed after the cutting. The trends of the signals recorded from the displacement probe 1, which is closer to the cutting region and the upper laser sensor are similar. The same behavior was observed in almost all the cutting tests. Therefore, it can be concluded that the signal from probe 1 represents the behavior of the cutting edge realistically. This also shows that the cutting accuracy of the guided saws directly depends on the vibration of the cutting edge during sawing. However, the profiles recorded by the laser probes are reduced in magnitude compared to the readings from displacement probes. This shows that the presence of wood restricts the movement of the cutting edge during cutting. These measurements support the earlier hypotheses of increased stiffness and damping in the presence of wood. Since the readings from the displacement probe 1 and surface readings of the upper edge of the workpiece are in good agreement, these will be referred frequently in the analysis of the data.

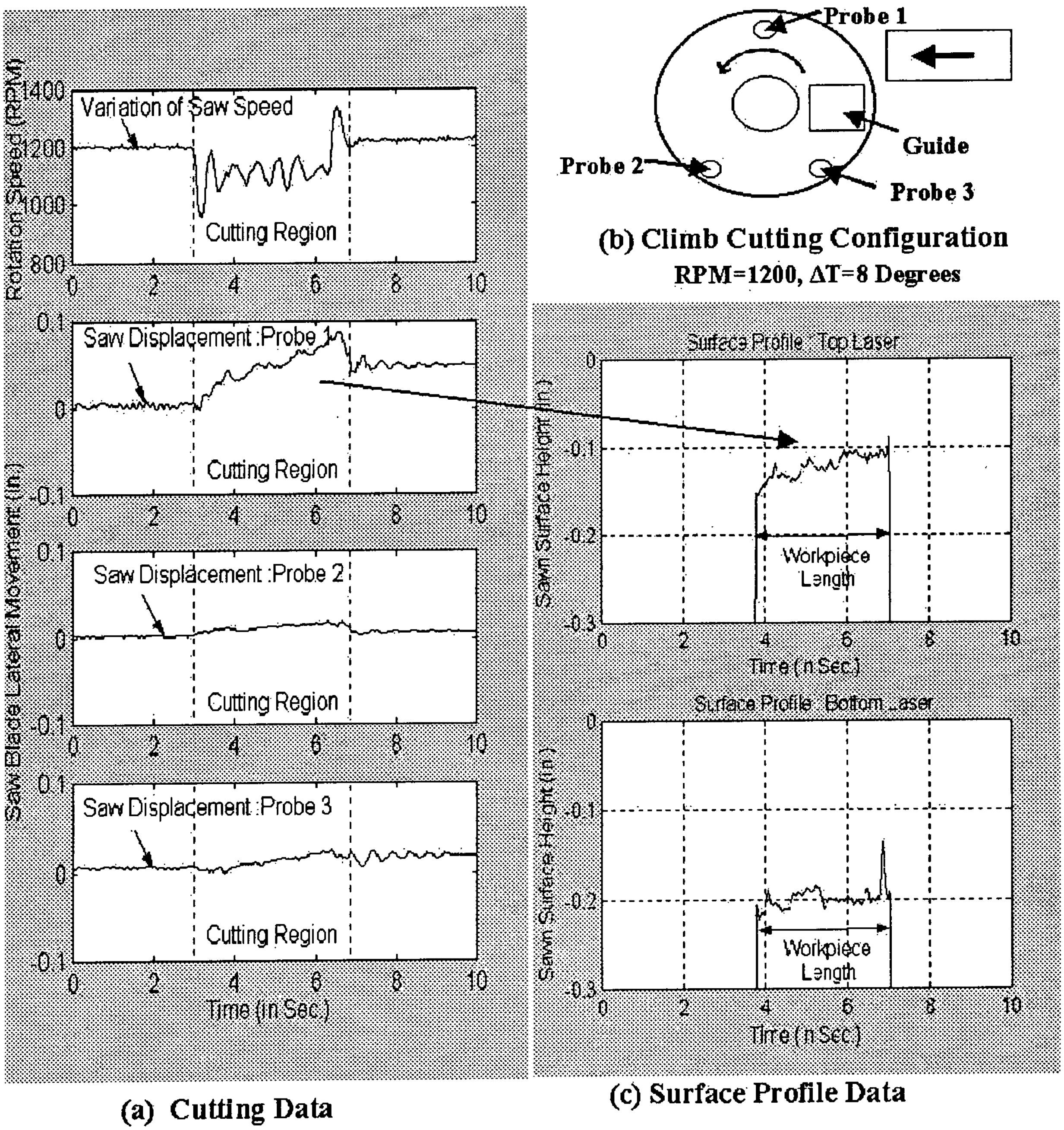
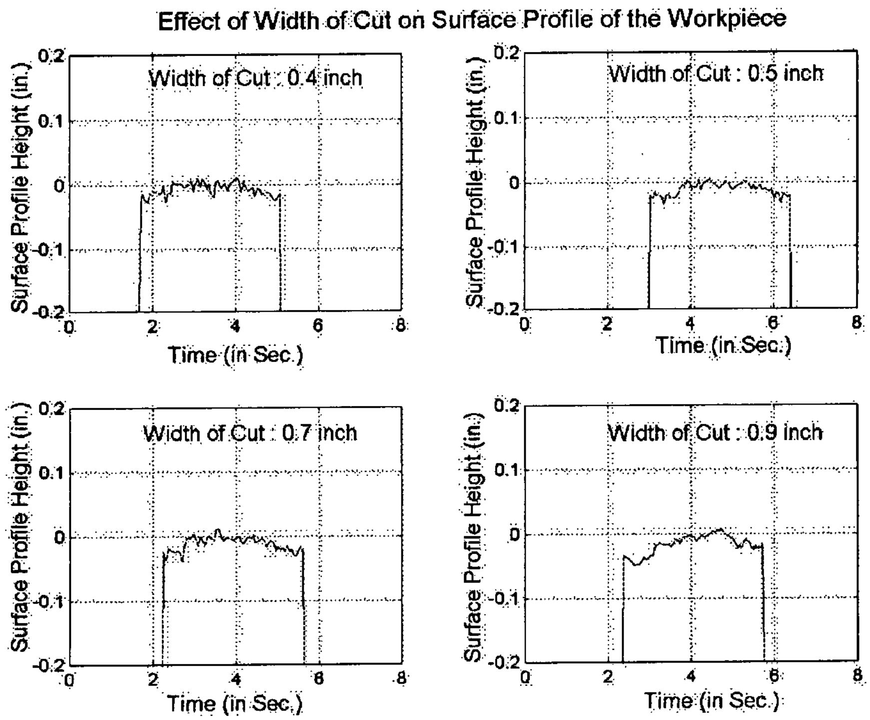


Figure 4-9 (a) Saw Lateral Vibration during Cutting (b) Sawing Configuration and Position of Probes (c) Corresponding Workpiece Surface Profile

4.3.3 Effect of Width of Workpiece



(a) Surface Profile of the Workpieces

(b) Variation of Saw Cut Standard Deviation
Counter Cutting Configuration, 1200 rpm /8 Degrees
0.032" Side Clearance

Figure 4-10 Experiments with Different Workpiece Width

Figure 4-10 shows the variation of sawcut standard deviation of the surface profiles produced with different width of cut. These tests showed that the there is no perceivable difference in the sawcut standard deviation when the width of cut changes substantially. In reality the lumber produced is of substantial size and offers resistance on both side of the sawblade. Keeping all these in points and also the amount of wood required to conduct the experiment it has been decided to have width of cut of each of the pieces to be 0.5 inch.

4.4 Experimental Plan

Extensive comparative cutting tests with various side clearances and guide configurations were performed to examine the effect of tooth side clearance as the primary variable in deciding saw-workpiece interaction. These tests were based on the parameters and cutting conditions selected earlier. Table 4.2 lists all the parameters and their values as applicable to the experiments.

Parameter	**Parameter values**
Side Clearance	0.032", 0.024", 0.016", 0.010", 0.004"
Configuration	Counter, Climb
Workpiece Lateral Shifting	With Shifting, Without Shifting
Tensioning (RPM/Temp)	800/12, 1200/8, 1600/4, 1600/4 (Two Guides).
Repetition	Six Repetitions of Each Sawing Condition

Table 4-2 Variables and their Values for the Experiment

The experiments started with the side clearance value of 0.032". This was reduced systematically by grinding to get the required side clearance values. This reduction in side clearance investigates saw-workpiece interaction and its influence on cutting accuracy. For each side clearance step, experiments were conducted with different sawing configurations, workpiece lateral movements and saw tensioning states. For a particular side clearance, these sawing conditions covered counter and climb cutting configurations, with and without shifting of workpieces, 800 rpm/12° C, 1200 rpm/8° C and 1600rpm/4° C tensioning states. Each of these sawing conditions was repeated six times to get statistically significant data.

However, the possible effect of tooth and guide wear can seriously complicate comparisons of sawing performance. To minimize these complications, the cutting tests were selected so as to spread these effects equally among different sawing configurations. In addition the following points are considered while sequencing the experiments.

- Starting the sequence with a most stable cut
- Minimization of guide changes for climb and counter cutting
- Minimization of systematic errors such as tooth sharpness and guide wear
- Minimization of random error by repeating the experiment

Based on above conditions, experiments were sequenced as follows. Here the number inside the cell indicates the order of the experiment.

Configuration	Simulated Feed Error	Tensioning State (rpm/ΔT)				Guide Change
		800 /12 (Snaking)	1200/8 (Stable)	1600/4 (Dished)	1600/4 (Two Guides)	
Climb	Not included	**3**	**1**	**5**	**7**	**1**
Climb	Included	**4**	**2**	**6**	**8**	
Counter	Not included	**13**	**11**	**15**	**9**	**2**
Counter	Included	**14**	**12**	**16**	**10**	

Table 4-3 Cutting Plan for One Cycle

This cycle was repeated so that six cuts have been made for all the combinations at the end. This results in total of **96** cutting experiments. Similar sets of experiments were carried out for **5** different side clearances resulting in total of **480** cuts. Additional experiments were carried out to get much more information on saw-workpiece interaction by changing the amount of shifting. In total, finally **540** experiments were done using 54 stacks of wood.

The wood boards used in the cutting tests were selected to be as uniform as possible. The boards were weighed and grouped into stacks of three having approximately same average weight. Cutting tests with the same sawing conditions and cutting directions were conducted in the different stacks of wood. This arrangement randomizes the variations in cutting performance due to natural differences in the wood boards and wear of teeth.

During each cut, sawblade lateral displacement was detected at the three positions as shown in Figure 4-5. After removal of the sawn pieces, the two laser displacement probes measured the surface profiles along the top and bottom edge of the sawn surfaces.

CHAPTER 5 ANALYSIS OF EXPERIMENTAL DATA

An extensive series of experiments was carried out to seek answers to the fundamental questions raised earlier. This resulted in the collection of a comprehensive set of data for different side clearances, saw configurations, tensioning levels and simulated feed system errors. This chapter presents the analysis of the collected data followed by discussions about the implication of the results. The first phase of the analysis tries to identify the effect of tooth side clearance on the cutting accuracy of guided saws for different sawing configurations and tensioning levels. This is followed by discussions on the effect of two-guided configurations and simulated feed system errors on cutting accuracy. The final phase of this chapter compares different sets of data, presents unified representation of results and draws out conclusions about the cutting process.

5.1 Effect of Tooth Side Clearance

The effect of tooth side clearance is studied for climb cutting, counter cutting and two guided configurations (in the critical speed region). The sawcut standard deviation of the surface profile produced quantifies the surface profile and represents the accuracy of the cut (Refer Appendix II for details).

5.1.1 Climb Cutting Results:

Figure 5-1 summarizes the sawcut standard deviations of the climb cutting configuration at different saw tooth side clearances and saw tensioning. The diagram shows the measured sawcut standard deviations of the workpiece surface profiles cut by a climb cutting saw in three different sawing conditions and at five different side clearances. Each point in the graph is an average of six measurements. Errors bars plotted indicate the limits of standard error for a set of measurements.

The most important point of Figure 5-1 is the fact that a guided climb cutting saw could cut the wood successfully even at side clearances as small as 0.004" in all the configurations. However, the sawcut standard deviations associated at 0.004" are much higher compared to the other side clearances. Interestingly, irrespective of the configurations, the cutting accuracy deteriorates with a reduction in saw tooth side clearance. This observation supports the earlier expectations derived from the hypotheses. The increased sawcut standard deviation with a reduction in tooth side clearance is mainly due to the increased saw-workpiece interactions. Results from the displacement probes and laser probes indicated increased saw-workpiece interaction at small side clearances. These results will be presented in the subsequent section discussing the sawblade behavior during climb cutting.

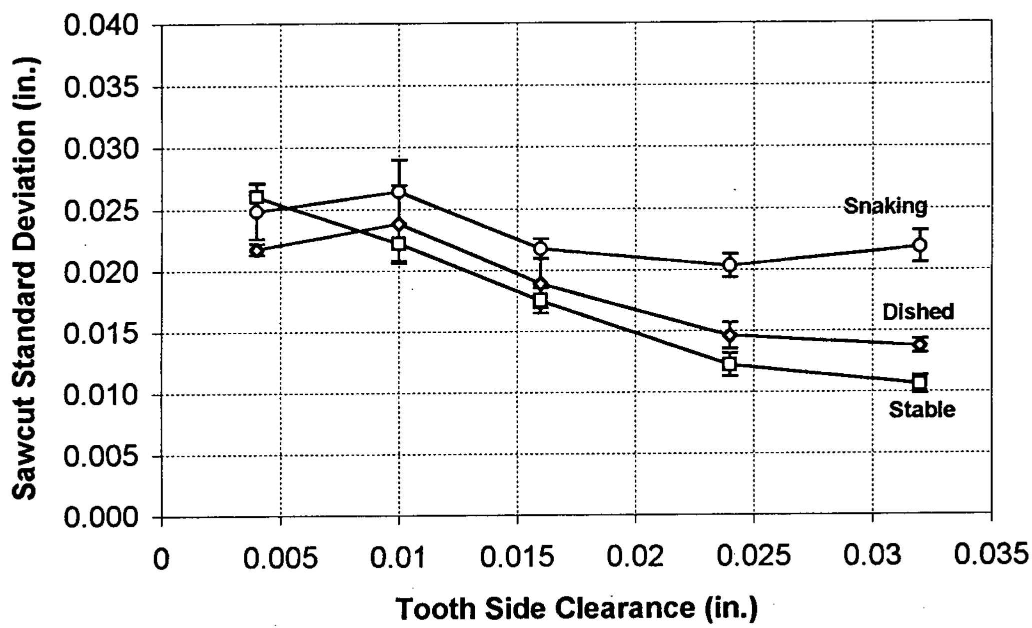


Figure 5-1: Measured Sawcut Standard Deviations of Climb Cutting Saw

In Figure 5-1, the cutting behavior of the climb-cutting saw conforms the general expectations from the critical speed theory. The sawblade operating in the stable region performs better than saws operating in the snaking and dished regions for the same side clearance. The difference in the cutting accuracy of the stable saw and the other configurations is substantial at higher side clearances. As the side clearance decreases the sawcut standard deviations increase gradually for all the configurations. However, the difference in sawcut standard deviations of the stable saw and the other configurations decreases as the side clearance is reduced. This is because the sawcut standard deviations of the stable saw deteriorate quickly.

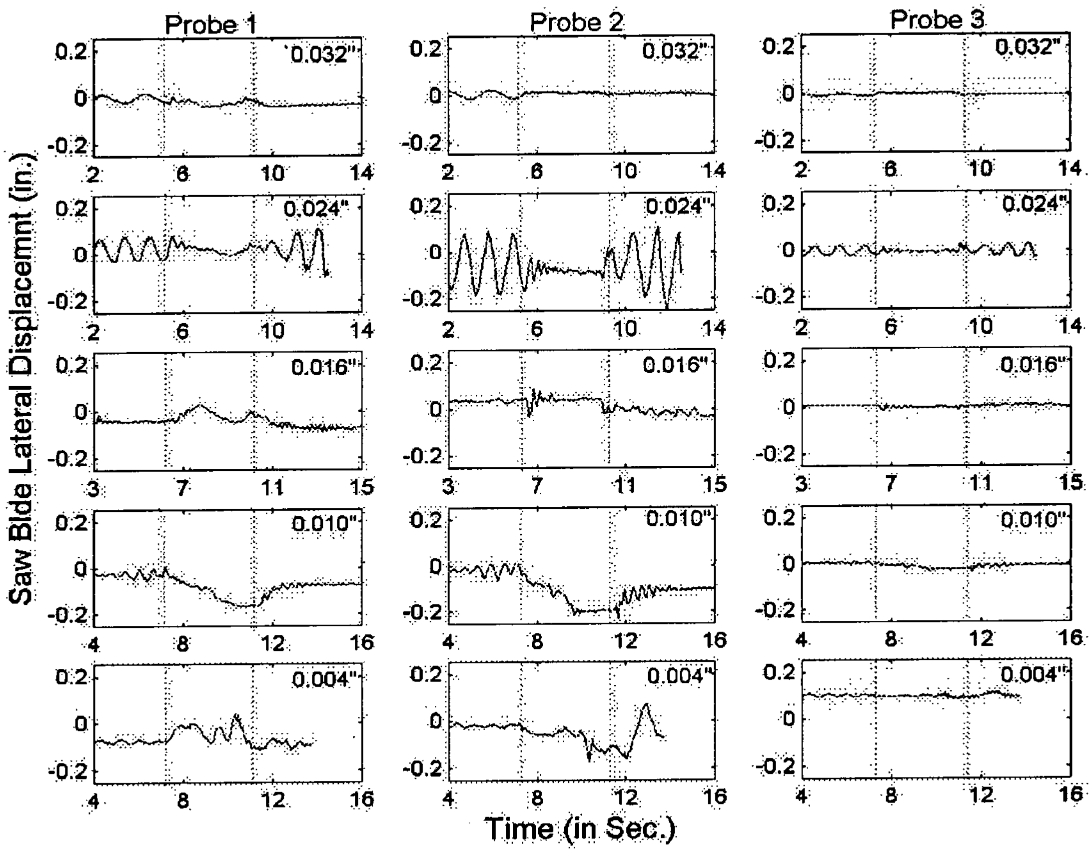
For the saw operating in the stable region, the sawcut standard deviation is much smaller when the side clearance is very large. However, for the same cutting capacity and operating conditions, the sawcut standard deviations increase with a reduction in tooth side clearance. This suggests that the tooth clearance has a definite influence on the cutting behavior of the guided saws.

Cutting accuracy of the sawblade operating in the stable region is affected greatly compared to the saws working in snaking and dishing region. In case of a stable sawblade, the cutting edge leaving the guides has well defined position. When the side clearance is higher, the contact between the workpiece and the sawblade is minimum and hence the cut produced is accurate. However, as the tooth side clearance gets smaller, introduction of additional stiffness in the form of workpiece results in regions of increased lateral stiffness close to the guides. At the same time reduced side clearance results in increased sawbody and workpiece contact close to the guides. Any lateral movement of the sawblade inside the cut can result in high lateral forces and unstable cutting edge and reduced cutting accuracy. In case of a snaking and dishing saw, the lateral movement of the sawblade is so large that any variation in the saw-workpiece interactions caused by the reduction in tooth side clearance does not influence the cutting accuracy greatly.

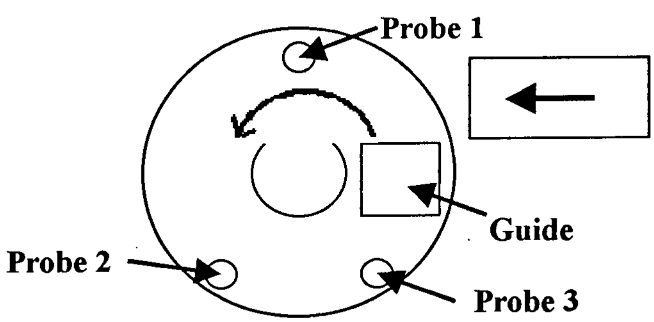
Even though the sawcut standard deviations increase gradually with a reduction in saw tooth side clearance, the difference between maximum and minimum for a particular configuration is of the order of 0.010"-0.020". This difference is not large. Therefore, when sawblades of greater thickness/ diameter ratio (or stiffer plates) are used for the experiment, there is a possibility that the trend presented here may get masked due to the deviations present in the measured values. This possibly explains why experiments of *Lehmann* [16] did not show substantial evidence about the influence of tooth side clearance on cutting accuracy in climb cutting configurations.

Figure 5-2(a) represents the vibration of the sawblade during cutting as recorded by the three displacement probes. The configuration of the sawblade and the position of the probes are depicted in

Figure **5-2**(b). Two dotted vertical lines indicate the cutting region. Vibration of the sawblade for 0.032", 0.024", 0.016", 0.010" and 0.004" are represented. The sawblade was working in the stable region at 1200 rpm and 8° C temperature difference.



(a) Sawblade Lateral Vibration



(b) Climb Cutting Configuration

RPM=1200, ΔT=8 Degrees

Figure 5-2 Typical Vibration of the Sawblade at Different Side Clearances

The observations of sawblade lateral movement during cutting closely follow the earlier research observations. A low frequency saw oscillation appears during idling condition. This idling oscillation decays or entirely disappears during cutting. *Wang* [37] observed a similar phenomenon in his experimental work.

The vibration of the sawblade during idling as recorded by the displacement probes depends mainly on the lateral stiffness of the sawblade. The increased stiffness of the sawblade in regions close to the guides results in sawblade lateral vibrations of reduced amplitude. This is indicated in the data recorded from displacement probe 3, which is located close to the guides. Sawblade lateral movement increases with distance away from the guides. The data collected from displacement probe 1 and displacement probe 2 show increased sawblade lateral vibrations.

Even though the idling oscillations change in their amplitude at different regions of the sawblade, they showed a definite phase relationship in the readings obtained from the displacement probes. The signals collected from the probes showed a slow backward traveling wave moving around the sawblade during idling. However, during cutting, this traveling wave disappears and the disturbance caused during cutting dominates the idling vibrations. This is represented in the data collected by probe 1 and probe 3 during cutting. Typically these disturbances are caused by the lateral forces acting on the sawblade during cutting or by the interaction of the wood and the workpiece. There observations clearly suggest that the cutting behavior of the sawblade is different from the idling behavior and is governed by the lateral cutting forces acting on the blade and sawblade-workpiece interaction.

Interestingly, cutting disturbances does not affect the readings of probe 3 and the sawblade appears to be stable even during cutting in regions close to probe 3. Since data from probe 3 represents the sawblade entering the guide, it can be assumed that the sawblade leaving the guide is also equally stable. This indicates that in case of climb cutting, the beginning of the cut is well guided and stable.

Sawblade lateral movement during cutting increases with a decrease in saw tooth side clearance. When the side clearance is large, the lateral movement of the blade is gradual, moving slowly from one side to the other. However, when the side clearance becomes very small, this motion becomes faster and results in a rapid oscillatory motion of the blade. This can be seen in the readings of probe 1 for 0.004" side clearance.

When the side clearance is large, there is enough space between the sawblade and the workpiece. Any oscillation of the cutting edge could be easily accommodated and the interaction between the wood and the workpiece tend to push the sawblade back to the line. When the side clearance is small, this motion becomes detrimental as the contact between the workpiece and the sawblade takes close to the cutting edge and could result in high reaction forces. Also when the side clearance becomes very small, the workpieces while moving rub the surface of the sawblade. This results in frictional heating of the blade and reduces the temperature difference between the center region and outer region of the sawblade. Reduced thermal tensioning shifts the operating region of the sawblade from stable region towards snaking region and results in heavy lateral movement of the sawblade during cutting.

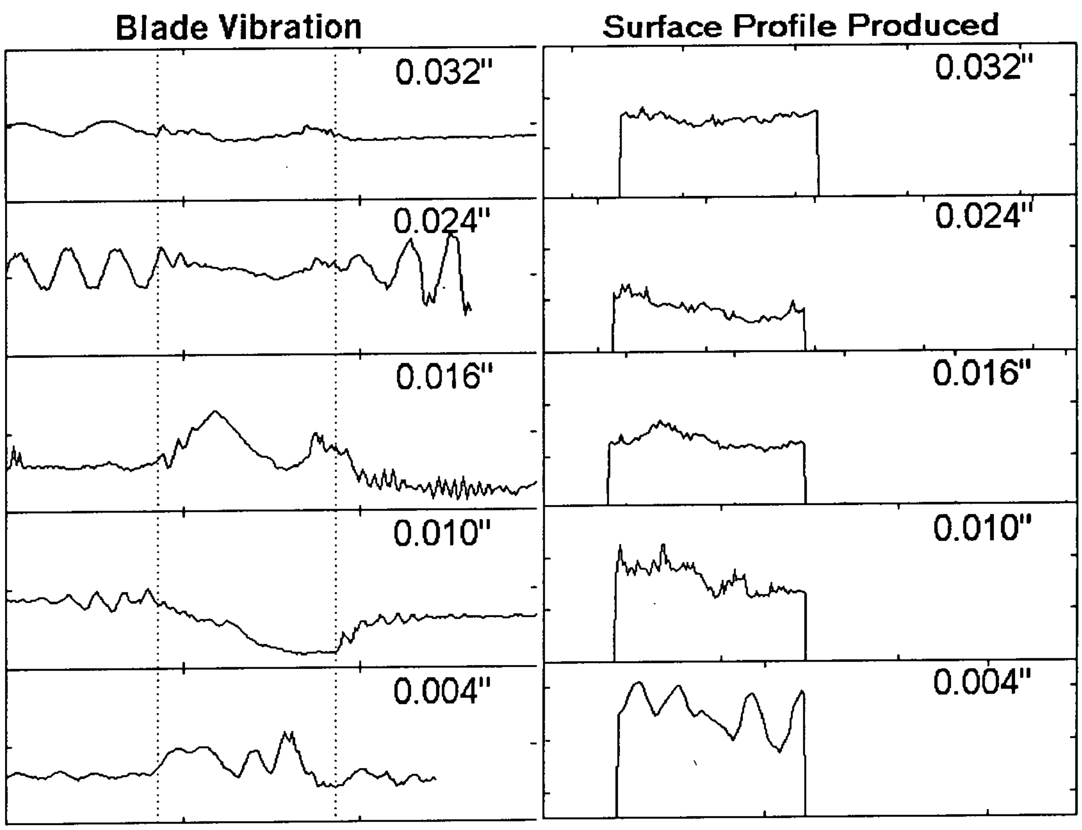


Figure 5-3 Sawblade Vibration and the Corresponding Surface Profile Produced at Different Side Clearances

X axis: 1 Division = 4 seconds Y axis: 1 Division = 0.1 inch

Figure 5-3 shows the vibration of the sawblade recorded displacement probe 1 and the corresponding surface profile as measured by the upper laser probe. As shown in the diagram, there is a good correlation between the vibration of the blade as sensed by the probe and the data gathered from the upper laser profile. When the side clearance is large, the lateral movement of the blade is small and the corresponding surface produced is also accurate. As the side clearance reduces, the surface profile also deteriorates. However, during early stages of side clearance reduction, even though the vibration of the blade is greater, the corresponding surface profile does not show much variation. When the side clearance becomes very small, even a small vibration of the sawblade lateral movement causes highly inaccurate surface profiles. This is quite significant because it shows the importance of having sufficient side clearances for climb cutting. This indicates that reduced side clearance acts as an amplifier of the inaccuracies present in the cutting.

5.1.2 Counter Cutting Results:

Figure 5-4 shows the measured sawcut standard deviations of the workpiece surface profiles cut by counter cutting saw in three different sawing conditions and at four different side clearances. Each point in the graph is an average of six measurements. Counter cutting could not be done at 0.004" side clearance because the saw always turned to one side and become wedged in the cut. Errors bars plotted indicate the limits of standard error for a set of measurements.

The upper most curve represents the sawcut standard deviation of a snaking saw. As the side clearance becomes smaller, sawcut standard deviation of the snaking saw rapidly increases. Representing these values on a single graph with other configurations becomes difficult as they obscure the variation of other values. Therefore, these values are represented by trend lines and the associated values are labeled.

For all side clearances a normal saw performs better than a snaking saw. This validates the predictions made by critical speed theory. In the initial stages of saw tooth clearance reduction, sawcut standard deviations of both the stable saw and the snaking saw increases gradually. However, when the side clearance becomes small, the sawcut standard deviations of the snaking saw increases rapidly whereas the stable saw remain at the same level. This behavior is in contrast with climb cutting results. This essentially highlights the difference in the climb and counter cutting mechanisms.

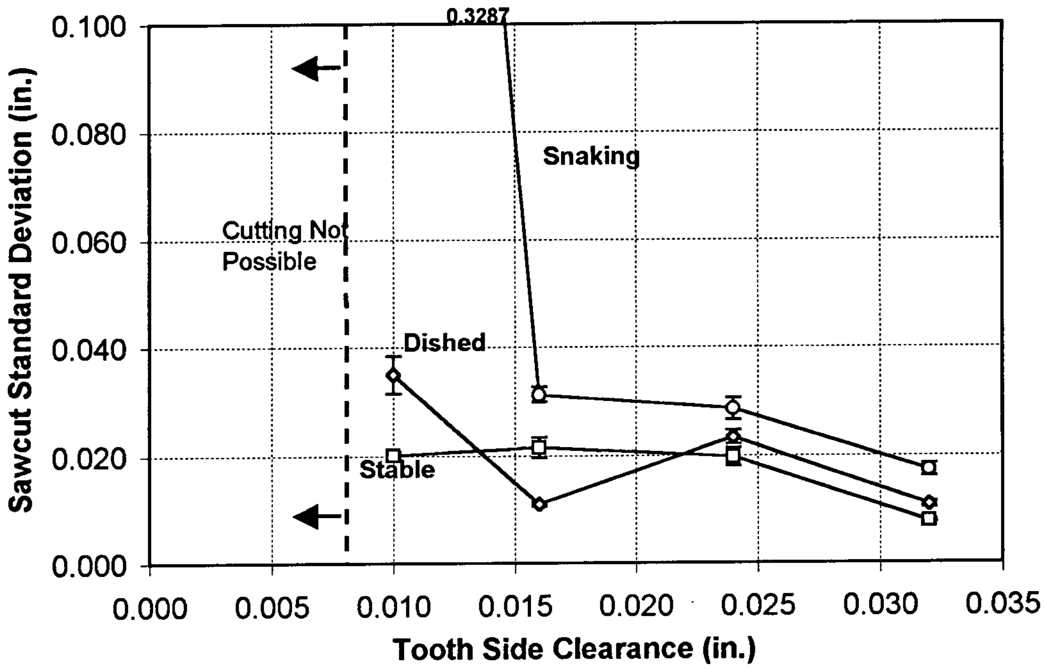


Figure 5-4 Measured Saw Cut Standard Deviations of a Counter Cutting saw

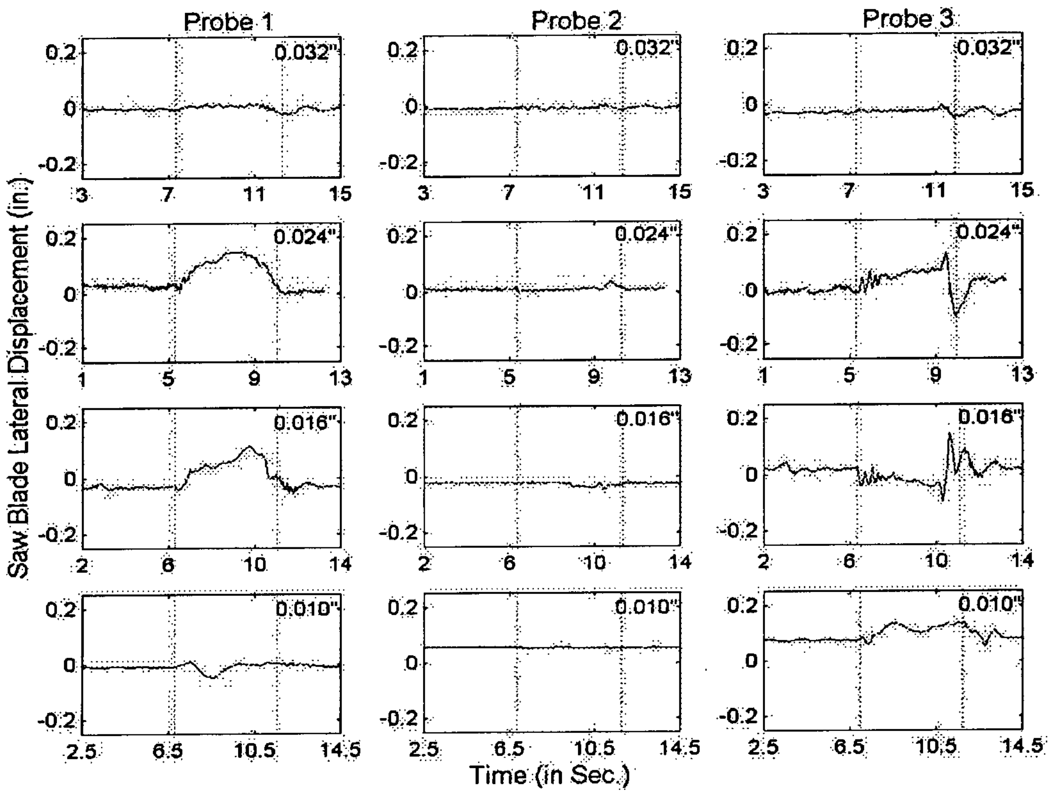
As discussed in the development of hypotheses, accuracy of counter cutting largely depends on the state of the saw tooth entering the cut. When the side clearance is very large there is hardly any contact between the sawblade and workpiece. As long as the sawblade is free from disturbances and has sufficient stiffness at the beginning of cut (usually a region of low stiffness), the standard deviation assumes low values and hardly depends on tooth side clearance. This trend is represented in the sawcut standard deviations of the stable sawblade. Observations during experiments indicated that when the side clearance is very small the sawblade easily binds with in the workpiece, resulting in heating of the sawblade and a shifting of the sawblade from a stable region to an unstable condition. This effect is more noticeable with the sawblade is working in snaking region. The sawcut standard deviations at 0.010" support this argument. At 0.010" side clearance, sawblade working in stable region cuts without any drop in cutting accuracy, whereas the snaking saw results in highly oscillating cuts having very high sawcut standard deviation.

The most important aspect of the graph is the inability of the counter-cutting configuration to perform at very small side clearances. The results obtained for counter cutting suggest the existence of 'critical side clearance' for counter cutting below which it cannot perform stable cutting operation. The value of the 'critical side clearance' depends on the operating region of the sawblade. Current results indicate that the critical side clearance decreases as one shifts from snaking region to stable region.

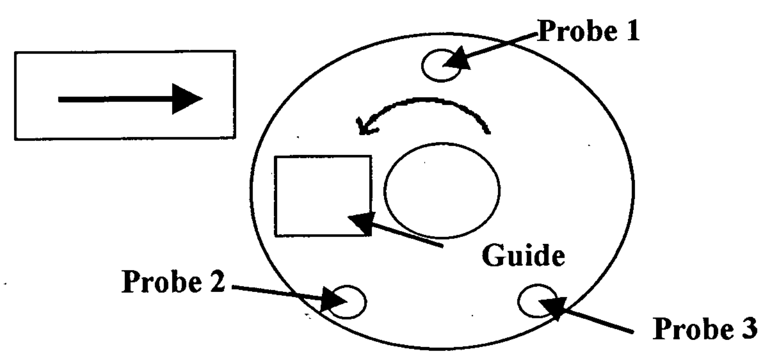
Sawcut standard deviations of the dished saw do not show any specific trend in its measured sawcut standard deviation values. At side clearances less than 0.008", the cutting with dished saw was not feasible. However, at higher side clearances the variation in the cutting accuracy was arbitrary. The reason for this arbitrary variation is not known.

Analyzing the sawblade behavior during cutting shows some other aspects of counter cutting. Figure 5-5(a) represents the vibration of the sawblade during counter cutting operation as recorded by the three displacement probes. The configuration of the sawblade and the position of the probes are depicted in Figure 5-5(b). Two dotted vertical lines indicate the cutting region. The vibration of the sawblade for 0.032", 0.024", 0.016" and 0.010" are represented. The sawblade was working in the stable region at 1200 rpm and 8° C temperature difference.

Data recorded from the displacement probes follow the general observations of the climb cutting. As the probe 2 is close to the guide, it shows minimum lateral movement of the sawblade. In case of counter cutting, the cutting accuracy mainly depends on the condition of the cutting edge entering into the cut. When the side clearance is large the vibration of the blade entering the cut is minimum. This shows that influence of saw-workpiece contact is negligible at higher side clearances. However, when the side clearance is in the 0.016"-0.024" range, data collected from the displacement probes showed typical movement of the blade during the cut. This is shown in the observations of 0.024" and 0.016" in Figure 5.5. This suggests increased contact of sawbody-workpiece near the eye of the sawblade. In case of counter cutting this happened to be region where the blade enters into wood and any disturbance near this region results in an increased sawcut standard deviation. The plot of the corresponding workpiece surface profiles in Figure 5.6 supports this argument.



(a) Sawblade Lateral Vibration



(b) Counter Cutting Configuration

RPM=1200, ΔT=8 Degrees

Figure 5-5 Typical Vibration of the Sawblade at Different Side Clearances

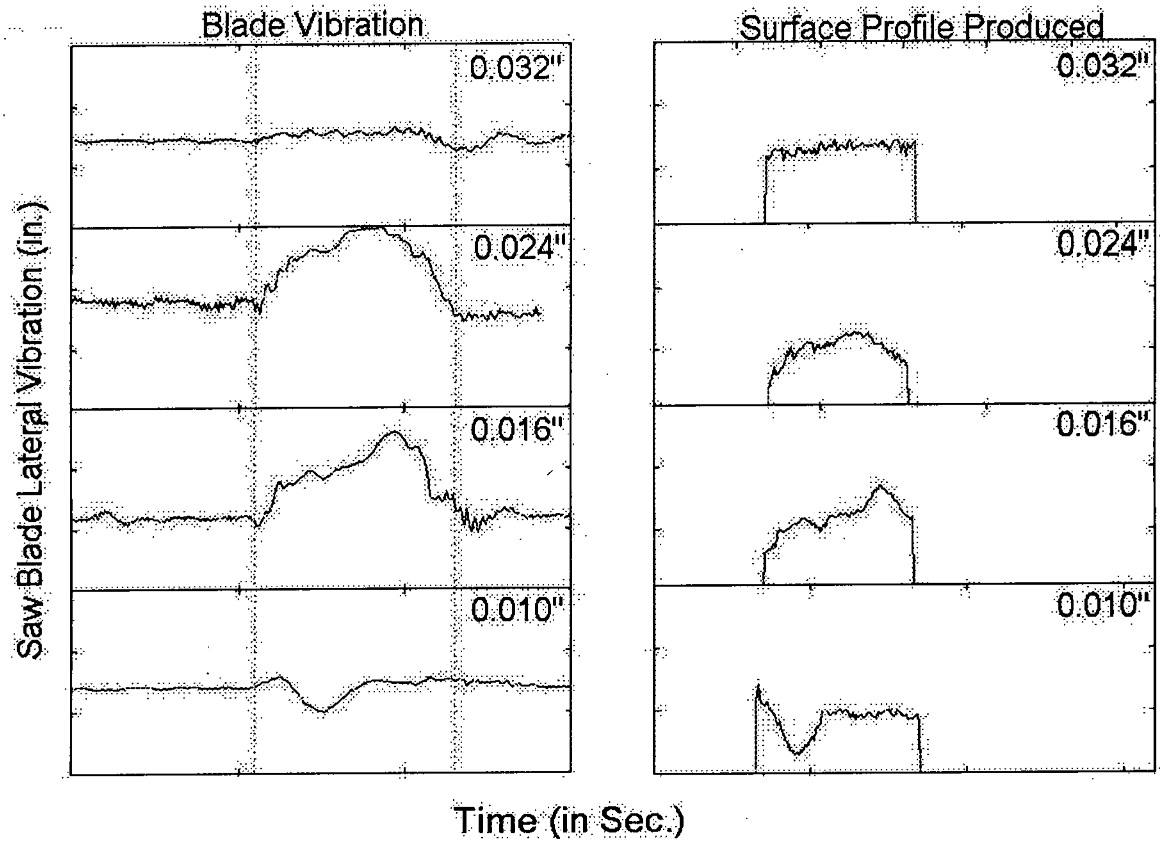


Figure 5-6 Sawblade Vibration and the Corresponding Surface Profile Produced at Different Side Clearances

X axis: 1 Division = 4 seconds   Y axis: 1 Division = 0.1 inch

5.1.3 Two-Guided Configuration Results

Additional guides locally increase the lateral stiffness of the sawblade. The two-guided arrangement provides additional stiffness at a region diagonally opposite to the first guide. Earlier experiments conducted by *Wang* [37] concluded that additional stiffness at regions away from the cutting edge deteriorates the cutting accuracy of guided saws. The hypotheses developed earlier in Chapter 2 also identifies the presence of additional guides as a region of increased stiffness and expects them to affect the cutting accuracy of the guided saws in the presence of saw-workpiece interactions at reduced saw tooth side clearances. The idea behind these experiments was to observe the behavior of the sawblade subjected to workpiece contact in the presence of stiff regions at the in feed and the out feed end of the sawblade.

Initial experiments were carried out with a stable saw at higher side clearances. However for higher side clearances there was no appreciable performance difference between single guided and two-guided configuration. This is because at higher side clearances the saw-workpiece contacts have negligible effect on cutting accuracy. Therefore, experiments were repeated with a snaking saw to clearly distinguish the effect of two-guided configuration on saw-workpiece interactions and cutting accuracy.

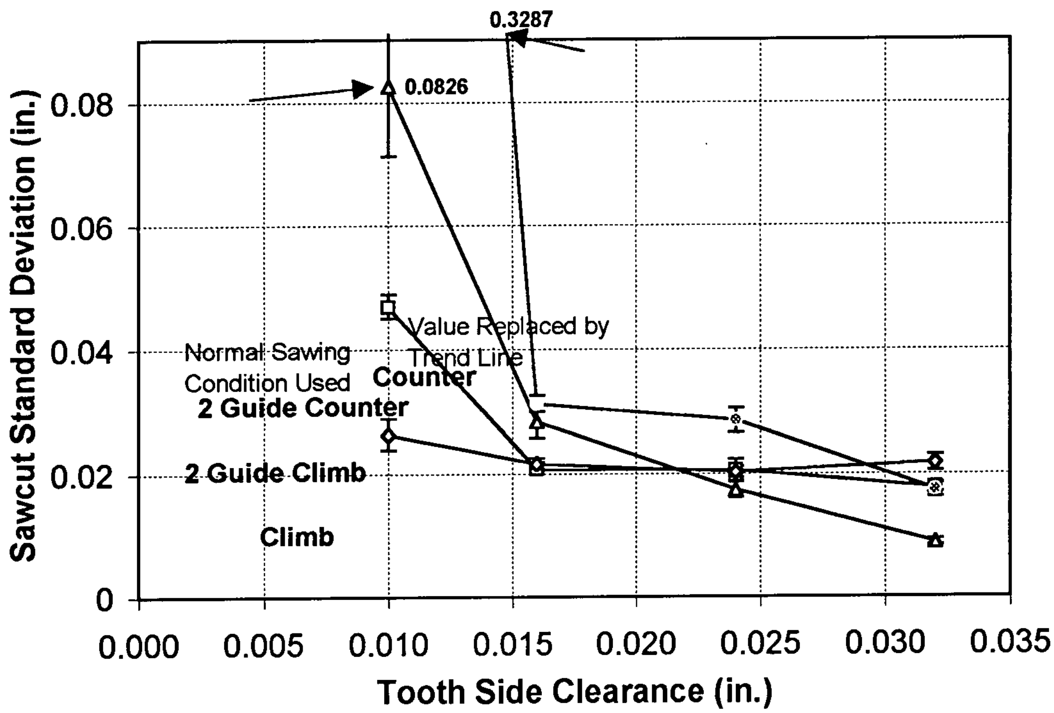


Figure 5-7 Sawcut Standard Deviations of Single Guided and Two-Guided Snaking Saws

Figure 5-7 summarizes the sawcut standard deviations of two-guided configurations and single guided configurations in climb and counter cutting. Experiments were carried out with the snaking blade at 0.032", 0.024", 0.016" and 0.010" saw tooth side clearances. Except for single guided climb cutting, experiments could not be performed at 0.004" tooth side clearance because the sawblade would bind in the workpieces. Therefore, comparison of the sawcut standard deviation has been done based on the sawcut standard deviations at four different side clearances. Errors bars plotted indicate the limits of standard error for a set of measurements

Each point in the graph is an average of six points, repeated as per the cycle of experiments. Very high sawcut standard deviations associated with counter cutting at small saw tooth side clearances were replaced by trend lines to show clearly the variations of other configurations. Cutting with two-guided counter configuration at 0.010" could not be done with the snaking saw due to the instability of the sawblade. Therefore, experiments for this configuration were done with the stable saw operating at 1200 rpm and 8° C temperature difference.

The variation of sawcut standard deviations in Figure 5-7 gives more insight into the cutting behavior of climb and counter cutting. In case of climb cutting, the presence of second guide increases the stiffness of the sawblade after it leaves cutting region. At higher saw tooth side clearances, the presence of this additional stiffness does not influence the cutting accuracy much. The difference in the cutting accuracy of single guided configuration and two-guided configurations is sublime. However, at smaller tooth side clearance, the presence of the second guide significantly hinders the cutting accuracy of two-guided configuration. This observation supports the hypothesis of additional stiffness added by the workpieces at reduced saw tooth side clearances. When the side clearance is very small the presence of workpiece itself adds stiff regions in between two guides. This result in three highly stiff regions though which the sawblade has to pass. These additional stiff regions are far away from the cutting edge and reduce the flexibility of the sawblade after it leaves the cut. The reduced flexibility limits the ability of the guided saw to follow cut surface profile. Increased workpiece contact in this situation could cause high reaction forces on the sawblade leading to frictional heating and instability.

As stated in Chapter 2, the cutting accuracy of counter cutting configuration depends on the state of the blade entering the cut. In case of two-guided configuration, the presence of second guide increases the stiffness of the sawblade before it enters the cut and facilitates the accurate cutting of wood. This is observed typically at higher tooth side clearances where the two-guided counter cutting configuration performs better than the single-guided configuration. However, when the side clearance becomes very small, even the second guide fails to facilitate an accurate cut. The sawcut standard deviations of both single guided and two-guided configurations assume very high values. These results indicate that for counter cutting, with small side clearance, instability caused by the saw-workpiece interactions dominates other factors, resulting in highly unstable sawblade and inaccurate cuts.

Figure 5-7 also compares the cutting performance of climb and counter cutting in the snaking saw region. Climb cutting performs better than counter cutting in the single guided configuration. For all side clearances, the sawcut standard deviations for climb cutting is lower than that for counter cutting. As explained earlier, counter cutting fails to cut the workpieces whereas climb cutting performs well even at side clearances as small as 0.004". These observations clearly indicate the superior stability of the climb cutting in the snaking saw region. These results also suggest the higher tolerance of climb cutting to the critical speed instability and imperfections associated with sawing at reduced tooth side clearances.

At higher tooth side clearances, the sawcut standard deviations of the two-guided counter configuration is minimum among all the configurations. However, the difference in the sawcut standard deviations of climb cutting and cutting is very small. Improved performance by two-guided counter saw at higher side clearances suggests the need for disturbance free blade at the beginning of the cut for counter cutting. As the side clearance becomes small, sawcut standard deviations of counter cutting rapidly increases. At very low side clearance values two-guided climb cutting performs better than counter cutting. As discussed earlier, presence of two guides and workpieces introduce regions of increased local stiffness. Therefore it can be concluded that climb cutting configuration performs better than counter cutting even in adverse operating conditions.

5.2 Combined Representation of Cutting Accuracy Results

As discussed earlier cutting accuracy experiments were conducted at different saw tensioning states and saw tooth side clearances. Therefore cutting accuracy can be presented as a function of saw tooth side clearances and tensioning states. This is a function of two variables and can be represented by a surface whose height equals the sawcut standard deviation of a particular combination. Projection of the surface on to different planes gives the two-dimensional representation of the variation in cutting accuracy.

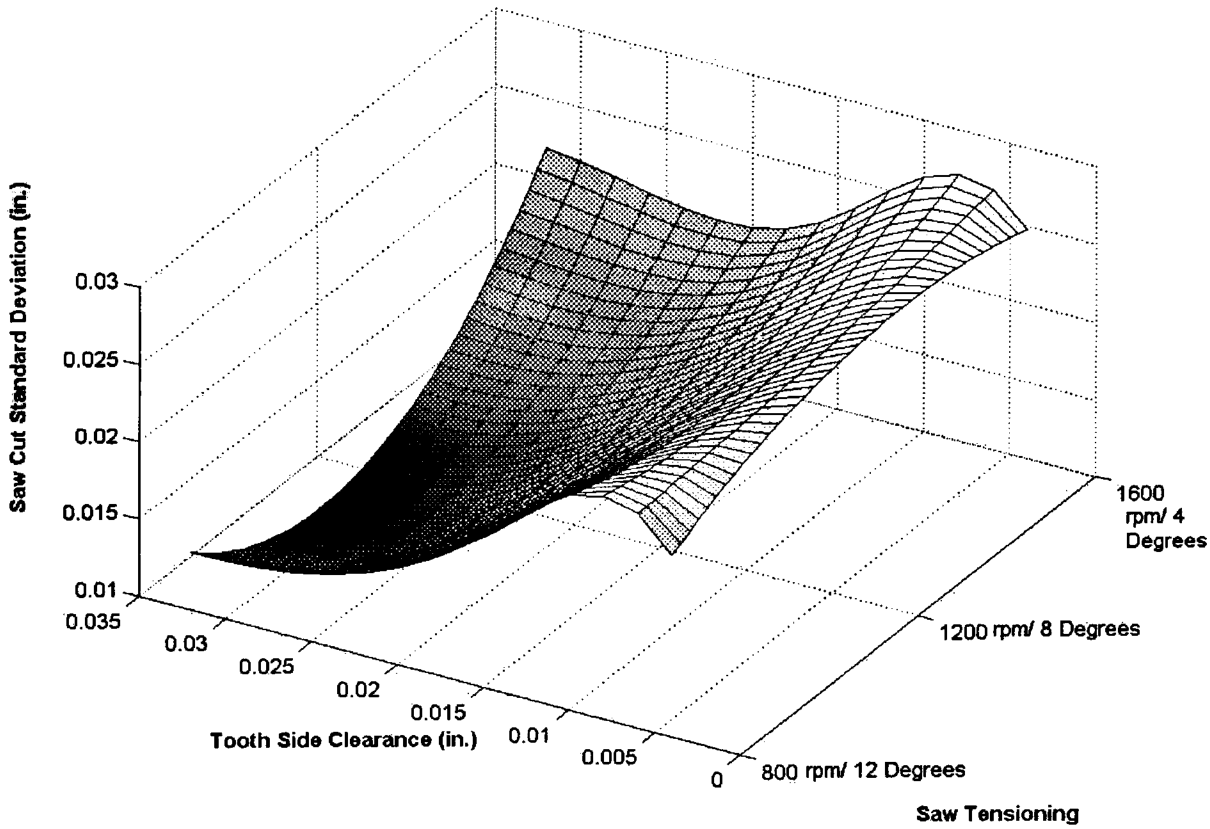


Figure 5-8 Sawcut Standard Deviation Surface of Climb Cutting as a function of Tooth Side Clearance and Saw Tensioning

Figure 5-8 shows the surface of sawcut standard deviation as a function of saw tooth side clearance and sawblade tensioning. The height of the surface represents the amount of inaccuracy present in the cut. Spline interpolation is used to interpolate the values in between. Figure 5.8 combines all the observations and presents an unified representation of the experimental results. Figure 5.8 shows clearly that as one moves away from the stable sawing region (1200 rpm/ 8 Degrees) sawcut standard deviations increase invariably. This increase is substantial at higher tooth side clearances. At small values of tooth side clearances, the sawcut standard deviations for all the configurations assumes very high values due to increased saw-workpiece interactions.

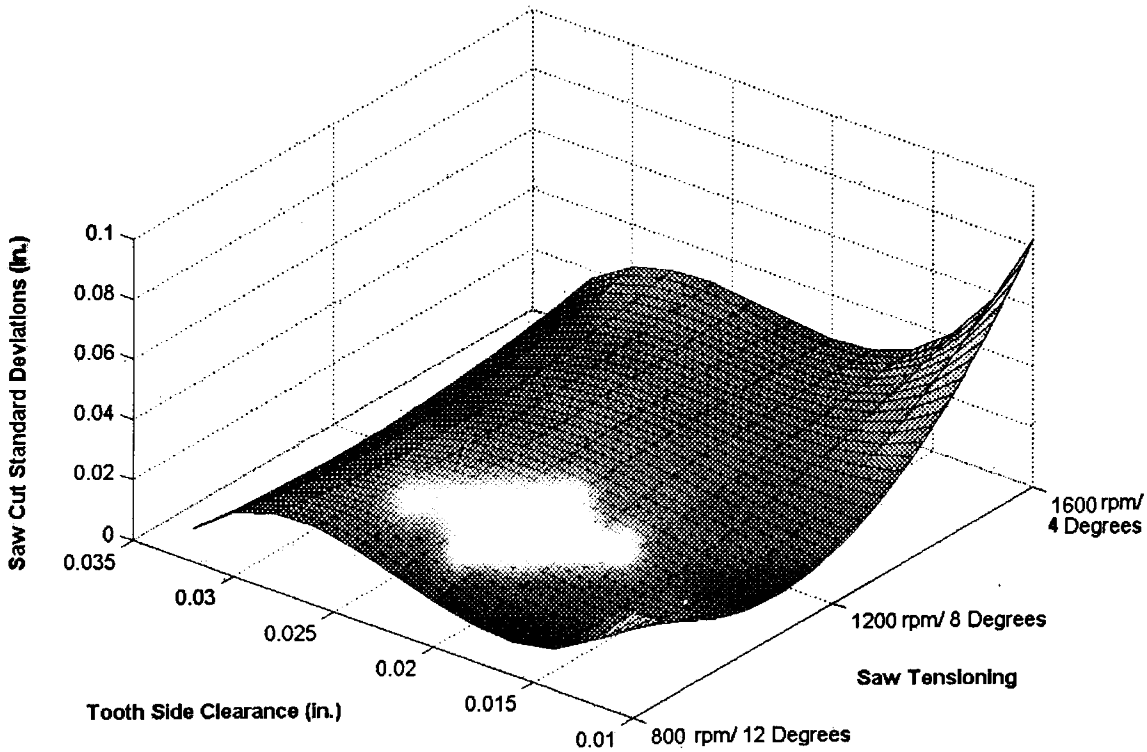


Figure 5-9 Sawcut Standard Deviation Surface of Counter Cutting as a function of Tooth Side Clearance and Saw Tensioning

Figure 5-9 shows the surface of sawcut standard deviations for counter cutting at different tooth side clearances and saw tensioning configurations. Figure 5.9 clearly shows the rapid change in cutting accuracy at lower tooth side clearances particularly for dished saw and snaking saw configurations. As discussed earlier, once the side clearance becomes smaller than 0.010", cutting in all saw configuration also becomes difficult.

5.3 *Effect of Sawblade Tensioning*

Projection of sawcut standard deviation surface on different planes facilitates the interpretation of results in a better manner. Analysis of variation in sawcut standard deviation with sawblade tensioning could be obtained by projecting standard deviation surface on to a plane defined by saw tensioning and sawcut standard deviation. Figure 5-10 shows the projection of climb cutting surface without interpolation. Error bars in Figure 5.10 represent ± standard error associated with the set of values.

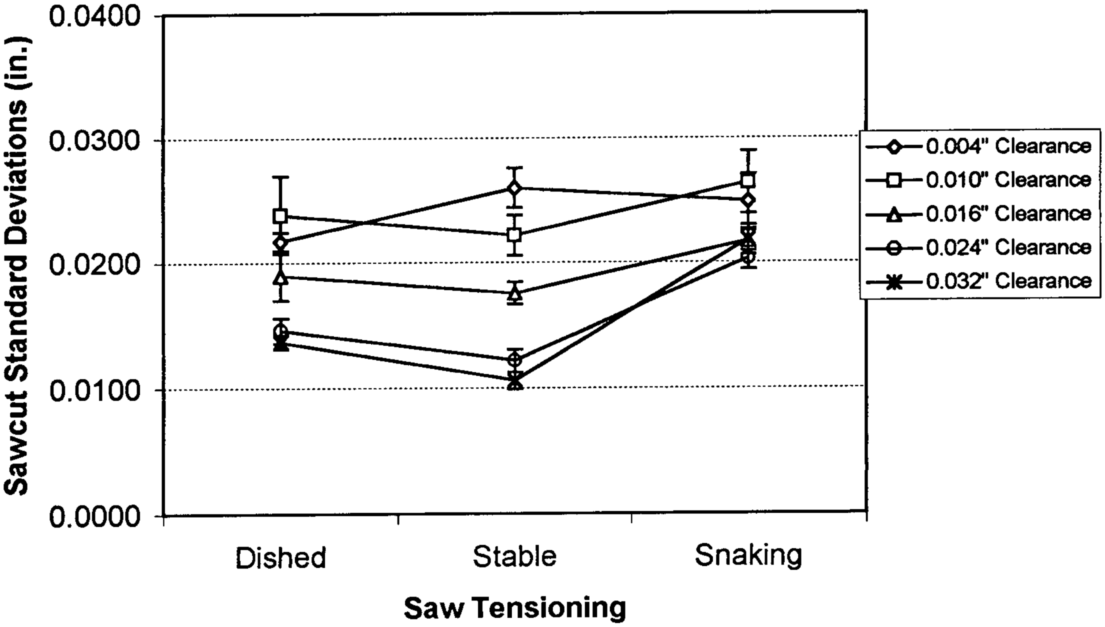


Figure 5-10 Sawcut Standard Deviations of Climb Cutting Configuration

For most of the side clearances, the minimum standard deviations occur with the stable sawblade. Stable saw performs better than dished and snaking sawblades. However, the minimum standard deviations that could be achieved for a side clearance, increases gradually with a reduction in tooth side clearances. Also, the figure clearly shows that the reduction in tooth side clearance affects stable saw greatly compared to dishing and snaking saws. The sawcut standard deviations of dished and snaking sawblades are high even at higher side clearance values.

Figure 5-11 shows the variations of sawcut standard deviations as a function of sawblade tensioning for counter cutting configuration. The observations are similar to the climb cutting configuration except for the variation of the dished sawblade, which does not conform to the expectations. The reason for this unexpected variation for dished sawblade is not known clearly.

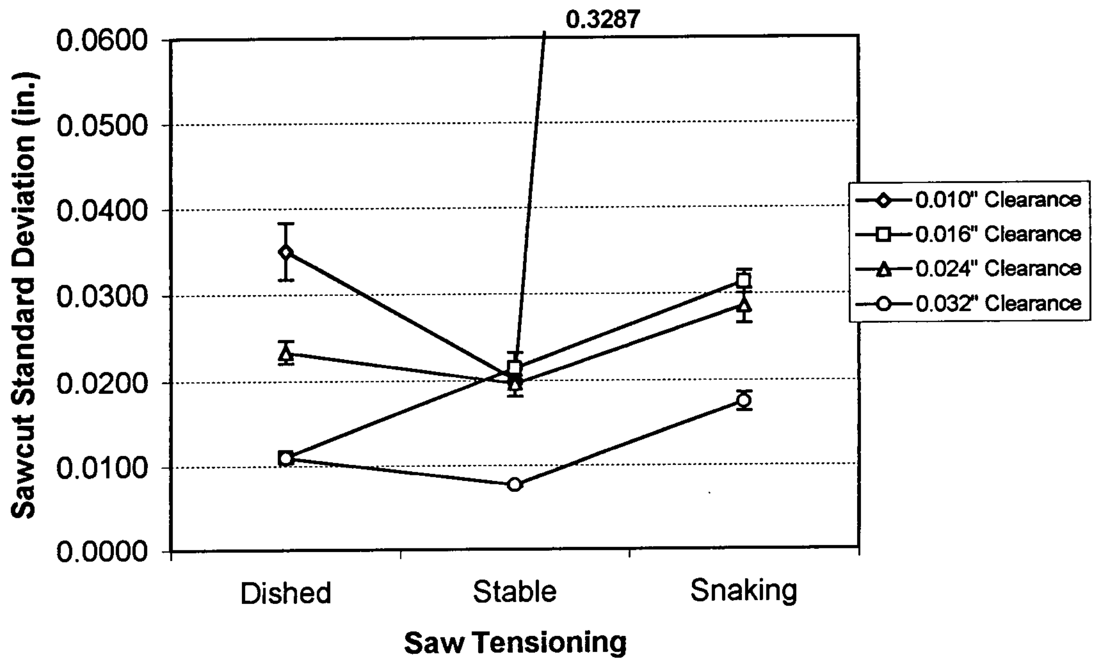


Figure 5-11 Sawcut Standard Deviations of Counter Cutting Configuration

5.4 Influence of Feed System Error on Sawing Accuracy

5.4.1 At Different Saw Tooth Side Clearances

Experiments were conducted to evaluate the effect of error in the workpiece feed system on the cutting accuracy of guided circular saws. Small lateral movement of the workpieces during the cut simulated workpiece feed system error. The arrangement for this lateral shifting has been already discussed in Chapter 4. Amount of shifting held at a constant value of 0.020 inch. Effect of shifting on the cutting performance of climb and counter cutting are discussed in this section.

Figure 5-12 summarizes the sawcut standard deviations of the counter and climb cutting configurations with simulated workpiece feed system error. Sawcut standard deviations of the stable sawblade without feed system error are also plotted on the same graph to evaluate the effect of workpiece feed error on cutting accuracy at different tooth side clearances.

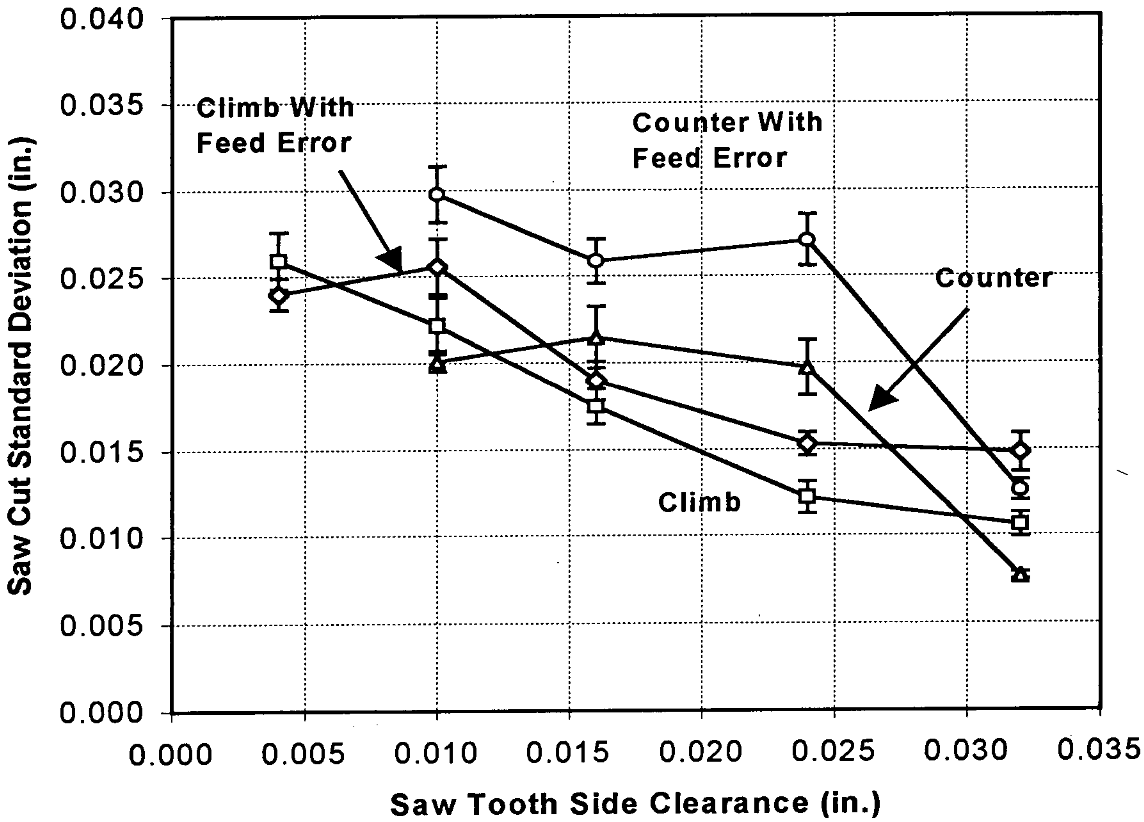


Figure 5-12 Sawcut Standard Deviations of the Stable Saw in Climb and Counter Cutting Configurations with Simulated workpiece Feed System Error

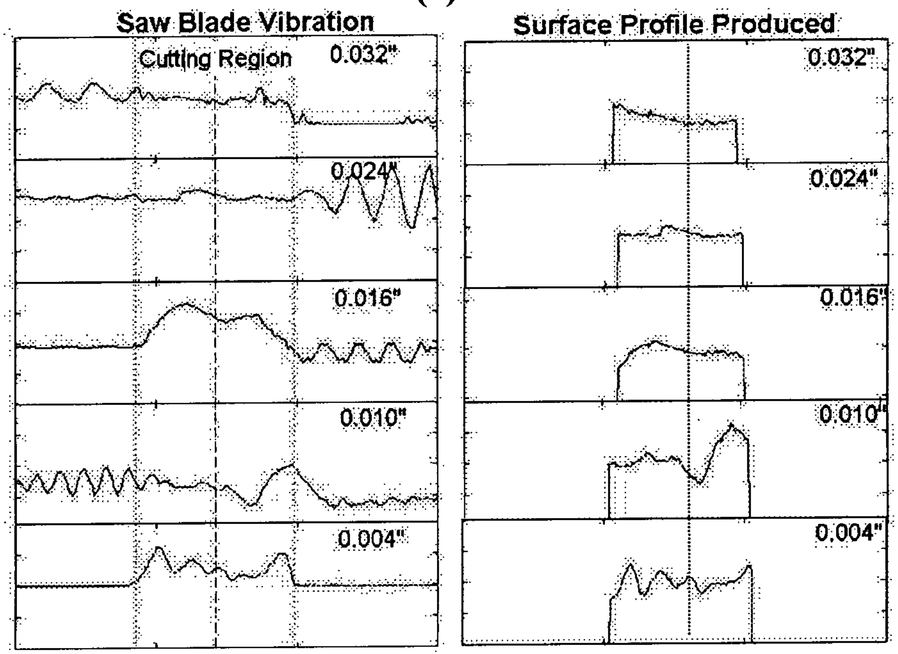
Figure 5-12 shows that irrespective of sawing configurations, sawcut standard deviations with simulated workpiece feed system error is much higher. These results indicate that the presence of workpiece feed error impair the cutting accuracy of both counter and climb cutting configurations. The difference in sawcut standard deviations of climb cutting configuration with and without feeding error is small when compared with counter cutting configuration. These support the earlier conclusion regarding the higher capability of climb cutting to withstand the inaccuracies of the sawing system. Sawcut standard deviations of counter cutting also follow the trend of climb cutting. However, the difference in sawcut standard deviations of counter cutting with and without workpiece feed error is much higher. The sawcut standard deviations of counter cutting with feed system error increases rapidly at smaller side clearance values. These results show that counter cutting is more sensitive to the variation in sawing parameters especially in the region of reduced side clearances.

The data points plotted in Figure 5-12 could be also used to compare climb cutting with counter cutting in the stable cutting region. In general, climb cutting performs better than counter cutting except at very high side clearances. Most importantly, as discussed earlier, climb cutting could perform cutting at side clearances as small as 0.004", even though with high sawcut standard deviations. However, counter cutting fails to perform at very low tooth side clearances even though it performed better than climb cutting at slightly higher side clearances.

Figure 5-12 represents the effect of workpiece shifting numerically in terms of sawcut standard deviations at various saw tooth side clearances. However, the conclusions made in the earlier discussion could be verified by analyzing the behavior of the blade and the corresponding surface produced at various saw tooth side clearances in the presence of workpiece feed error. Figure 5.13 (a) and 5.13 (b) represent this for climb cutting and counter cutting configuration respectively. Sample sawblade movement and the surface profile produced at different saw tooth side clearance are represented at different side clearances sequentially. The number on the right corner represents the tooth side clearance. Two dotted vertical lines in sawblade vibration profiles identify cutting region. Dashed line in between these two dotted lines represents the instant at which the workpieces were moved laterally by 0.020".

Figure 5-13 clearly indicate that both climb and counter cutting does not show the influence of shifting at large side clearances. This is true especially for 0.032" and 0.024" side clearances, where the value of side clearance is more than the lateral movement of the workpieces. However, at smaller values of side clearance, the effect is clearly visible in both sawblade vibration data and in the corresponding surface profiles measured. This substantiates the conclusion about the detrimental effect of workpiece feed system error when the lateral shifting of the wood is greater than the side saw tooth side clearance values.

(a)



(b)

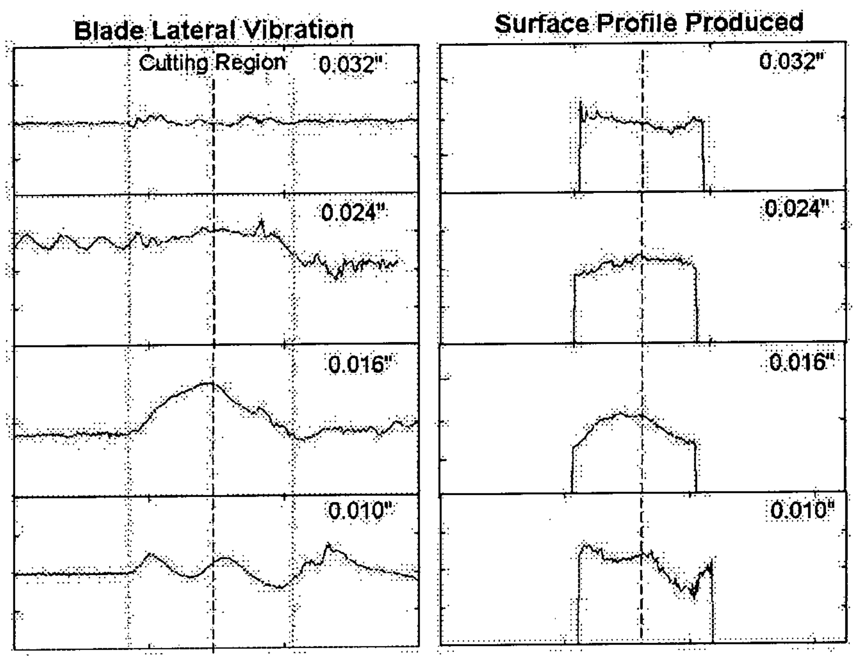


Figure 5-13 Sawblade Vibration and the Corresponding Surface Profiles for 0.020" Workpiece Shifting (a) Climb Cutting, (b) Counter cutting

X axis: 1 Division = 4 seconds Y axis: 1 Division = 0.1 inch

5.4.2 Variable Lateral Shifting of Wood

In the earlier experiments, lateral shifting of the wood was held at a constant value of 0.020" and the side clearance was varied to verify the effect of feed system error. However, a similar effect could be achieved by varying the amount of shifting while keeping the side clearance constant. Experiments were conducted at various side clearances and the results obtained match the expectations from earlier experiments and hypotheses. The present discussion is based on some sample results obtained at 0.024" side clearance.

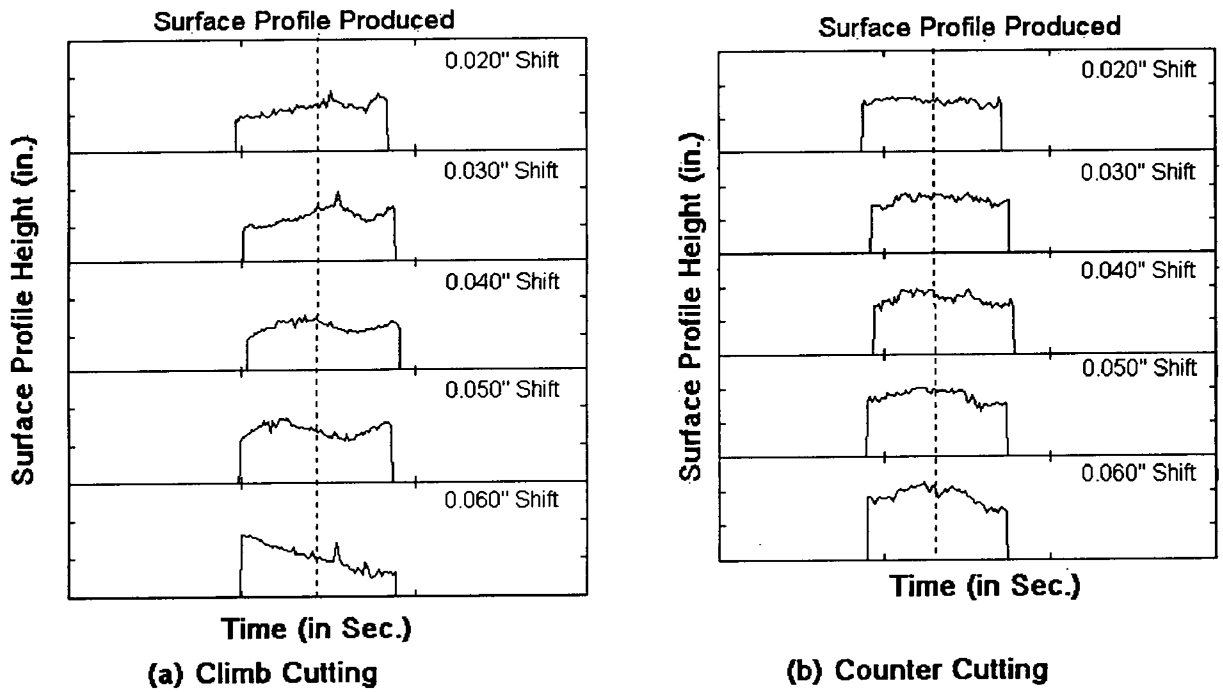


Figure 5-14 Variation of the Surface Profile with Lateral Shifting of Workpieces (a) Climb Cutting, (b) Counter Cutting. Configuration: 1200 rpm/ 8 Degrees of Temperature Difference

X axis: 1 Division = 4 seconds   Y axis: 1 Division = 0.1 inch

Figure 5-13 represents the surface profiles of climb and counter cutting as a function of workpiece lateral shifting. The vertical dotted line represents the beginning of lateral shifting approximately. The numbers at the right corner indicate the amount of lateral shifting used. Whenever, the lateral shifting is less than the side clearance value (i.e. 0.024"), its influence on the cutting performance is not obvious. However, as the shifting exceeds the side clearance, increased saw-workpiece contact results in the deterioration of the surface profile produced. This is visible in the part of the surface profile after the dotted line, which is produced during the movement of the wood.

5.5 Discussion

The data collected from the displacement probe 1 and the corresponding surface profiles are presented in Figure 5.3 and 5.6 for climb and counter cutting respectively. These graphs clearly indicate the correlation between the sawblade lateral vibration during cutting and the corresponding surface generated. However, the magnitude of the surface profile variation as recorded by laser probes is always less than the blade vibration magnitude. This is true especially at higher tooth side clearances. As the data collected from the probe 1 corresponds to the point close to the cutting region where the blade enters or leaves the cutting region, these observations clearly indicate that the presence of workpieces restricts the lateral movement of the blade during cutting and results in a surface profile of reduced magnitude. This is in accordance with the hypotheses made in Chapter 2, assuming that the presence of workpieces introduce additional lateral stiffness.

Sawblade lateral vibration profiles in Figures 5.2 and 5.5 indicate that lateral forces acting on the sawblade dominate the blade behavior during cutting. The movement of the sawblade was gradual in most of the observations. These results show that the blade behavior during cutting is influenced by forces, which push the sawblade to a side gradually rather than high frequency forces. Generally, this kind of behavior could be observed when the moving workpieces push the blade to a side during the cutting process. These observations suggest that the saw-workpiece interactions are the key factors controlling the behavior of guided saws during cutting. This further support the hypotheses made earlier.

The hypotheses presented in Chapter 2 identified saw tooth side clearance as one among the controlling variables, influencing saw-workpiece interactions and cutting accuracy. Experimental results strongly substantiate this. The variation in sawcut standard deviations of both climb and counter cutting presented in Figure 5.1 and 5.4 clearly showed the dependency of cutting accuracy on the saw tooth side clearance. In general, both the variations showed that cutting accuracy deteriorates with a reduction in tooth side clearance. Careful analysis of the experimental results showed that increased sawcut standard deviations at lower side clearances is mainly due to the increased lateral vibration of the blade. Even though the readings from probe 1 did not exemplify the shift in contact region as predicted in the hypotheses explicitly, they indicted clearly that at small side clearances the lateral movement of the blade influences the cutting accuracy greatly. This is because at smaller side clearances, the interactions take place close to the cutting edge and have greater influence on cutting accuracy than at larger side clearances.

It has been identified in the hypotheses and in the earlier research work that a guided saw with stiff cutting region combined with a more flexible body might have an advantage of achieving better cutting accuracy. This was verified by using two-guided configuration for both climb and counter cutting. The experiments were performed with a snaking sawblade to clearly identify the differences in cutting accuracies. The climb cutting results shown in Figure 5.7 clearly indicated that the presence of additional guides at the out feed end could be detrimental to improving cutting accuracy. However, counter-cutting configuration showed better cutting performance in the presence of additional guides at higher tooth side clearances. In case of counter cutting, the presence of guides increases the stiffness at the beginning of the cut and stabilizes the cutting edge. This can result in an improved cut only when the sawbody-workpiece interactions are not severe. For smaller side clearances, when there is substantial saw-workpiece reaction forces, the advantage of additional guides get obscured due to high sawcut standard deviations. This essentially highlights the need to have a stabilized cutting edge close to the cutting region and increased flexibility away elsewhere for guided circular saws.

As shown in the summarized results in Figure 5.7 and 5.12, climb cutting performed much better than the counter cutting both in the stable and the snaking region. This coincides with the industrial experience. Most importantly, the climb cutting could perform the cutting even at side clearance as small as 0.004 in all the regions where as counter cutting could not perform below the 'critical tooth side clearance'. Even though the standard deviations deteriorate at smaller side clearances, saw could cut the wood stably even with a snaking sawblade. The difference in the standard deviations at higher tooth side clearance and lower side clearance are small and of the order of 0.010"-0.020".

These results are very important as they suggest some guidelines for any method aimed at industrial sawing performance improvement. They clearly indicate that any project aiming at the reduction of 'kerf' could achieve better results in climb cutting than in counter cutting configuration. The result also point out that any supercritical sawing should consider the climb cutting as it performs better than the counter cutting in the snaking region. The results strongly suggest that for large diameter saws comparable with the experimental saw dimensions, optimum recovery and production rates could be achieved with climb cutting configuration.

Experimental observations and results of counter cutting gave more insight into the requirements of counter cutting to produce accurate sawn surfaces. The sawcut standard deviation results shown in Figure 5.4 showed a large difference in sawcut standard deviations of stable saw and snaking saw. At 0.010" side clearance stable saw performed well with a reasonable cutting accuracy, whereas the snaking saw became unstable and produced wavy cuts. This clearly shows the cutting accuracy of counter cutting is strongly influenced by the state of the sawblade entering into the cut. Therefore for better cutting performance, counter cutting needs to have a stable cutting edge entering the cut especially when the saw tooth side clearance is very small.

Experiments conducted to evaluate the effect of simulated feed system error, revealed observations of practical significance. Experiments showed any movement of the workpiece during cutting affect the cutting accuracy. Analysis also revealed that the detrimental effect of lateral shifting of wood becomes severe, when the amount of shifting exceeds the tooth side clearance at small tooth side clearances. These results have practical significance as in most of the wood cutting industry, where small lateral movement of the logs on the conveyor is inevitable during cutting.

In general, the experimental results and observations do give strong support to the hypotheses of tooth side clearance is a primary variable influencing saw-workpiece interactions and cutting accuracy of guided saws and therefore an important design factor. The theoretical model developed in Chapter 5, complements these experimental observations and simulates the behavior of guided circular saws.

CHAPTER 6 CONCLUSIONS

This thesis presents an extensive theoretical and experimental investigation of the key factors controlling guided saw cutting behavior and provides more insight into the factors to be considered for the optimum design of guided circular saws. This study was motivated by the previous experimental observations regarding the saw-workpiece interactions observed in case of guided saws. Earlier studies concluded that these interactions are the key factors influencing the superiority of guided circular saws. However, the saw-workpiece interaction itself is a function of many variables. The variables influencing the saw-workpiece reactions and their effect on cutting accuracy was not studied in detail in the earlier research activities. The present study sequentially goes through a series of procedures including the examination of earlier saw-workpiece interaction experiments, identification of controlling variables, development of the hypotheses about the effect of controlling variables on cutting accuracy, development of a theoretical model based on hypotheses, design of experiments, preparation of experimental equipments and measurement systems and experimental studies to verify the theoretical expectations.

Examination of the previous experimental results was conducted to verify the earlier conclusions about the difference in idling and cutting behavior of guided circular saws. The analysis of guided saw stability presented in Chapter 2 agrees with the earlier conclusions that the presence of workpieces influences the cutting mechanism of guided saws. This analysis has been done essentially to form a basis for the identification of controlling variables influencing saw-workpiece interactions.

The geometric models identified saw tooth side clearance and saw tensioning states as the variables controlling saw-workpiece interaction and cutting accuracy. These models were used to develop the hypotheses about the influence of saw tooth side clearance as a primary variable. A simple theoretical model was developed based on the hypotheses made and verified the predictions made by the hypotheses. The theoretical model was based on time domain calculations and modeled saw-workpiece interactions fairly well. The variation of saw natural frequency of an idling saw matched well with experimental results and thus validating the model behavior.

The results of the theoretical model substantiated the predictions from the hypotheses. These models clearly showed that sawblade working at higher tooth side clearance generates better surface than a sawblade working with small tooth side clearances. Models also indicated increased sawbody-workpiece interactions at reduced side clearance values. According to the model the sawblade working in the stable region performs better than a snaking saw. The trend of these results strongly supported the expectations from the hypotheses and provided the necessary theoretical justification.

Experiments were designed to include saw tooth side clearance, sawblade tensioning, simulated feed system error, sawing configurations and two-guided configuration as variables. Preliminary experiments were conducted to decide the values for the experimental variables and parameters. Experiments were conducted at five saw tooth side clearances and three saw tensioning levels. Sawcut standard deviation was used to measure the cutting accuracy of the experiments. Lateral vibrations of the blade during cutting were recorded to identify saw-workpiece interactions during cutting.

Irrespective of saw tensioning and cutting configuration, all sets of data demonstrated the strong influence of tooth side clearance on cutting accuracy of guided circular saws. This is clearly indicated in the results of climb, counter and two-guided configurations in Figure 5.1, 5.4 and 5.7. Results showed that the cutting accuracy of guided saws deteriorates with a reduction in saw tooth side clearance. This observation is in agreement with the theoretical expectations. The blade lateral vibrations recorded clearly showed increased saw-workpiece interaction and shifting in saw-workpiece contact region with a reduction in saw tooth side clearance. This substantiates the hypotheses about the behavior of guided saws. These results strongly suggested that saw-workpiece interaction is one among the key factors affecting the cutting performance of guided circular saws.

Experiments clearly indicated the superiority and greater level of stability of climb cutting saws. A stable saw in single-guided climb cutting configuration had minimum sawcut standard deviation compared with all other configurations. Also, climb cutting could perform cutting successfully even at very small side clearances where counter cutting failed. These results are in agreement with the industrial experiences.

Extensive comparative cutting tests conducted with various guide configurations, tooth side clearances, feed system error and sawing states helped in understanding the cutting mechanisms of guided saws and resulted in the following conclusions.

- The sawblade vibration profiles recorded during the experiments clearly showed a gradual sidewise movement of the sawblade during cutting. Incidentally, the surface profile produced also simulated this gradual movement. This type of gradual movement could be achieved only by the interaction of sawbody with the moving workpieces. Therefore, it can be concluded that saw-workpiece interactions are one among the key factors influencing the cutting behavior of guided circular saws.

- Saw-workpiece interactions in regions close to the cutting edge hinder the cutting performance of climb cutting configuration. This is clearly shown in the results of climb cutting in Figure 5.1. At low side clearances, combined effect of shift in saw-workpiece contact region and increased level of sawbody-workpiece interactions results in heavy lateral vibration of the blade and results in deterioration of cutting accuracy. However, climb cutting performs better than counter cutting due to the stable cutting edge at the beginning of the cut.

- Cutting accuracy of counter cutting depends mainly on the state of the sawblade entering the cut. Counter cutting could cut the workpieces fairly well with a stable saw especially at higher tooth side clearances. However, at lower side clearances and other saw tensioning states, heavy lateral movement of the cutting edge results in poor cutting accuracy as evidenced in Figure 5.2. This results in different 'critical tooth side clearances' for various saw tensioning states below which counter cutting could not be able to perform cutting.

- Results of counter and climb cutting clearly suggest that any 'kerf' reduction program associated with the tooth side clearance should give priority to climb cutting because of its superiority to perform well even at small tooth side clearances.

- The presence of additional guides impairs the cutting accuracy of climb cutting saws. This is shown clearly in the comparative study of cutting accuracy of single guided and two-guided configurations in Figure 5.7. The presence of the second guide reduces the flexibility of the sawblade and results in multiple regions of increased stiffness. This results in high reaction forces especially at small side clearances and deteriorates the cutting accuracy.

- The presence of additional guides enhances the cutting accuracy of counter cutting saws at higher tooth side clearances. Additional guides stabilize the cutting edge before it enters the cut. However, the advantage of having additional guides gets obscured at lower side clearance values mainly due to the increased saw-workpiece interaction close to the cutting region.

- Based on the observations of two-guided configurations it can be concluded that both climb and counter cutting configurations require stiff cutting edge and flexible body elsewhere.

- Climb cutting configuration exhibits greater stability and cutting accuracy than other configurations. Therefore any supercritical sawing if attempted should consider climb cutting as the first choice.

- Experiments conducted with the simulated feed system error indicated deterioration of cutting accuracy in the presence of lateral movement of workpieces. This is because the lateral movement of the workpieces results in forced saw-workpiece interactions and unstable cut. The sawblade lateral movement during these experiments as shown in Figure 5.12 and 5.13 clearly indicated this. However, the accuracy of cutting deteriorates greatly when the lateral movement of the workpieces exceeds tooth side clearance.

In summary, this study analyzed the cutting behavior of guided saws as a function of number of variables and presented the impact of each of the variable in terms of cutting accuracy. Important conclusions were deducted from the results of the experiments having practical significance. The results obtained also gave more insight into the cutting mechanisms of climb and counter cutting. The conclusions derived surely act as guidelines for any attempt to optimize the design of guided saws.

6.1 Suggestions for Future Research

- Results of the present study indicate the strong influence of tooth side clearance on cutting accuracy of guided saws. However, similar studies with slightly stiffer saws, did not find a good correlation between tooth side clearance and cutting accuracy. Further studies are needed to investigate this and formulate a relationship between tooth side clearance and cutting accuracy for saws of all dimensions.
- Theoretical model developed here can be extended to complete plate model to simulate saw-workpiece interactions. This will help in understanding the importance of variables associated with sawing more clearly.
- Preliminary tests indicated that clearance between sawblade and guides affect the idling behavior of guided saws. However, their effect in controlling the cutting behavior is not known clearly. Further work has to be done to optimize this.

REFERENCES:

1. "A status report on research in the circular sawing of wood," American Machine & Foundry Co. Stamford, Conn. Central Research Laboratory, 1957.
2. Birkeland, Rolf "Wood Machining – Research and Education, Where are we going?" *Proceedings of 13 th International Wood Machining Seminar, pp 17-22*, June 17-20, 1997, Vancouver, Canada.
3. Bonac, T. "Influence of Grinding Accuracy on the Deflection of Carbide Tipped Circular Saws," *Seventh Wood Machining Seminar*, University of California, Forest Products Laboratory, Richmond. October 18-20, 1982.
4. Brown, T. D. "Quality Control in Lumber Manufacturing," Miller Freeman Publications, San Francisco, CA 1982.
5. Campbell, W. "The Protection of Steam Turbine Disc Wheels from Axial Vibration," *Transactions of ASME*, Vol. 46, 1924, pp 31-160, 1924.
6. Dimarogonas, A. "Vibration for Engineers," Second Edition, 1996, Prentice-Hall, New Jersey.
7. Dugdale, D.S. "Stiffness of a Spinning Disc Clamped at Its Centre," *Journal of Mech. Phys. Solids, 1966*, Vol. 14, pp. 349-356. Pergamon Press Ltd.
8. Franz, N. C. "Analysis of Wood Cutting Process," *University of Michigan Press Engineering Research Publications*, 1958, Ann Arbor Michigan.
9. Higgs, Mike "Economic Advantages of Saw Management," *Technical Report, Sawing Technology, Forest Industries/ World Wood, pp T17-T19*, May 1989.
10. Hutton, S. G. "The Dynamics of Circular Sawblades." *Holz als roh- und Werkstoff, Vol. 49, pp. 105-110*, 1991.
11. Hutton, S. G. and Lehmann, B. F. "Self-Excitation in Guided Circular Saws," Trans ASME, *Journal of Vibration, Acoustics, Stress and Reliability in Design*, July 1988, Vo. 110, pp. 338, 1988.
12. Hutton, S. G. and Tian, Jifang "Analysis of Instabilities in Wood Cutting," *Proceedings of the 13 th International Wood Machining Seminar, pp 217-230*, June 17-20, 1997, Vancouver, Canada.
13. Kirbach, E. "Accurate determination of Minimum Side Clearance for Saws," *Proceedings of Saw Tech'97 International Conference, pp 55-63, October 30-31*, 1997, Seattle, Washington, U.S.A.
14. Kivimaa, E. "Cutting Forces in Wood Working," 1950, *The State Institute of Technical Research*, Helsinki, Finland.
15. Lehman, B. F. and Hutton, S. G. "The Mechanics of Band Saw Cutting," *Holz als Roh- und Werkstoff*, Vol. 54, No. 6, pp423-427.
16. Lehmann, B. F. "Tooth Grinding Tolerances for Circular Saws: Side Clearance," Technical Report, June 1999, *Forintek Canada Corporation*, Vancouver, Canada.

17. Lister P. "Understanding the Relationship Between Circular Saw Kerf Width, Sawing Variation and Feed Speed," *Proceedings of Saw Tech '97 International Conference*, pp 17-25, October 30-31, 1997, Seattle, Washington, U.S.A.

18. Lister, P. F., Hutton, S.G. and Kishimoto, K. J. " Experimental Sawing Performance Results for Industrial Supercritical Speed Circular Saws," *Proceedings of 13 th International Wood Machining Seminar*, Vancouver, Canada, June 1997.

19. Martin, H. C. "Introduction to Matrix Method of Structural Analysis," 1966, McGraw-Hill, Toronto.

20. McKenzie, W. M. 'Effects of Beveling the Tooth of Rip Saws,' *Wood Science and Technology*, Vol. 34, pp 125-133, 2000.

21. McKenzie, W. M. "Tooth Action Leading to Excessive Sawing Deviations," *Proceedings of the 13 th International Wood Machining Seminar, pp 429-443*, June 17-20, 1997, Vancouver, Canada.

22. McKenzie, W.M. "Wood is easy to cut -or isn't it?," *Proceedings of the Eleventh International Wood Machining Seminar*, The Norwegian Institute of Wood Technology, Oslo, Norway. Oct 21-23 1993.

23. Mote, C. D. and Szyaani, R. "Principal Developments in Thin Circular Saw Vibration and Research: Part 1: Vibration of Circular Saws." *Holz als Roh- und Werkstoff*, 35, 1977, pp. 219-225. 1977.

24. Mote, C. D. and Szymani, R. "Principal Developments in Thin Circular Saw Vibration and Research: Part 1: Reduction and Control of Saw Vibration." *Holz als Roh- und Werkstoff*, 35, 1977, pp. 219-225. 1977.

25. Mote, C.D. "Circular Saw Stability," *Forest Products Journal, Vol. 16, No. 6, pp 244-250* 1964.

26. Mote, C.D. "Stability of Circular Plates Subjected to Moving Loads," *J. Franklin Institute, Vol. 290, No.4, pp. 329-344*, 1970.

27. Scahajer, G.S. "Guided Saw Critical Speed Theory, " *Proceedings of SawTech '89*, Oakland, California, October 2-3, 1989.

28. Schajer, G. S. "Guided Saw Hunting," *Forest Products Journal*, Vol. 38, NO. 4, pp 47-50, 1988

29. Schajer, G. S. "Simple Formulas for Natural Frequencies and Critical Speeds of Circular Saws," *Forest Products Journal*, Vol. 36, No. 2, pp 37-43, 1986.

30. Schajer, G. S. "The Vibration of a Rotating Circular String Subject to a Fixed Elastic Restraint," *Journal of Sound and Vibration*, Vol. 92(1), pp 11-19, 1984.

31. Schajer, G. S. "Vibration Modes of Guided Circular Saws," *Proceedings of 10 th International Wood Machining Seminar*, Berkeley, CA, October, 1991.

32. Schajer, G. S. "Why Guided Circular Saws More Stable Than Unguided Saws?" *Holz als Roh- und Werkstoff*, 44, 1986, pp. 465-469, 1986.

33. Schajer, G. S. and Kishimoto, K. J. "High Speed Sawing Using Temporary Tensioning," *Holz als Roh-und Werkstoff, pp 361-367*, V54, 1996.

34. Schajer, G. S. and Kishimoto, K. J. "Non Classical Critical Speed Behavior of Guided Circular Saws," *Proceedings of 13 th International Wood Machining Seminar, pp* , June 17-20, 1997, Vancouver, Canada.

35. Schajer, G. S. and Mote, C. D., Jr. "Analysis of Roll Tensioning and its Influence on Circular Saw Stability. *Wood Science Technology*, Vol. 17, pp 287-302, 1983.

36. Schajer, G. S. and Wang, S. "Effect of Workpiece Interaction on Circular Saw Cutting stability," *Proceedings of 14 th International Wood Machining Seminar, pp* June 17-20, 1999, Ephinal, France.

37. Wang, S . "Factors Controlling Guided Circular Saw Cutting Behavior," M.A.Sc. Thesis, April 1999, Department of Mechanical Engineering, The University of British Columbia, Vancouver, Canada.

38. Williston, Ed M. "Saws: Design, Selection, Operation and Maintenance," *Miller Freeman Publications,* San Francisco, California 94105, USA 1989.

39. Yang, L and Hutton, S. G. "Nonlinear Vibrations of Elastically Constrained Rotating Disks," *Journal of Vibration and Acoustics*, Vol.120, No.2, pp. 475-479, 1998.

40. Young, Warren C. "Roark's Formulas for Stress and Strain," Sixth Edition, 1989, McGraw-Hill, New York.

APPENDIX I FEED SPEED CALCULATION

Feed Speeds of the workpiece are calculated based on *Gullet Feed Index*. Value of 0.28 is used for *Gullet Feed Index*.

By definition *Gullet Feed Index* is related to the *Feed per Tooth* as follows.

$$Gullet\ Feed\ Index = \frac{Feed\ per\ Tooth \times Depth\ of\ Cut}{Area\ of\ the\ Gullet}$$

For the experimental sawblade the area of gullet = 0.89 in^2. For a value of 0.28 for *Gullet Feed Index* results in *Feed per Tooth* value 0.041".

Feed speed of the workpieces in feet per minute can be calculated by

$$Feed\ speed = \frac{Feed\ per\ Tooth \times Number\ of\ Teeth \times Saw\ Rotation\ Speed}{12}$$

For number of teeth =32 and *Feed per Tooth* =0.041", Feed speeds are calculated for three sawing conditions as shown in the following table. These values were used in the calibration of the carriage subsequently.

Saw Rotation Speed (rpm)	800 (Dished)	1200 (Stable)	1600 (Critical)
Feed Speed (fpm)	87.46	131.20	174.93

Table A I-1 Feed Speeds for Different Saw Rotation Speeds

APPENDIX II SAWCUT STANDARD DEVIATION CALCULATION

Sawcut standard deviation of the cut surfaces calculated in the present research work differs from the industrial way of calculating sawcut standard deviations, which is mainly based on workpiece thickness measurements [4].

Once the cut is completed the cut surfaces were removed and the carriage carrying the workpieces was moved forward with the feed speed used for cutting. The laser probes captured the surface profiles at the top edge and the bottom edge (shown as dotted lines in the figure). The data acquisition rate was at 20 Hz. This has resulted in 90-100 points having the information about the cut surface profile.

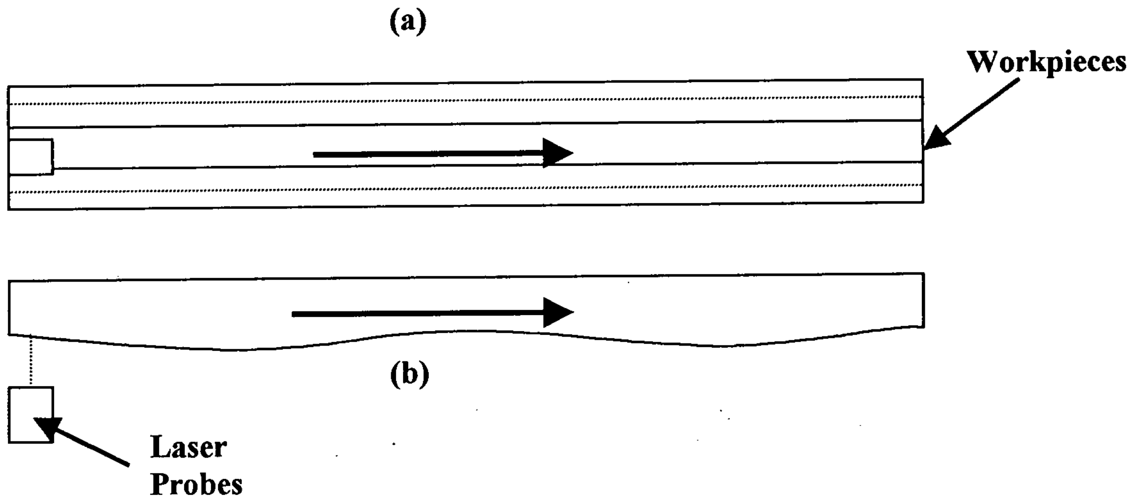


Figure A II-1 Laser probes measuring the surface profile
(a) Front view of the arrangement (b) Plan view of the arrangement

Arithmetic mean of the surface profile was calculated as follows.

$$\overline{Y} = \frac{\sum_i Y_i}{n} \qquad A\ II\text{-}1$$

where Y_i is the value of individual measurements and n is the total number of points.

Sawcut standard deviations of the cut surface was calculated using the relation

$$S.D. = \sqrt{\frac{\sum_i \left(Y_i - \bar{Y}\right)^2}{n-1}} \qquad A\ II\text{-}2$$

Example : Following Figure shows the surface information captured by the two laser probes. The markers on the graph represent the value recorded by the probes.

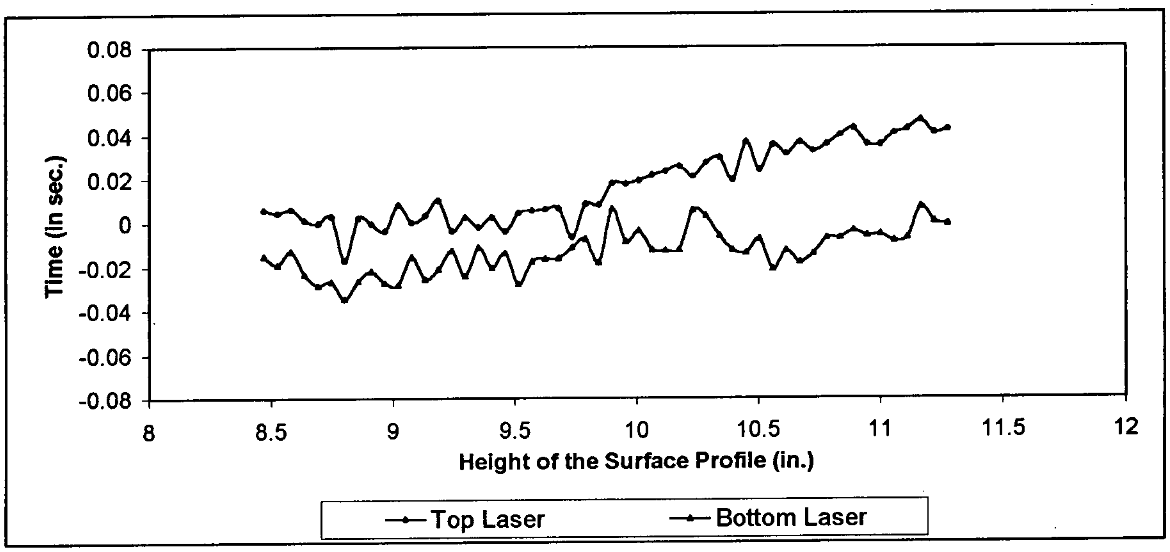


Figure A II-2 Surface Profile Captured by Laser Probes

Spreadsheet in the next page shows the calculations used for the determination of the sawcut standard deviations of the surface profiles shown in Figure A II-2.

Each sawing condition was repeated six times. This has resulted in six sawcut standard deviations representing the sawing accuracy. The graphical representation in the Chapter 5 uses the arithmetic mean of these six observations.

Counter	Time	Laser 1	Laser 2
1	8.47	0.0058	-0.0152
2	8.525	0.0043	-0.0189
3	8.58	0.0062	-0.0128
4	8.635	0.0012	-0.0231
5	8.69	-0.0003	-0.0283
6	8.745	0.0028	-0.0267
7	8.8	-0.0169	-0.0347
8	8.855	0.0022	-0.0263
9	8.91	-0.0004	-0.0218
10	8.965	-0.0037	-0.0272
11	9.02	0.0081	-0.0282
12	9.075	0.0003	-0.0154
13	9.13	0.0032	-0.0254
14	9.185	0.0103	-0.021
15	9.24	-0.0037	-0.0125
16	9.295	0.0024	-0.024
17	9.35	-0.0019	-0.0111
18	9.405	0.0025	-0.0202
19	9.46	-0.0039	-0.0137
20	9.515	0.0044	-0.0279
21	9.57	0.0055	-0.0174
22	9.625	0.0061	-0.0162
23	9.68	0.0064	-0.0161
24	9.735	-0.0065	-0.0111
25	9.79	0.0084	-0.0073
26	9.845	0.0081	-0.018
27	9.9	0.018	0.0061
28	9.955	0.0177	-0.0086
29	10.01	0.0191	-0.0037
30	10.065	0.0217	-0.0122
31	10.12	0.0235	-0.0125
32	10.175	0.0258	-0.0121
33	10.23	0.021	0.0055
34	10.285	0.0273	0.0028
35	10.34	0.0298	-0.0058
36	10.395	0.0195	-0.0123
37	10.45	0.0366	-0.0137
38	10.505	0.024	-0.0075
39	10.56	0.0356	-0.021
40	10.615	0.0314	-0.0126
41	10.67	0.0367	-0.0179
42	10.725	0.0327	-0.0142
43	10.78	0.0357	-0.007
44	10.835	0.04	-0.0069
45	10.89	0.0431	-0.0037
46	10.945	0.0359	-0.0059
47	11	0.0356	-0.0054
48	11.055	0.0408	-0.0082
49	11.11	0.0426	-0.007
50	11.165	0.0464	0.0071
51	11.22	0.0411	0.0005
52	11.275	0.0424	-0.0007

Counter	Time	Laser 1	Laser 2
53	11.33	0.0509	-0.0037
54	11.385	0.0374	-0.0072
55	11.44	0.0434	0.0123
56	11.495	0.0392	-0.0074
57	11.55	0.0423	-0.0191
58	11.605	0.045	-0.0062
59	11.66	0.0475	-0.0103
60	11.715	0.0343	0.0123
61	11.77	0.0437	-0.0101
62	11.825	0.0317	-0.0048
63	11.88	0.0446	-0.0083
64	11.935	0.0458	-0.0074
65	11.99	0.0362	-0.0032
66	12.045	0.0298	-0.0083
67	12.1	0.0467	0.0012
68	12.155	0.0282	-0.0081
69	12.21	0.0293	-0.0161
70	12.265	0.0385	-0.003
71	12.32	0.0343	-0.0015
72	12.375	0.0307	-0.0109
73	12.43	0.0276	-0.0103
74	12.485	0.031	-0.004
75	12.54	0.0379	-0.0079
76	12.595	0.0379	-0.0068
77	12.65	0.034	-0.0034
78	12.705	0.0373	-0.0069
79	12.76	0.0325	-0.0054
80	12.815	0.0297	-0.0091
81	12.87	0.0269	-0.0081
82	12.925	0.0326	-0.009
83	12.98	0.0485	-0.0092
84	13.035	0.0257	-0.0056
85	13.09	0.0286	-0.011
86	13.145	0.0413	-0.0101
87	13.2	0.0413	0.0007
88	13.255	0.032	-0.0055
89	13.31	0.0457	-0.0089
90	13.365	0.0454	-0.0061
91	13.42	0.0434	-0.0065
92	13.475	0.0433	-0.0115
93	13.53	0.0511	-0.0077
94	13.585	0.0478	-0.0045
95	13.64	0.037	-0.0076
96	13.695	0.0514	-0.0037
97	13.75	0.0412	-0.0184
Mean Surface :		**0.016825**	**-0.01341**
Sawcut Stanadard			
Deviation:		**0.017**	**0.010**