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An expert system to monitor drill condition.

Hui Kong. Lau

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AN EXPERT SYSTEM
TO
MONITOR DRILL CONDITION

by

Lau, Hui Kong

A Dissertation
Submitted to the Faculty of Graduate Studies and Research
through the Department of Mechanical Engineering
in Partial Fulfilment
of the Requirements for the Degree of
Doctor of Philosophy
at the University of Windsor

Windsor, Ontario, Canada
1992
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ABSTRACT

An expert system was developed to monitor the condition of drill bits to permit proper scheduling of tool replacement. Vibration was used as the sensing medium. The basic structure of the system consisted of the following five modules: design, monitoring, pattern and diagnosis, knowledge base, and update and learning.

The design module provides the recommended operating conditions and the predicted tool-life. The monitoring module captures, digitizes and transforms the vibration signals from the drilling process. The pattern and diagnosis module is the most essential component of the system. It includes a routine that calculates four primary descriptors (features) and two secondary descriptors. It also implements two fuzzy algorithms to assess the tool condition. It was found that only one of the four primary descriptors is sufficient to develop the system and the tool replacement is made when the grade of 'unnormal' drilling is predominant. The two fuzzy algorithms are both capable of classifying the vibration signals with a percentage of success of greater than 83 and 90, respectively. The knowledge base contains all the essential knowledge needed in the system. The update and learning module updates the knowledge base when a tool change occurs. With the recent drilling data and through a reinforcement learning scheme, the system relearns the parameters of the fuzzy algorithms and the coefficients of the tool-life equations, so that the performance of the system can be gradually improved.
Experimental measurements with a large number of drills of three sizes were
performed on several machine tools. Each drill was run until failure. Vibration
measurements were continuously obtained in order to relate observed changes to the
progressive wear and ultimate failure of these tools. After the expert system was
developed, its functioning effectiveness was tested by means of additional experimental
test runs. Eight major computer programs were developed for the operation of the
system.
Dedicated to

my parents and sisters
ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to Dr. Z. Reif and Dr. R. Gaspar for their guidance, patience, and support throughout my graduate studies.

Many thanks are owed to my colleagues, faculty, and staff members of the Mechanical Engineering Department at the University of Windsor, whose friendship, encouragement, and assistance I really appreciated while pursuing my education. I would also like to thank Dr. Chang, Mr. Fan, and Mr. Chana for their valuable assistance and inspiration in various aspects of this study.

Finally, I heartily thank my parents for their sacrifice of my being away from them and for their love and understanding during the course of this study.
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NOMENCLATURE

\( a_i \) = Coefficients of tool-life equations. \((i=0,1,2,3)\)

AI = Artificial intelligence.

\( b_{ji} \) = Bray-Curtis coefficient.

BUE = Built-up-edge.

c = Chisel edge length, mm

CAD = Computer-aided design.

CAE = Computer-aided engineering.

CAM = Computer-aided manufacturing.

D = drill diameter, mm

d = unworn portion of the drill along the cutting lips, mm

d_e = Depth of cut, mm

Dev. = Deviation.

f = Feed rate, mm/rev

\( F_{i} \) = Frequency of occurrence in \( i^{th} \) class. \((i=1,2,...,N)\)

\( F_{ij} \) = Normal distribution function.

FFT = Fast fourier transform.

fpm = Feet per minute.

freq = Frequency spectrum.

FMS = Flexible manufacturing system.

GPS = General-purpose problems solver.

Hb = Material hardness, kg/mm\(^2\)
HSS = High speed steel.
IMS = Intelligent manufacturing system.
L = Tool-life, total number of holes drilled.
M = Thrust, N
M_\text{fe} = Fuzzy partition space.
M_r = r\textsuperscript{th} moment of the distribution. (r=1,2,3,4)
N_\text{a} = Number of averages performed in HP35660A FFT analyzer.
NC = Numerical control machine.
P = Number of drilling states.
rev. = Revolution.
RMS = Root mean square.
rpm = Revolution per minute.
r = Learning rate.
r_\text{pk} = Pearson product-moment correlation coefficient.
S_i = Summed grades of membership.
std = Standard deviation, mV
T = Torque, N.m
T_s = Time required in HP35660A FFT analyzer, s
U = Update rate used in HP35660A FFT analyzer.
u_j = Membership function.
V = Cutting speed, rpm
Var. = Variance, mV²

ν_i = Cluster centers.

X_i = Class. (i=1,2,...,N)

x_i = Vibration signal.

α = Exponential Smoothing constant.

μ = Mean value of the distribution, mV

μ₃ = Skewness of the distribution.

μ₄ = Kurtosis of the distribution.

σ = Standard deviation of the distribution, mV
CHAPTER I

INTRODUCTION

Metal cutting, an operation which involves removal of metal in shaping the workpiece, is indispensable in many manufacturing processes. Of all the metal cutting operations, drilling is the most common and widely used, and accounts for one-third of all the metal cutting processes in industry[27,16]. It is a quick and economical method of hole production. It can be used to perform precision work, but, in general, it is applied in situations where precision work is not of prime concern and its main advantages are a high penetration rate and longer tool life. Very frequently, it is a preliminary operation to reaming, boring or grinding, where final finishing and sizing takes place.

1.1. Drill

The drill, the basic hole-producing tool, is of an ancient origin and was one of man's earliest machining achievements. In fact, the need for such a tool has been so great that we can find drills of one type or another in nearly all civilizations for which there is any recorded history. Nevertheless, the first machine-made twist drills were not produced until about 1860, and truly modern twist-drill development begins with the invention of high speed steel (HSS) around the year 1900[12,30].

The basic design of a twist-drill has remained virtually unchanged for the past one hundred years and has the general configuration shown in Figure 1.1. The cutting
Figure 1.1 Standard terms used to describe elements of twist drills[11]
elements comprise of two main cutting edges (or lips) lying in parallel planes displaced from each other by the distance equal to the thickness of the web. These are connected by a chisel edge which is formed by the intersection of the flank surfaces extending rearwardly from the main cutting edges. The basic cutting action of a drill bit can be summarized by the following steps; a small hole is pierced by the rotating web, metal chips are formed by the rotating edges (lips) and are rejected through the flutes, and finally the drill is guided into the hole already produced by the margin.

Twist drills are manufactured in a variety of styles and in many different sizes - fractional, number, letter, and metric - ranging from 0.150 to 89 mm. Figure 1.2 illustrates some of the commonly used types of twist drills[11]. Based on sales of more than 50 million standard twist drills, the statistics compiled by National Twist Drill showed that a median of 90% of all sales falls between 1.27 to 10.16 mm in diameter and with 3.2 mm diameter being the most popular size[11,9,7].

The process of drilling is a complex three dimensional cutting operation. Due to the common elements involved in the cutting dynamics as in a single-point cutting tool, most of the theories developed were for a much simpler two dimensional orthogonal cutting and they were far from reaching the goal of metal cutting research which can be stated as:

"To establish a predictive theory or analytical system which enables us, without any cutting experiment, to predict cutting performance such as chip formation, cutting force, cutting temperature, tool wear and surface finish[34]"
Figure 1.2 Some conventional and special-purpose twist drills[11]
The present theories are, at best, able to explain the mechanism of the metal cutting phenomena. They have a narrow application range and their effectiveness is significantly reduced in most cases when subjected to hostile environmental conditions as in actual production.

All tools wear because of the constant contact with the workpiece and the chips produced. Gradual tool wear is the main cause resulting in abnormal tool performance and, in general, it is the extent of this type of tool wear that determines the tool life. Therefore, it is very important that the cutting state of the tool be determined so that tool-replacement can be performed at the right time. Numerous tool wear sensing techniques have been developed and are used today. They can be classified into two categories: direct and indirect methods. In this research, a vibration-based monitoring system will be used, because of the following advantages.

1. It is more capable of withstanding damage under hostile environmental conditions.

2. Accelerometers, which are predominantly used as sensors for this purpose, are generally small, reliable, and cost effective.

3. It is very suitable for on-line, in-process monitoring.

4. It can be easily adapted for computer control.

1.2. Historical Development

To fully appreciate the undertaking of this research study, a brief account is necessary of how our manufacturing technology has evolved from the past to present and how it may develop in the future.
Historically, a machinist does everything from machine set-up, monitoring the process, changing the tool, sharpening the tool, etc. Success of an operation is strictly dependent on his skills and experience. As demand and costs increase, machinists are being replaced by machines with increasing levels of automation, including the application of numerical control (NC) machines and also the concept of adaptive control. As part of the process, tool replacement on a statistical basis has evolved. Unavoidably, this is not practical and also not economical. Despite its disadvantages, it is still a very common and popular practice. With the advancement in computer technology and intense competition on a global scale, a lot of advanced technologies were developed. These include computer-aided design (CAD), computer-aided engineering (CAE), computer-aided manufacturing (CAM), flexible manufacturing system (FMS), intelligent manufacturing system (IMS), computer integrated manufacturing (CIM), etc., which are all intended to optimize the production process. This is approximately the position at which our present manufacturing technology stands. There is a lot of information available from various sources and an inadequate ability to do much with it. The popular term used to describe such a scenario is "information explosion". Not until recently, with the help of artificial intelligence (AI) research, were people able to engineer knowledge from that information. As a result, a new breed of systems, so called intelligent systems, is being developed and some have recently made their commercial appearance. The most successful is the type called "Expert System".
1.3. Needs

From the above discussion, the needs of this research can be stated as follows:

1. How to replace the cutting tool at the right time? Tool life is one of the most important economical elements of a machining process. Presently, tools are replaced after a predetermined number of cuts. Because of the large scatter of tool life, which exists even for nominally identical new tools, this procedure leads to heavy under-utilization of tools and unscheduled machine downtime. Presently, the best strategy of tool-replacement is to continuously monitor the tool condition in-process via some sensor and replace tools only if the failure criteria are exceeded.

2. How to emulate the operational skills of a machinist? In the past, tool replacement and its operation were mainly controlled by an experienced machinist. Based upon a combination of vision, hearing, and touch skills of the machinist, wear conditions were assessed and the tool was replaced, without performing in most cases a complete physical measurement of the actual tool wear. This procedure was successful, but expensive. The advent of automation made it necessary to introduce different procedures for monitoring the condition of tools.

3. Due to commercial pressures of recent years, more and more emphasis is placed on controlled optimization of the machining process in order to improve the product quality and productivity and to reduce the machine downtime. In order for industry to remain competitive in the future, the
system should possess an ability to monitor, diagnose, learn, and also possess an efficient decision-making procedure regarding a machining process; the so-called "intelligent system".

4. The information generated by our present monitoring systems is tremendous. Therefore, it is necessary that this information be transformed into knowledge, so as to avoid an "information explosion" crisis.

1.4. Objectives

The importance of this machining process and the need for a more efficient and productive machining control scheme, has led to the objectives of this research to be chosen as:

1. To develop an efficient drill condition monitoring system using vibration as the sensing medium

2. To experimentally investigate some descriptors which will assist in the development of an expert system to monitor the condition of drills.

3. To develop an expert system that possesses an ability to monitor, diagnose, learn, and which also includes an efficient decision making procedure.
CHAPTER II

LITERATURE SURVEY

The following topics will be included in this chapter:

1. Drilling
2. Basic mechanics of the drilling process.
3. Tool wear and tool-life.
4. Tool wear sensing techniques.
5. Artificial intelligence and expert systems.

2.1. Drilling

Drilling is the most common machining operation used in industry today[27]. It produces about 75% of all metal cutting chips in the United States and is often the bottleneck operation in high volume transfer lines[27,22].

The cutting action of a twist drill is complex. The geometrical shape of the drill point is not efficient in cutting due to the lack of centering, poor cutting action at the center, and with different radii along the cutting edges subjected to different cutting conditions. Because of these inefficiencies, during the past thirty years, many new drill point designs were developed, such as multifacet drill, split point, racon and others[31,2,12,13,24,3].

9
The most desirable characteristics of a drill are: good wear resistance, toughness, and hot hardness[7,33]. The most commonly used high speed steels (HSS) for general industrial applications are: M1, M2, M7, and M10. However, in recent years the use of carbide drills, especially of larger sizes, has increased in industry because of carbide’s longer tool-life, higher speed capabilities, and faster penetration rate. The disadvantages of carbide drills are their brittleness, which requires a more rigid machine-tool and higher cost[9]. For normal drilling, the hole depth, in general, is limited to three to five times the drill diameter whereas a greater depth (deep hole drilling) requires the use of step-drilling, or the woodpeckering technique in order to avoid chip clogging in the flutes[16]. Errors do occur in the drilled hole’s geometry and they can be attributed to the dimensional inaccuracies of the drill bit used. Some of the commonly encountered errors can be seen in Figure 2.1[11]. Typically, the surface finish produced by a drilling process is in the range of 2.54 to 6.35 micrometers[9].

The design of a drill bit is a careful balance among factors affecting chip formation, chip ejection, and tool rigidity for any given application. In general, the drill geometry represents a compromise of several conflicting requirements, which include[30]:

1. A small web to reduce thrust on the drill but a larger web for greater resistance to chipping and greater torsional rigidity.

2. Large flutes to provide a larger space for chip transport but small flutes for better torsional rigidity.

3. An increase in the helix angle to remove chips quickly but a decrease in the helix angle for a greater length of the cutting edges.
Figure 2.1 Common errors in hole geometry experienced in drilling[11]
Less obvious compromises are associated with the choice of the geometric parameters that influence the effective rake and relief angle[30,17,19].

2.2. Basic Mechanics of the Drilling Process

2.2.1. Chip-Formation Mechanism

In the 1950s, Oxford and Shaw[28], and since then many others were able to freeze the cutting action of a twist drill. They found that the chip-formation mechanism along the cutting edges(lips) appears to be basically the same as for any other single-point metal-cutting operation and was relatively efficient, as shown in Figures 2.2(d,e,f)[12]. However, the chip-formation mechanism under the chisel edges was quite complex and not very efficient as illustrated in Figures 2.2(a,b,c). At the very center of the drill point, the only tool velocity is that of the feed in the axial direction and the deformation of the metal resembles that caused by a indenting punch. Toward the sides, deformation becomes more complex and more severe because of the combination of rotational and feed velocities.

2.2.2. Cutting Forces

In drilling, the thrust and torque are generally the measurements of greatest interest. Most of the drill torque results from the cutting action at the outer portion of the cutting edges where the largest material removal occurs. In fact, for a drill with regular proportions (standard design), the web contributes about 15 percent of the total torque and about 50 percent of the total thrust[11]. Figure 2.3 shows the effect of chisel edge length, which is proportional to the web thickness, on the drill torque and thrust.
Figure 2.2 Series of photomicrographs of sections through chisel point drill and partly formed chips at successive points along cutting edge from axis to periphery [12]
Figure 2.3 Effects of chisel edge length on the drill torque and thrust[11]
In general, cutting forces are also influenced by many other quantities such as work material and structure, drill diameter, helix angle, point angle, number of cutting edges, speed, feed rate, and drill sharpness[11,22,26]. For instance, a harder workpiece material, a decrease in the drill sharpness, a larger drill diameter, and a higher feed rate will tend to increase the cutting forces. Depth of cut and cutting speed have a negligible effect, particularly when the cutting speed is operated within the commercial range of greater than 60 fpm[4].

For standard, sharp drills, the ratio of chisel edge length and drill diameter, c/D, is about 0.18. Research and analysis have indicated that the torque and thrust can be expressed as functions of drill diameter, chisel edge length, feed rate, and workpiece material[4]:

\[ M = 0.031 \times H_b \times f^{0.8} \times D^{1.8} \]  \hspace{1cm} 2.1

\[ T = 6.962 \times H_b \times f^{0.8} \times D^{0.8} + 0.0022 \times H_b \times D^2 \]  \hspace{1cm} 2.2

where  \( M = \) thrust, N

\( T = \) torque, N.m

\( D = \) drill diameter, mm

\( f = \) feed rate, mm/rev

\( H_b = \) material hardness, kg/mm²
These two empirical equations generally agree with those presented by other investigators[26,11,30]. An extra 30 to 50 percent should be included to allow for dulling[30].

With wear occurring at the drill-point, different characteristics of behaviour of the cutting forces are noticed. Subramanian and Cook[32] were able to predict the relations of thrust and torque with hardness of work material, feed rate, diameter of the drill and also the quantity termed average flank wear as shown in Figure 2.4. Those relations were observed in drilling cast iron using HSS drills of 10.32 mm diameter at 690 rpm.

Built-up-edge (BUE), as illustrated in Figure 2.5[15,25], occurs quite frequently in drilling operations, it alters the tool angles, influences cutting forces, cutting temperatures, tool-life, and other elements of the drilling process[10]. Generally, with the presence of the BUE, the values of the cutting force will decrease due to the increase of effective rake angle. It also has a significant influence on the surface finish of the product because as the BUE grows forward, it will usually also grow downward. This causes the finished surface to be undercut and degrades the quality of the finish, as can be seen in Figure 2.5. BUE has a more pronounced effect near the chisel edge than at the cutting edges. Figure 2.6 shows how the principal cutting force varies for several feeds and also the type of BUE formed with speed.

2.3. Tool Wear and Tool-life

2.3.1. Tool Wear

Tool wear is a very complex phenomenon. It is difficult to monitor because it depends on numerous factors, including type of drill, size, shape and point style, operating
FLANK WEAR = \frac{A - B \cdot C \cdot Q}{4}

Figure 2.4 Average flank wear[32]

Figure 2.5 Effect of built-up-edge on the surface finish of the product
Figure 2.6 Variations of the principal cutting force with cutting speed for several feeds [25]
conditions, such as speed and feed rate, workpiece hardness, microstructural changes, lubricant, etc[8,7,9]. In drilling operations, generally, there are seven dominant types of wear taking place at the active cutting zones of the drill, namely, tip wear, outer corner wear, flank wear, crater wear, margin wear, chisel edge wear, and chipping at the cutting edges, as can be seen in Figure 2.7[20]. The severity of each type of wear is significantly influenced by the speed of operation, feed rate, and tool and workpiece configuration. However, the wear which occurs at the outer corner of the cutting edges can be used to evaluate the performance of the drill[20].

The main cause of wear is the increased temperature in the tool due to the transformation of the mechanical work into heat during the cutting operation. It has been found that over 98 percent of the power used in machining is transformed into heat[6]. The two main sources of the heat at the cutting edges are the shear zone, where the metal of the workpiece is being formed into a chip (primary shear zone), and the tool-chip interface, where the chip rubs against the cutting tool (secondary shear zone), as shown in Figure 2.8. At high cutting speeds, because the tool moves so rapidly, less heat is conducted into the workpiece and most of the heat is taken off with the chips. The high chip-tool temperature will promote crater wear on the tool face. An increase of the feed rate will cause an increase in the interface temperature and heat generation. The depth of cut generally will not increase the interface temperature except through redistribution of the heat flow into the cutting edges. If a workpiece of higher hardness is used, a greater amount of work is needed to form and remove the chip, which brings about a higher interface temperature and hence an increase in tool wear.
Figure 2.7 Different types of drill wear[21]
Figure 2.8 Main sources of heat at the cutting edge
2.3.2. Mechanisms of Tool Wear

There are four wear mechanisms, which can operate singly or in various combinations, to produce tool wear. These four mechanisms are adhesive wear, abrasive wear, electrochemical wear, and diffusive wear[36,8]. At low temperatures, mechanical wear processes, such as abrasion and adhesion, are rate-controlling and the wear of the tool is determined by its hardness. At high temperatures, the wear rate is predominantly determined by the chemical properties of the tool-workpiece material, hence diffusion wear will dominate.

2.3.3. Tool-life

The single most important economical element in metal cutting is the tool-life. It can be defined as the cutting time required to reach a tool-life criterion or when the tool no longer produces a ‘satisfactory’ part. Therefore, all conditions which lead to a shorter tool-life are uneconomical because of the higher tool-replacement cost. On the other hand, low speed and feed rate which bring about longer tool-life is uneconomical as well, because of the low production rate. Hence, a compromise is required in order to seek the optimum tool-life. Tool-life criterions can be due to:

1. Gradual or progressive wear at the cutting edges.

2. Tool breakage.

3. Chipping.

4. Colorization at the cutting edges.

5. Vibration generated as wear increases.
According to a number of researchers[20,18,23], the main cause of the large scatter of tool-life can also be caused by the geometrical inaccuracies of the drill bit used. Each geometrical error may influence the tool-life by 30 percent and some combinations of errors may double or even triple this reduction[24]. Scattering of tool-life could have a coefficient of variation as high as 0.6 and as low as 0.2 to 0.3[23]. For drilling, generally, the maximum wear land at the cutting edges or flank wear is limited to about 0.25 mm[9].

2.3.4. Tool-life Prediction Curve

Accurate tool-life estimation is a prime concern to the progress of integration, optimization, and automation of a production system. Since the pioneering works of Taylor, there are many forms of tool-life equations available. The majority of them are modified or extended versions of the basic equation defined by equation 2.3.

\[ VL^{a_0} = a_1 \]  

where \( a_0, a_1 \) are constants

\( V \) is the cutting speed, [rpm]

\( L \) is the tool-life

Within a reasonably narrow speed range, many researchers have agreed that the basic Taylor’s equation can predict the tool-life well enough for all practical purposes[9].

2.4. Tool Wear Sensing Techniques

The primary objective of the conventional approach to monitor tool condition is to replace the human senses of vision, hearing and touch of an experienced machine operator with transducers to monitor either sound, vibration, force, temperature or a
combination of these. Numerous sensing strategies have been developed and are used in industry today. They can be broadly categorized into direct and indirect methods. Each technique has its own advantages and drawbacks; unfortunately, no single technique has proven to be completely reliable over the complete range of operating conditions.

Direct sensing methods are those that utilize effects which are caused directly by tool wear. Tool wear and tool-life are closely related and it is generally the extent of tool wear that determines tool-life. The available direct sensing methods include direct measurement of wear by means of optical scanning, electrical resistance, and radioactive techniques; measurement of tool geometry, change of workpiece size, and analysis of tool wear particles in the chips or coolant. Generally, these are more difficult to implement and impossible to use for "in-process" monitoring, especially if there is a continuous contact between the tool and workpiece.

On the other hand, indirect sensing methods, involve keeping track of one or more parameters and correlating changes in them to changes in tool wear. These include measurement of driving power, forces, torque, current, machine tool vibration, acoustic emission, machined surface roughness and temperature. Generally, they are much easier to implement.

2.5. Artificial Intelligence and Expert System

The following topics will be discussed in this section, namely,

1. What is artificial intelligence?
2. What is an expert system?
3. Areas of application of expert systems.

5. Basic expert system terminology.

2.5.1. What is Artificial Intelligence?

Artificial intelligence (AI) is a field of study that is concerned with the development of theories and techniques that can be used to make computers behave intelligently. The present day AI was started by a group of AI scientists in 1956 at a conference. Since then, two groups of AI researchers have emerged. One group conceptualizes their work as exploration into the nature of human intelligence. Their goal is to develop a computer model that can emulate the functionality of our human reasoning process. It was only in the last five years, that this group of researchers has enjoyed a measurable degree of success, mainly because of the much improved computer technology, which includes neural networks. The other group of AI researchers, so called computer scientists, believes that anything a human can do, can be implemented on a computer. In the sixties, they started to develop a general-purpose computer program (GPS) which used a common problem-solving method to solve many different problems in different areas. Their initial attempt was unsuccessful. In the late seventies, it was realized that the problem-solving power of a program came from the knowledge it possessed and not just from the formalism and inference procedures used. This realization can be regarded as the birth of the present day expert system technology. This historical development of AI is illustrated by Figure 2.9.
Figure 2.9 Historical development of artificial intelligence
2.5.2. What is an Expert System?

An expert system is an intelligent computer program that uses knowledge and inference procedures to solve problems which are sufficiently difficult to require a human expert for their solutions. It is, at present, the most successful application of AI technology and has taken AI out of research and development laboratories and has made its commercial appearance during the past three to five years. In fact, since 1985, over 80% of the 500 largest companies in the United States have explored the potential of using expert system techniques[14]. This technology marks a transition between conventional approaches and the next generation of software oriented toward representing knowledge, communicating in natural language, and reasoning by logical rather than by mathematical means. The basic structure of an expert system and its interaction with the environment is shown in Figure 2.10.

The basic structure of an expert system consists of a knowledge base and an inference engine. The knowledge base contains knowledge, i.e., facts and heuristics, which are associated with the problem. In general, there are two common ways to represent knowledge, namely, rule-based (production rule) and frame-based. Rule-based is the simplest and most commonly used method of knowledge representation in current expert systems. It uses a simple IF-condition THEN-action type of statement. Frame-based knowledge representation, basically, consists of a networks of nodes organized in a hierarchy. Each node represents a concept described by attributes and values.
Figure 2.10 Basic structure and interaction of expert system with the surrounding
The inference engine or control structure, contains some inference procedure (control strategy) that utilizes the knowledge in the knowledge base for the solutions to the problem. There are two types of control strategy, namely, forward chaining and backward chaining. Forward chaining is the control that works forward from the given facts to the conclusion. Backward chaining is the control that starts from the known conclusion or hypothesis and works backward to the facts or data supporting it.

On the right side of Figure 2.10, the expert system acquires knowledge through knowledge acquisition software tools from a knowledge engineer who, in turn, acquires the knowledge from a domain expert. On the left side, the expert system interacts with the user. From the user, the system gathers facts and suppositions of varying degree of probable truth about the problem and supplies answers, recommendations or diagnoses of some degree of reliability. The user usually works through a keyboard interface in a formal language. As a natural language capability becomes available, it can make this interchange more friendly. Eventually, speech recognition and generation may replace the keyboard. Table 2.3 includes some of the basic expert system terminology used.

2.5.3. Areas of Application of Expert Systems

Expert systems have been built to handle many different types of problems but their basic activities can be grouped into the ten categories shown in Table 2.1[35].

Since many expert systems perform more than just one activity, for example, diagnosis often occurs with debugging, monitoring with control, and planning with design, therefore, it would be more meaningful to categorize expert systems by the type of problem they solve[35]. Table 2.2 shows some of the problem domains in which expert
<table>
<thead>
<tr>
<th>Category</th>
<th>Problem addressed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpretation</td>
<td>Inferring situation descriptions from sensor data.</td>
</tr>
<tr>
<td>Prediction</td>
<td>Inferring likely consequences of given situations.</td>
</tr>
<tr>
<td>Diagnosis</td>
<td>Inferring system malfunctions from observable.</td>
</tr>
<tr>
<td>Design</td>
<td>Configuring objects under constraints.</td>
</tr>
<tr>
<td>Planning</td>
<td>Designing actions.</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Comparing observations to expected outcomes.</td>
</tr>
<tr>
<td>Debugging</td>
<td>Prescribing remedies for malfunctions.</td>
</tr>
<tr>
<td>Repair</td>
<td>Executing plans to administer prescribed remedies.</td>
</tr>
<tr>
<td>Instruction</td>
<td>Diagnosing, debugging, and repairing student behavior.</td>
</tr>
<tr>
<td>Control</td>
<td>Governing overall system behavior.</td>
</tr>
</tbody>
</table>

Table 2.1 Generic categories of expert system applications[35]

<table>
<thead>
<tr>
<th>Agriculture</th>
<th>Manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry</td>
<td>Mathematics</td>
</tr>
<tr>
<td>Computer science</td>
<td>Medicine</td>
</tr>
<tr>
<td>Electronics</td>
<td>Meteorology</td>
</tr>
<tr>
<td>Engineering</td>
<td>Military science</td>
</tr>
<tr>
<td>Geology</td>
<td>Physics</td>
</tr>
<tr>
<td>Information mgmt</td>
<td>Process control</td>
</tr>
<tr>
<td>Law</td>
<td>Space technology</td>
</tr>
</tbody>
</table>

Table 2.2 Application areas of expert system
systems are now working. Of these areas, the medical domain seems to be the most popular, with chemistry as a close second.

2.5.4. Expert Systems in Manufacturing

Currently in manufacturing, expert systems are being developed for CAD/CAM integration, robotics, process control, scheduling, simulation, and process planning. Out of those areas, most of the systems were developed to solve problems in process planning. However, the promise and benefit of the expert system technology is being discovered in more and more areas of manufacturing.
### 2.5.5. Basic Expert System Terminology

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artificial intelligence</td>
<td>The part of computer science concerned with developing intelligent computer programs.</td>
</tr>
<tr>
<td>Backward chaining</td>
<td>An inference method where the systems starts with what it want to prove.</td>
</tr>
<tr>
<td>Database</td>
<td>The set of facts, assertions, and conclusions used to match against the rules in the rule-based system.</td>
</tr>
<tr>
<td>Domain expert</td>
<td>A person who, through years of training and experience, has become extremely proficient at problem solving in a particular domain.</td>
</tr>
<tr>
<td>Domain knowledge</td>
<td>Knowledge about the problem domain.</td>
</tr>
<tr>
<td>Expert system</td>
<td>A computer program using expert knowledge to attain high levels of performance in a narrow problem area.</td>
</tr>
<tr>
<td>Forward chaining</td>
<td>An inference method where rules are matched against facts to establish new facts.</td>
</tr>
<tr>
<td>Heuristics</td>
<td>A rule of thumb or simplification that limits the search for solutions in domains that are difficult and poorly understood.</td>
</tr>
<tr>
<td>Inference engine</td>
<td>That part of an expert system that contains the general problem-solving knowledge.</td>
</tr>
<tr>
<td>Knowledge base</td>
<td>The portion of an expert system that contains the domain knowledge.</td>
</tr>
<tr>
<td>Knowledge engineer</td>
<td>The person who designs and builds an expert system.</td>
</tr>
<tr>
<td>Rule</td>
<td>A formal way of specifying a recommendation, directive, or strategy, expressed as IF condition THEN action.</td>
</tr>
<tr>
<td>User</td>
<td>A person who uses an expert system, such as an end-user, a domain expert, a knowledge engineer, a tool builder, or a clerical staff member.</td>
</tr>
</tbody>
</table>

Table 2.3 Basic expert system terminology
CHAPTER III

EXPERIMENTAL DETAILS

In this chapter, a detailed discussion of the equipment and experimental procedure used will be given.

3.1. Equipment

Basically, there are three major groups of equipment associated with the various phases of this research, namely:


2. Equipment used for data acquisition.

3. Equipment involved in the data analysis.

3.1.1. Machine-Tool

In this research, four lathes and a milling machine were selected for study. Most of the experimental work was performed on the lathes, with the drill bit held stationary in a chuck and the workpiece rotated. Since the setups were different from the usual practise of a drilling operation, namely, rotating the drill bit with the workpiece held stationary, experimental work was also done with the milling machine to investigate the differences, if any. The four types of lathes used were Harrison M400, Colchester Master 2500, Okuma type LS, and Stanko, and the milling machine was a Bridgeport.
3.1.2. Tool and Workpiece

Proper selection of the drill and workpiece combination is very important because it not only gives a rough idea of the operating speed and feed rate required for proper cutting but also provides some insight into the mechanism involved, such as heat generation, type of chip formed, wear, etc.

Since the use of high speed steel (HSS) drill is so common in industry and because of its ability to retain high hardness at high temperature (hot-hardness) while maintaining good wear resistance, this type of tool was chosen for this research. Figures 3.1 and 3.2 show, respectively, the hot hardness and recovery hardness for several types of cutting tool materials including HSS. The selection of the drill size for this research was made on the basis that smaller drill sizes are used more often than larger sizes. As a matter of fact, the mean size range for all twist drills manufactured is around 4 mm[9,11]. In this research, three drill sizes were selected, namely, 2.38 mm (3/32 in), 3.18 mm (1/8 in), 6.35 mm (1/4 in).

The workpiece materials were selected on the basis of trial and error. After investigating a number of materials such as AISI 1018, AISI 4140, AISI 4340 and so on, AISI 4340 alloy steel was found to be most desirable due to its ease of machinability. Under the recommended operating conditions, the tool-life obtained was considered to be appropriate for this study. Table 3.1 shows the different percentages of constituents of the alloy steel used.

In this experiment, the recommended operating speeds for the sizes of drills and workpiece material were obtained from a number of machining handbooks and they are
Figure 3.1 Hot hardness for several types of cutting materials[11]

Figure 3.2 Recovery hardness for several types of cutting materials[11]
expressed as rules in the knowledge base of the system. A more detailed discussion of these rules is included in a later chapter and also in Appendix B.

<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>C</td>
<td>0.38 - 0.43</td>
</tr>
<tr>
<td>Manganese</td>
<td>Mn</td>
<td>0.6 - 0.8</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>P</td>
<td>&lt; 0.035</td>
</tr>
<tr>
<td>Sulphur</td>
<td>S</td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td>Silicon</td>
<td>Si</td>
<td>0.2 - 0.35</td>
</tr>
<tr>
<td>Nickel</td>
<td>Ni</td>
<td>1.65 - 2.0</td>
</tr>
<tr>
<td>Chromium</td>
<td>Cr</td>
<td>0.7 - 0.9</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>Mo</td>
<td>0.2 - 0.3</td>
</tr>
<tr>
<td>Brinell Hardness</td>
<td></td>
<td>207</td>
</tr>
</tbody>
</table>

Table 3.1 AISI 4340 Alloy Steel[26]

3.1.3. Equipment for Data Acquisition

Equipment for data acquisition includes the transducer used for the vibration pickup and also the means to store the vibration signal.

In this research, accelerometers were used as the vibration sensors. The vibration signals were stored on magnetic tape. The locations of accelerometers were selected as close to the drilling action as possible to ensure the predominance of vibration from the drilling operation. For experimental work using the lathe, they were located on the tool post, as shown in Figure 3.3. On the milling machine they were located on the workpiece and on the table, as indicated by Figure 3.4. They were stud-mounted on a disc and glued onto the tool post, or workpiece and table, depending on the types of machine-tool used. Two different types of accelerometers were used in this research to suit the type of tape-recorder being used. Table 3.2 gives specifications of the two accelerometers and tape-recorders used.
Figure 3.3 The experimental set-up on the lathe
Figure 3.4 The experimental set-up on the milling machine
<table>
<thead>
<tr>
<th>TAPE RECORDER</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>B&amp;K 7005</td>
<td>Nagra IV-SJ</td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>0 to 60 kHz</td>
<td>2.5 to 35 kHz</td>
</tr>
<tr>
<td>Weight</td>
<td>8.8 kg(19.4 Lbs)</td>
<td>7.3 kg(16 Lbs)</td>
</tr>
<tr>
<td>Recording Speed</td>
<td>38.1 cm/s</td>
<td>38.1 cm/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ACCELEROMETER</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>B&amp;K 4348</td>
<td>PCB 307A</td>
</tr>
<tr>
<td>Sensitivity (mv/g)</td>
<td>8.39</td>
<td>100</td>
</tr>
<tr>
<td>Resonant frequency(Hz)</td>
<td>62,000</td>
<td>&gt;40,000</td>
</tr>
<tr>
<td>Frequency Range(Hz)</td>
<td>0 to 20,000</td>
<td>2 to 10,000</td>
</tr>
<tr>
<td>Weight (gm)</td>
<td>11</td>
<td>31</td>
</tr>
<tr>
<td>Amplifier/ power unit</td>
<td>Vibration unit</td>
<td>480B power</td>
</tr>
<tr>
<td></td>
<td>ZM 0060</td>
<td>unit</td>
</tr>
</tbody>
</table>

Table 3.2 The accelerometers and tape-recorders used.

3.1.4. Equipment for Data Analysis

Equipment for the data analysis can be sub-divided into three groups:

1. that used to capture the time-amplitude vibration signal and the frequency spectrum (data acquisition);

2. that used to perform the data reduction, and;

3. that used to present the data acquired and the results of the data analysis.
3.1.4.1. Data Acquisition

In this research, a vibration signal was analyzed in two different domains, namely, time and frequency domains. Therefore, different forms of the vibration signal were needed, namely, the time-amplitude vibration signal in the time domain analysis and the frequency spectrum of the vibration signal in the frequency domain analysis.

3.1.4.1.1. Time Domain Analysis

In the time domain analysis, the analog signal from the tape-recorder was digitized with the use of the Prowler digital oscilloscope. The digitized signal was then sent to the computer and stored on the computer disc for further processing.

The Prowler is a powerful digital oscilloscope manufactured by Norland Co. It has three functional characteristics:

1. It is capable of acquiring signals from DC to 20 MHz and displaying two signal traces at the same time.
2. It is equipped with a variety of pre-programmed operations.
3. It is programmable, namely, it allows the user to enter a series of key-strokes as a programmed routine which can be stored in the Prowler's memory for later use.

It is equipped with both RS232 and IEEE488 interfaces. A user friendly program, written in Basic, called 'Prowler', was developed to transfer the digitized data from the Prowler to the computer. The listing of this program is included in Appendix A. This program allows the user to specify the amount and format of the digitized data on the Prowler to be transferred, and once the datz are in the computer memory, the user has
the choice of displaying the captured data on the computer monitor, and/or storing them onto the computer disc either in decimal or binary format.

3.1.4.1.2. Frequency Domain Analysis

In the frequency domain analysis, the analog signal from the tape-recorder was processed by the HP35660A FFT analyzer, to obtain its frequency spectrum. It was then transferred to an IBM computer and stored on the computer disc. The frequency spectrum obtained was an RMS average of frequency spectra in a drilling sequence. The number of averages performed per drilling sequence was determined by using equation 3.1.

\[ N_s = 11.11T_s - 10.14 - 3.53U \]  \hspace{1cm} \text{equation 3.1}

where \( T_s \) is the time taken per drilling sequence in seconds.

\( U \) is the update-rates on the screen.

\( N_s \) is the number of averages performed.

A more detailed derivation of the above equation can be found in Appendix C.

The HP35660A FFT analyzer is capable of performing either two-channel or single-channel measurements. In a single-channel measurement mode, the analyzer can handle signal frequencies of up to 102.4 kHz. In a two-channel measurement, it can handle signal frequencies up to 51.2 kHz. This instrument is equipped with an IEEE488 interface, on-board memory, internal disc, and is programmable using the HPBasic language.
A simple computer program, written in Basic, called 'HP35660A', was used to capture the frequency spectrum from the HP35660A FFT analyzer. A listing of the program is included in Appendix A.

3.1.4.2. Data Reduction

An IBM PC-XT equipped with an IEEE488 interface card (GPIB PC-II) in one of its expansion slots was used to perform the data acquisition tasks described previously, in addition to other analyzing tasks which will be described in the next chapter. All software used was developed using Quickbasic version 4.5.

3.1.4.3. Data Presentation

The data acquired and results obtained can be presented, with the use of various computer programs developed, on the computer monitor (EGA), the printer (Epson LX 80), and also the plotter (HP 7475A).

3.2. Experimental Procedure

Before the start of any drilling operation, the drill was cleaned in order to get rid of any packaging grease as dry drilling was desired. The drill was fitted to the chuck which was mounted in a tool post. The alignment between the tip of the drill and the center of the face of the specimen was carried out so as not to introduce any extraneous vibration into the process. Workpieces were prepared differently depending on the types of machine tool used. For those workpieces used on the lathe, the pieces were cut from bar stock into lengths of 50.8 mm and 25.4 mm depending on the drill size used. They were also center-drilled in order to eliminate the wander action at the drill-point when the drill first makes contact with the workpiece. The workpieces used by the milling machine
were cut into a square plate with sides of 15.24 cm long and of 2.54 cm in thickness. They were center-drilled with the use of a computerized lay-out function on the radius of a circle.

After the initial preparation of the drill, workpiece, and when the proper set-up was achieved, the following steps were taken to perform the drilling operation:

1. The lathe or milling machine was turned on.
2. The tape-recorder was turned on and the necessary comments regarding the drill conditions and observations were recorded on the magnetic tape.
3. The feed was engaged to start drilling after constant or steady state tape-speed condition was attained.
4. The drilling operation was stopped after the desired depth of cut was achieved. The recommended depth of cut is between three to five times the drill diameter[26]. In this research, the depth of cut was three times the drill diameter.
5. The tape-recorder was turned off.
6. The drill was removed from the chuck and placed in a drill-holder for tip wear measurement. See Figure 3.5.
7. The drill was placed back into the chuck at the same location and orientation as before in order to maintain consistency in the experiment.
8. The sequence from step (2) to step (7) was repeated until drill failure occurred, namely, when the drill broke or became excessively worn.
The tip wear measurement was performed on a travelling microscope which has a magnification of 20X and an accuracy of measurement to the nearest 0.01 mm. Tip wear is defined in accordance with normal industrial practice as the length of worn portion of the drill at the drill-point along the cutting edges. Figure 3.6 shows this distance as the drill diameter minus the distance "d".

All information about the operating conditions, tip wear measurements and accessories for the drilling operation were recorded on data sheets for ease of future analysis and reference.
Figure 3.5 The schematic diagram of the tip-wear measurement

Tip-wear = D - d

Figure 3.6 Definition of tip-wear
CHAPTER IV

DATA ANALYSIS

Humans are intelligent, computers are not. Therefore, the intent of this chapter is to take a closer look at human intelligence (how we perceive and interpret information) and develop an algorithm analogous to the human reasoning process in order to make the computer behave more intelligently, specifically in the areas of data analysis. The major topics included in the discussion are:

1. The procedures developed to calculate descriptors (features) from the vibration signals stored on the magnetic tapes.

2. Selection of the potential descriptors that can be used to develop an expert system.

3. Classification of vibration signals.

4. Assessing the tool condition.

5. Tool-life prediction curves.

4.1. Data Reduction

As stated in Chapter 3, in this research, vibration signals are analyzed in the time and frequency domains. Time domain analysis involves manipulation of signals with
respect to time whereas frequency domain analysis is concerned with the frequency contents of the signals.

Data analysis begins with the playback of the vibration signals stored on the magnetic tapes and the signals are respectively digitized by the Prowler digital oscilloscope and the HP35660A FFT analyzer, as illustrated in Figure 4.1. Digitized vibration signals and frequency spectra are obtained as a result.

4.1.1. Time Domain Analysis

Vibration signals obtained from the drilling process are random in nature as shown in Figure 4.2 and it is very difficult to describe them by any mathematical functions (non-deterministic). However, from the Figure, as wear increases, there is a distinct increase in the amplitudes of the vibration signals. Therefore, any descriptor which utilizes these distinct characteristic changes will be meaningful and effective in this application.

In this study, five statistical descriptors were chosen to describe the various amplitude characteristics of the signals, such as its central tendency, spread/dispersion, symmetry, and peakedness. They are:

1. Mean value.
2. Standard deviation.
3. Skew.
5. RMS height of the distribution.
Figure 4.1 Block diagram of the data analysis
Figure 4.2 Vibration signals at various degrees of wear
To calculate these statistical descriptors, vibration signals were grouped to obtain the frequency distributions. The grouping process involves dividing the amplitude scale into classes or intervals of equal width and tallying the number of times data values fall in each class. Figure 4.3 shows the process of digitization and grouping of digitized data, to obtain the frequency of occurrence distribution. The grouped data or frequency distribution is also known as the amplitude distribution of the signal. The most obvious advantage of performing computations on the grouped data instead of the ungrouped raw data is the significant reduction in the computation speed required, as illustrated in Figure 4.4.

There is no optimum way to select the number of intervals or classes used. It has to be a compromise between too many and too few. The specific number of intervals is determined by the amount of data and the variability of the data. In this research, the number of intervals used is 200.

Suppose there are N number of classes, \( \{x_1, x_2, ..., x_N\} \), and each class has its corresponding frequency of occurrences, \( \{F_1, F_2, ..., F_N\} \) as shown in Figure 4.5. The expression for \( r^{th} \) central moment can be defined as:

\[
M_r = \frac{\sum_{i=1}^{N} F_i (x_i - \mu)^r}{\sum_{i=1}^{N} F_i}
\]

4.1
Figure 4.3 The schematic diagram of digitization and grouping process[21]
Figure 4.4 Computation time required to calculate those statistical parameters of grouped data as compared to ungrouped data.
Figure 4.5 Typical frequency distribution
\[ \mu = \frac{\sum_{i=1}^{N} F_i \cdot x_i}{\sum_{i=1}^{N} F_i} \]

4.1.1.1. Measure of Central Tendency

Observations generally have the tendency to center or group themselves around a central value. The mean, \( \mu \), which is the first moment about the origin, can be used to measure this characteristic.

4.1.1.2. Measure of Spread/Dispersion

Dispersion can be defined as the degree of clusterness of observations about the mean. This characteristic of the distribution can be measured by either the variance (second order central moment, \( M_2 \)) or the standard deviation, (the positive square root of variance, \( \sigma \)).

\[ \sigma = \sqrt{M_2} \]

4.1.1.3. Measure of Asymmetry

Consider the three distributions shown in Figure 4.6. Distribution A is symmetrical, whereas distribution B and C show lack of symmetry. Skew, \( \mu_3 \), which is a normalized third order central moment can be used as a measure of the amount and direction of asymmetry. It is defined by equation 4.4.
Figure 4.6 Distributions with different degree of asymmetry

Figure 4.7 Distributions with different degree of peakedness
The numerical value of \( \mu_3 \) reflects the extent of the asymmetry or skewness of the distribution, with the sign of \( \mu_3 \) indicating the direction of the asymmetry. From Figure 4.6, distribution A has the value of \( \mu_3 \) equal 0 whereas distributions B and C have the sign of \( \mu_3 \) to be positive and negative respectively.

4.1.1.4. Measure of Peakedness

As shown in Figure 4.7, all three distributions exhibit more or less the same central tendency, dispersion, and the same symmetry, but different degrees of peakedness. Kurtosis, \( \mu_4 \), the fourth order normalized central moment is the measure that is needed to describe this characteristic of the distribution and it is defined in equation 4.5.

\[
\mu_4 = \frac{M_4}{M_2^2}
\]

However, this measure is very sensitive to the tails of the distribution, dominated by the standard deviation to the fourth order. From Figure 4.7, distribution B has a larger deviation than A, hence its kurtosis will be smaller. Since distribution C has the largest deviation among the three, its kurtosis will be the smallest.

Another measure of the peakedness of the distribution, which is not as sensitive to the spread of the tails of the distribution, is the RMS height of the distribution defined by the following formula:
\[
\text{RMS} = \sqrt{\frac{\sum_{i=1}^{n} F_i^2}{n}}
\]

4.6

Where \( n \) is defined as the number of classes confined between the minimum and maximum amplitude of the signal.

4.1.2. Frequency Domain Analysis

The HP35660A FFT analyzer is an anti-aliasing device that samples at 2.56 times the highest frequency of interest and the transformed data (frequency spectrum) is represented by 400 sampled values. Figure 4.8 shows a typical frequency spectrum of a vibration signal when the drill is moderately dull. The acceptable linear frequency range of the accelerometer used is from 0 to 20 \( \text{kHz} \), therefore, the last spike in the figure is not accurately indicative of the vibration generated during the drilling operation. Even though the progress of tool wear excites all frequencies from 0 to 20 \( \text{kHz} \), in this research only those in the range from 0 to 12.8 \( \text{kHz} \) were considered in the analysis.

Figure 4.9 illustrates the frequency spectra of vibration signals at various degrees of wear, namely, when the drill is sharp, at 50% and 60% tip-wear. As wear increases, there is an overall increase in the amplitude of the frequency spectrum. Therefore, the total RMS of the spectrum is chosen as one of the descriptors. Also, it can be seen from the examples presented that at some particular frequency bands, greater changes in vibration levels are observed. Therefore, bandpass RMS of the frequency spectrum was also selected as one of the descriptors.
Figure 4.8 Frequency response from 0 to 25.6 kHz
Figure 4.9 Frequency spectra at various degrees of wear
To summarize, the two descriptors chosen in the frequency domain analysis are:

1. Total RMS of the spectrum.
2. Bandpass RMS of the spectrum.

The frequency bands selected for the five machine-tools used are summarized in Table 4.1.

4.2. Selection of the Potential Descriptors

In this section, the chosen descriptors, in both the time domain and the frequency domains, are discussed and their potential for use in an expert system development is also evaluated.

Figure 4.10 shows how standard deviation, $\sigma$, changes with wear. As can be seen from the figure, this curve can be described as composed of three distinct portions: a portion with linear and very gradual increase in values, a small transition portion, and a portion where a rapid increase in values is observed. The latter corresponds to the state where drill failure is imminent. Similar characteristic trends are observed when the total RMS of the frequency spectrum (0-12.8 kHz) and bandpass RMS of the spectrum are plotted against hole number, as illustrated in Figure 4.11. Because of this distinct characteristic trend of rapid increase in values when failure is imminent, they are chosen as the primary descriptors for developing the expert system.

Figure 4.12 shows how the skewness of the distributions behaves as the number of holes drilled (hole number) increases. As shown in the figure, skew values are scattered for a major portion of the tool-life and some convergence to a small number is observed at the latter portion of the tool-life, namely, when failure is imminent.
<table>
<thead>
<tr>
<th>Bandpass #</th>
<th>Harrison M400</th>
<th>Master 2500</th>
<th>Okuma LS</th>
<th>Bridgeport</th>
<th>Stanko</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>192-928</td>
<td>128-992</td>
<td>192-544</td>
<td>1392-1856</td>
<td>800-2592</td>
</tr>
<tr>
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<td>2624-4224</td>
<td>992-3008</td>
<td>192-2592</td>
<td>1856-2432</td>
<td>3744-7776</td>
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<td>3</td>
<td>4224-5248</td>
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<td>2592-3424</td>
<td>2432-3232</td>
<td>9280-11424</td>
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<td>5248-6464</td>
<td>5024-7936</td>
<td>3424-4192</td>
<td>3232-3936</td>
<td>0-12800</td>
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<td>7936-10720</td>
<td>2592-4192</td>
<td>2432-3936</td>
<td></td>
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<td>0-12800</td>
<td>9216-10080</td>
<td>6496-7392</td>
<td></td>
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<td>10646-12160</td>
<td>0-12800</td>
<td>3936-7392</td>
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<td></td>
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<tr>
<td>9</td>
<td>0-12800</td>
<td></td>
<td></td>
<td>0-12800</td>
<td></td>
</tr>
</tbody>
</table>

* All frequencies are expressed in terms of hertz, Hz.

Table 4.1 The frequency bands selected
Figure 4.10 Standard deviation versus percentage tip-wear

Figure 4.11 Spectrum RMS versus hole number
Figure 4.12 Skew versus hole number
A similar characteristic trend is seen in kurtosis with the increase in the number of holes drilled as shown in Figure 4.13. Because of this convergence of values to a small number when failure is imminent, which is an opposite trend to previously discussed descriptors, they can be used as secondary descriptors.

Mean values of the vibration signals are approximately zero when plotted against hole number, as shown in Figure 4.14. RMS height of the distribution more or less demonstrates an inverse characteristic with the number of holes drilled, as can be seen in Figure 4.15. As both descriptors do not demonstrate a distinctive trend with the increase in the number of holes drilled or the progress of tool wear, they are judged to be unsuitable for the development of an expert system.

By dividing variance over RMS height of the distribution, a better descriptor is obtained, which is more sensitive to wear when failure is imminent, as illustrated in Figure 4.16.

Therefore, descriptors that are deemed to be suitable for an expert system development are:

1. Standard deviation, total RMS of the spectrum, bandpass RMS of the spectrum, and variance/RMS height of the distribution.
2. Skew and kurtosis.

### 4.3. Classifying the Vibration Signal

Thus far, by visual inspection of the characteristics of raw data, grouped data, and the frequency spectrum, decisions were made on the choice of the descriptors chosen.
Figure 4.13 Kurtosis versus hole number

Figure 4.14 Mean versus hole number
Figure 4.15 RMS height of the distribution versus hole number

Figure 4.16 Variance/RMS height of the distribution versus percentage tip-wear
Also by plotting these chosen descriptors against tip-wear or hole number, the descriptors which demonstrated a unique characteristic trend with wear, especially when failure was imminent, were selected for the development of the expert system, as discussed in the previous sections.

In this section, discussion will be directed towards classifying vibration signals, with the help of the selected descriptors, into defined drilling states. Basically, this is analogous to the fundamental steps involved in pattern recognition, as shown in Figure 4.17. Figure 4.18 shows the plot of a typical normal tip-wear curve. Superimposed on it is the characteristic curve of the selected primary descriptor. In the figure, normalized tip-wear is defined as the ratio of the tip-wear and the maximum tip-wear obtained just prior to the failure of the tool. Normalized hole number is defined as the number of holes drilled divided by the maximum number of holes drilled. As shown in the figure, the tip-wear curve can also be described as being composed of three distinct portions (wear states): a rapid wear in the first portion, a linear or uniform wear in the second portion, and followed by a third portion of increased wear rate until failure. Intuitively, the optimum time to replace the tool is at the end of the second portion or beginning of the third portion of the tip-wear curve which is described as the transition portion of the characteristic curve of the primary descriptor.

In this research, three drilling states are defined: normal drilling, transition drilling, and severe drilling, as shown in Figure 4.19. Normal drilling generally includes the first and second portion of a tip-wear curve, the state where no replacement of a drill is necessary.
Figure 4.17 A pattern recognition system
Figure 4.18 A typical set of normalized standard deviation and normalized tip-wear versus normalized hole number.
Figure 4.19 The three drilling states
By looking at various plots, humbly, it is possible to define the three drilling states and locate the optimum time to replace the tool without any major problem. The question posed is: how can the computer be instructed to perform the same tasks?

As mentioned above, the classification of vibration signals is analogous to the process involved in pattern recognition. Literally, there are thousand of algorithms that are available, so choices have to be made to select some that are most effective in this application. Two algorithms were selected and the discussion of each algorithm will be included in the following sections.

4.3.1. Fuzzy Clustering Algorithm

Basically, cluster analysis is an approach in the pattern recognition. It uses various similarity and distance measures as a criterion for clustering pattern samples in the feature space.

The state of drill wear is a vague concept and exhibits a certain degree of uncertainty. Conventional clustering algorithms, where a data set is assigned to exactly one wear state, are not well suited in this application. The fuzzy clustering algorithm was selected instead because of its ability to group a data set into imprecisely defined classes or states, and the degree of belongingness of the data set to a particular state is determined and represented by the grade of the membership.

Let $X=\{x_1, x_2, \ldots, x_n\}$ be a finite set with feature vector, $x_i=\{x_{i1}, x_{i2}, \ldots, x_{ic}\}$; $W_{ca}$ is the set of real $c \times n$ matrices; $c$ is an integer, $2 \leq c < n$. The fuzzy partition for $X$ is the set
\[ M_f = \{ U \subset W_c | u_{ik} \in [0,1] \ \forall i,k; \ \sum_{i=1}^{c} u_{ik} = 1 \ \forall k; \ 0 < \sum_{j=1}^{n} u_{ij} < n \ \forall i \} \]  

\( M_f \) is a fuzzy partition space associated with \( X \). \( U = \{ u_{ij} \} \) is the membership function and takes on any value between 0 and 1. \( U_{ij} = u_j(x_i) \) is called the grade of membership of \( x_i \) in fuzzy set \( u_j \). The total membership of each \( x_j \) in \( X \) is 1.

The fuzzy real-valued functional can be defined by

\[ J_m(U,V) = \sum_{k=1}^{n} \sum_{i=1}^{c} (u_{ik})^m \ (d_{ik})^2 \]  

where \( d_{ik} = \| x_k - v_i \| \).

\( U \subset M_f \) is a fuzzy partition of \( X \).

\( V = \{ v_1, v_2, ..., v_c \} \) are the cluster centers.

The fuzzy functional, \( J_m \), is a weighted, least-squares objective function: the measure of dissimilarity is \( d_{ik} \) (the distance between each data point \( x_k \) and a fuzzy prototype \( v_i \)); the square distance is weighted by \( (u_{ik})^m \), the \( m \)th power of \( x_k \)'s membership in fuzzy cluster \( u_i \).

This fuzzy clustering algorithm is more popularly known as ISODATA (iterative self-organizing data) algorithm and is derived by minimizing the functional \( J_m \), subjected to a constraint, as stated below:

\[ \text{minimize} \ J_m(U,V) \]  

\[ (U,V) \in M_f \]
The constraint equation is

\[ M_{fc} = \{ (U, V) | \sum_{j=1}^{c} u_{jq} = 1 \} \]  \hspace{1cm} 4.10

By applying a Lagrange multiplier, \( \lambda \), to the constraint, the following objective function can be formed:

\[ F(\lambda, u_{ik}, v_i) = \sum_{i=1}^{c} (u_{ik})^m \| x_k - v_i \|^2 - \lambda (\sum_{i=1}^{c} u_{ik} - 1) \]  \hspace{1cm} 4.11

Differentiating equation (4.11) with respect to \( \lambda \), \( u_{ik} \), and \( v_i \), and equating the results to zero, and with some manipulation, the equations used to determine the grade of membership and the cluster center are obtained and expressed as:

\[ U_{ik} = \frac{1}{\sum_{j=1}^{c} \left( \frac{\| x_k - v_i \|}{\| x_k - v_j \|} \right)^{\frac{2}{m-1}}} \]  \hspace{1cm} 4.12

\[ V_i = \frac{\sum_{k=1}^{n} (u_{ik})^m x_k}{\sum_{k=1}^{n} (u_{ik})^m} \]  \hspace{1cm} 4.13

Equations 4.12 and 4.13, can not be solved analytically but can be easily solved by the following iterative procedure:

1. Fix \( c \), \( 2 \leq c \leq n \); fix \( m \), \( 1 < m < \infty \); and fix control error, \( \delta \).

   Initialize \( U^{(0)} \in M_{fc} \).

2. Calculate \( \{ v_i \} \) with equation 4.13.

3. Update \( \{ U^{(k)} \} \) with equation 4.12.
4. Calculate, $\Delta = \|U^{(L+1)} - U^{(L)}\|$. If $\Delta < \delta$ stop, otherwise return to step 2.

The fuzzy clustering algorithm is an infinite family of interactive procedures (one
for each m, $1 \leq m < \infty$). In general, the larger the m, the 'fuzzier' is the membership
assignment. In this research, m equal to 2 seems to be adequate for this application.
Until now, a theoretical basis for an optimal choice for m has not yet emerged. The
initial matrix, $U^{(0)}$, defined in the procedure, cannot be selected arbitrarily. It has been
determined that as long as no two rows of the matrix contain the same elements, this
algorithm will perform satisfactorily. In this research, a built-in random number function
(RND) defined in Quickbasic, is used to initialize the matrix, $U^{(0)}$. This function will
generate random numbers in the range between 0 and 1, which is ideal in this application.

There are two aspects to this fuzzy clustering algorithm that must be addressed
before it can be used to classify vibration signals, namely, training and classification.

4.3.1. Training

Training or learning involves the determination of cluster centers from a
training set or labelled samples using the iterative procedure described above. A program
called 'Cluster' was developed to perform this specific task and the program listing is
included in Appendix A.

4.3.1.2. Classification

Classification involves the assignment of grades of membership to the
features selected. In other words, it determines the degree of belongingness of the feature
vector to a drilling wear state. With the cluster centers determined by the program
'Cluster', the current observation or feature vector can be classified using equation 4.14.
\[ U_{ik} = \frac{1}{\sum_{j=1}^{c} \left( \frac{\|x_k - v_{kj}\|^2}{m-1} \right)} \]

where \( x_k \) is the current observation and \( U_{ik} \) is the fuzzy grade of the current observation being assigned to the \( k^{th} \) wear state.

### 4.3.2. Fuzzy Relation Algorithm

Conceptually, this is a very simple algorithm. Its aim is to establish the fuzzy relationship (membership) functions between the selected descriptors and the three drilling states from some training samples and use them to classify the unknown vibration signals. In this research, the relationship function selected is the normal distribution and a detailed derivation of these distribution curves will be discussed in the training phase of this algorithm. The program listing of this algorithm, called ‘Relation’, is included in Appendix A.

Suppose there are \( N \) number of vibration signals in a training set, \( X = \{X_1, X_2, ..., X_N\} \), each vibration signal is described by \( M \) descriptors (features), \( \{X_{i1}, X_{i2}, ..., X_{iM}\} \), and there are \( P \) number of drilling states, \( \{W_1, W_2, ..., W_P\} \). Before this algorithm can be used to perform the classification task, it has to be trained. The following sections will discuss those two aspects of this algorithm, namely, training and classification.

#### 4.3.2.1. Training

Training is sometimes also referred to as learning. In this project, the training samples are obtained from previous drilling operations. The steps that are needed in the training are described as follows:
1. Find the maximum and minimum value of each descriptor.

\[ \text{Xmax}(j) = \text{Max}\{X_{ij}, X_{2j}, \ldots, X_{Nj}\} \]

\[ \text{Xmin}(j) = \text{Min}\{X_{ij}, X_{2j}, \ldots, X_{Nj}\}, \quad j=1,2,\ldots,M \]

2. Divide the interval between Xmax and Xmin into L sub-intervals or classes. The mid-points of each class are represented by \( \{x(i), i=1,2,\ldots,L\} \).

3. Group the vibration signals (training samples), \( \{X_1, X_2, \ldots, X_N\} \), into P drilling states. Let \( \{n(i), i=1,2,\ldots,P\} \) be the total number of vibration signals in the \( i^{th} \) state.

4. Calculate the mean and standard deviation for each drilling state and each descriptor.

These means and standard deviations can be easily and efficiently calculated provided the grouping process similar to the one described in the time domain analysis section is followed. In this case, the grouping process would involve tallying the number of occurrences for each descriptor in each class for each drilling state, given by \( \{R(i,j,k), i=1,2,\ldots,P \quad j=1,2,\ldots,M \quad k=1,2,\ldots,L\} \). Thus, the means and standard deviations can be calculated using the following equations.
\[ \mu_{(i,j)} = \frac{\sum_{k=1}^{L} x(k) \cdot R(i,j,k)}{\sum_{k=1}^{L} R(i,j,k)} \]  

\[ \sigma_{(i,j)}^2 = \frac{\sum_{k=1}^{L} (x(k) - \mu_{(i,j)})^2 \cdot R(i,j,k)}{\sum_{k=1}^{L} R(i,j,k)} \]

Where \( \mu_{(i,j)} \) = mean

\( \sigma_{(i,j)}^2 \) = variance

If the number of vibration signals in any of the drilling states, \{n(i), i=1,2,...,P\}, is small (less than 30) then the above grouping process is not necessary as the saving in computational time would be minimal. Instead the following equations can be used to calculate the means and standard deviations.

\[ \mu_{(i,j)} = \frac{\sum_{k=1}^{n(j)} X(k,j)}{n(i)} \]  

\[ \sigma_{(i,j)}^2 = \frac{\sum_{k=1}^{n(j)} (X(k,j) - \mu_{(i,j)})^2}{n(i) - 1} \]
5. Find the PxM number of discrete normal distributions (membership functions) given by \{F(i,j), i=1,2,...,P, j=1,2,...,M\}

The normal distribution is defined by

\[
F(i,j) = \frac{1}{\sqrt{2\pi} \sigma(i,j)} e^{-\frac{(x-\mu(i,j))^2}{2\sigma^2(i,j)}}
\]  

4.17

Where \(\mu(i,j)\) = mean
\n\(\sigma(i,j)^2\) = variance

**4.3.2.2. Classification**

Once the membership functions have been established through training, using equation 4.14, the classification of an unknown vibration signal can be achieved using the following steps:

1. Calculate the PxM number of grades of membership.

2. For each drilling state, sum up the grade of membership of all the descriptors using the following equation.

\[
S(i) = \sum_{j=1}^{M} F(i,j)
\]  

4.18

3. The maximum of the summed grades of membership will determine the drilling state for which that unknown vibration signal belongs to, i.e.,

\[i^* = \text{Max}\{ S(i) \} \quad i=1,2,...,P\]

\[i^* = \text{the drilling state corresponds to that unknown input vibration signal.}\]
4.4. The Selection of Features

As discussed before, there are quite a few potential descriptors that can be used for developing an expert system, such as standard deviation, total and bandpass RMS of the frequency spectrum, etc. However, another important decision also has to be made, namely, out of these selected descriptors, are there any descriptors that are similar or redundant. If it is so, then one must determine how to filter them out of the selections.

For instance, as shown in Table 4.2, data set B is separated from data set A by a constant amount of 20 (additive translation), data set C is twice those of data set A (proportional translation), and data set D is the mirror-image of data set A (mirror-image translation). The plot of these four data profiles is shown in Figure 4.20. From the figure, it can be easily seen that data profiles A, B, and C are similar based on their shape, i.e., ignoring the additive and proportional translations, and are dissimilar if the size displacements have to be taken into consideration. Data profile D is unique and dissimilar to the rest of the data profiles. Therefore, similarity is based either on the shape or the size displacement of the data profiles.

<table>
<thead>
<tr>
<th>Data set</th>
<th></th>
<th>Y-values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># 1</td>
<td># 2</td>
</tr>
<tr>
<td>A</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>C</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>D</td>
<td>-5</td>
<td>-10</td>
</tr>
</tbody>
</table>

Table 4.2 Values of the four data sets
Figure 4.20 Profile of the four data sets
Out of the many similarity as well as dissimilarity coefficients available, a similarity coefficient known as the correlation coefficient was chosen to perform the task of filtering the redundant features. This coefficient measures similarity based on the shapes of the data profiles (curves) rather than the size displacements between the curves.

4.4.1. Correlation Coefficient

Suppose there are two data sets given by \( X_j = \{x_{j1}, x_{j2}, ..., x_{jn} \} \) and \( X_k = \{x_{k1}, x_{k2}, ..., x_{kn} \} \), the correlation coefficient, \( r_{jk} \), more commonly known as the Pearson product-moment correlation coefficient, can be defined by:

\[
r_{jk} = \frac{\sum_{i=1}^{n} x_{ij}x_{ik} - (1/n)(\sum_{i=1}^{n} x_{ij})(\sum_{i=1}^{n} x_{ik})}{\sqrt{[\sum_{i=1}^{n} x_{ij}^2 - (1/n)(\sum_{i=1}^{n} x_{ij})^2][\sum_{i=1}^{n} x_{ik}^2 - (1/n)(\sum_{i=1}^{n} x_{ik})^2]}}
\]

This coefficient takes on values ranging between -1 and 1, with 1 indicating maximum similarity. If the size displacements between the data sets are not important, then this coefficient is considered to be the most commonly used. Using the data presented in Table 4.2, the correlation coefficients between data set A with B, C, and D, are respectively, 1, 1, and -1.

4.4.2. Filtering the Redundant Features

Preliminary analysis demonstrated that there are at least four primary and two secondary descriptors that are potentially suitable for the development of an expert system in this research, as indicated in Table 4.3. Intuitively, because all the primary and secondary descriptors follow their own unique trend characteristics with wear, one descriptor selected from each group should be sufficient for the development of an expert
system and the rest of the descriptors can be regarded as redundant. A more extensive
evolution into this aspect of logic will be included in the next chapter.

<table>
<thead>
<tr>
<th>Primary descriptor</th>
<th>Secondary descriptor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard deviation</td>
<td>Skew</td>
</tr>
<tr>
<td>Variance/RMS height</td>
<td>Kurtosis</td>
</tr>
<tr>
<td>Total RMS of the spectrum</td>
<td></td>
</tr>
<tr>
<td>Bandpass RMS of the spectrum</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 Selected primary and secondary descriptors

To illustrate the process of eliminating any redundant descriptors, a typical set of
vibration signals was used and the corresponding resemblance matrix was calculated, as
shown in Table 4.4. From the table, if the value is greater than 0.8, then the two
descriptors are considered to be highly similar. If it is greater than 0.6 and less than 0.8,
then they are considered to be mildly similar. Any values other than the two ranges will
be considered as dissimilar. As an illustration, row 2 of the table, indicates that standard
deviation is dissimilar to skew, kurtosis, and RMS height of the distribution (negative
values) but it is similar to the total and bandpass RMS of the frequency spectrum, and
the variance/RMS height of the distribution. Therefore, only one descriptor out of the
three similar descriptors is needed.

4.5. Smoothing

As shown in Figure 4.21, the plot of standard deviation against tip-wear, in
addition to the obvious trend of a small standard deviation which occurs for a major
<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00</td>
<td>-0.91</td>
<td>0.35</td>
<td>0.50</td>
<td>0.72</td>
<td>-0.93</td>
<td>-0.93</td>
<td>-0.81</td>
</tr>
<tr>
<td>2</td>
<td>1.00</td>
<td>-0.17</td>
<td>-0.44</td>
<td>-0.69</td>
<td>0.96</td>
<td>0.98</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>0.60</td>
<td>0.02</td>
<td>-0.18</td>
<td>-0.17</td>
<td>-0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
<td>-0.04</td>
<td>-0.45</td>
<td>-0.44</td>
<td>-0.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.00</td>
<td>-0.72</td>
<td>-0.76</td>
<td>-0.56</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.00</td>
<td>0.99</td>
<td>0.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.00</td>
<td>0.94</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>8</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 - Mean  
2 - Standard deviation  
3 - Skew  
4 - Kurtosis  
5 - RMS height of the distribution  
6 - Bandpass RMS of the frequency spectrum [2592 - 4192 Hz]  
7 - Total RMS of the frequency spectrum  
8 - Variance/RMS height of the distribution  

Table 4.4 The resemblance matrix of a typical drill.
Figure 4.21 A typical plot of standard deviation versus percentage tip-wear
portion of drill-life followed by a rapid increase in value when failure is imminent, there is a small fluctuation in the descriptor values superimposed on this trend. This phenomenon can be consistently seen when other chosen descriptors are plotted against the tip-wear. There are many explanations for it but the most effective of all is given by Braun[5]. He has postulated that the cutting lips of the drill bit are never symmetrical; hence, at any instant of time, there is always one lip doing more cutting or carrying more load than the other. As a result, that lip starts to wear more and at some point in time, the other lip, now sharper, will start to do more cutting. This cyclic reversal of cutting by one lip at a time will continue until both lips are severely worn and ultimately tool failure will occur. The small fluctuation in the descriptor values is due to these cyclic reversals of cutting by one lip at a time. Since, in this research, the goal is to investigate the overall performance of the system, which will be discussed in the next chapter, smoothing of the descriptor values may be necessary. A more detailed discussion of how to use the smoothed descriptor values and the effects on the performance of the system will be included in the discussion of results.

4.5.1. Smoothing Model

Smoothing, generally, involves the assignment of weights to the present as well as to the past values. The smoothing technique used in this research is called exponential smoothing. It assigns more weights to the present and less weight to the values further in the past. In fact, these weights decrease geometrically with age. Suppose a data set is given by observations, \( \{x_1, x_2, \ldots, x_n\} \), the smoothed observation of \( x_n \), \( S_n(x) \), can then be defined by equation 4.20.
\[ S_\alpha(x) = \alpha x_n + (1-\alpha)[\alpha x_{n-1} + \alpha(i-\alpha)x_{n-2} + \ldots] \]

\[ S_\alpha(x) = \alpha x_n + (1-\alpha)S_{\alpha-1}(x) \]

where \( \alpha \) is known as an exponential constant.

### 4.5.2. Selection of the Exponential Constant

A proper selection of the exponential constant is important. Too large an exponential constant, i.e., most of the weights are assigned to a few recent observations, will not result in a smooth curve. On the other hand, if the exponential constant is too small, many past observations will be considered and will result in a curve which is dissimilar to the original curve. Therefore, a compromise is needed between the smoothness and the similarity of the smoothed curve with the original.

In order to measure the similarity of the smoothed curve with the original, the Bray-Curtis coefficient, \( b_{BC} \), is used. This coefficient varies from 0 to 1, with 1 indicating maximum similarity. This coefficient is sensitive to the size displacement of the observations unlike the correlation coefficient. For example, using the data presented in Table 4.2, the values of this coefficient between data set A and B, C, and D, are respectively, 0.635, 0.667, and 0.

Suppose there are two data sets given by \( X_S = \{x_{11}, x_{12}, \ldots, x_{1n}\} \) and \( X_T = \{x_{11}, x_{22}, \ldots, x_{rn}\} \). the Bray-Curtis coefficient can be defined by:
\[ b_k = 1 - \frac{\sum_{i=1}^{n} |X_q - X_k|}{\sum_{i=1}^{n} (X_q - X_k)} \]  
4.21

In this research, the favourable range of the exponential constant used is between 0.15 to 0.3. As shown in Figure 4.22, this range of exponential constant allows the maximum level of smoothness with high level of similarity being maintained, between the smoothed and the original curve, ( \( b_k > 0.7 \)). Figure 4.23 illustrates how smoothed standard deviation curves differ from the original at four different exponential constants. Obviously, when the exponential constant is equal to 0.1, the curve obtained is the smoothest and deviates most from the original. At \( \alpha=0.5 \), the curve obtained resembles the original and the fluctuation of values is still quite distinct.

4.6. Reinforcement Learning

Machine learning is the key to machine intelligence, just like human learning is to human intelligence. Learning has been the subject of debate, and also a controversial research for many people in many disciplines. In this study, it can be roughly defined as a computer system, whose performance is gradually improved at a given task over time, without any reprogramming. A simple learning scheme known as reinforcement learning is used in this research.

Essentially, this learning scheme is the same as the exponential smoothing discussed before. Instead of obtaining a smoothed value based on the weighted previous values as in exponential smoothing, in reinforcement learning, a better predicted value is
Figure 4.22 Plot of Bray-Curtis coefficient versus exponential constant
Figure 4.23 Comparison between smoothed standard deviation with the original
obtained. This predicted value will converge (reach optimum) as training is allowed to proceed. This reinforcement learning scheme can be represented as follow:

\[ P(k+1) = rP(k) + (1-r)P(k-1) \]  \hspace{1cm} 4.22

where \( P(k) \) indicates the performance measure at instant \( k \) and \( r \) is the learning rate.

To illustrate how this scheme of learning works, a simple system governed by four system equations is selected as shown in Table 4.5. The quantity used to evaluate the performance of the system is given by \( Qe \). The objective of the study is to find out the optimum \( Qe \) under a certain set of operating conditions. This whole process is analogous to saying what is the predicted tool-life under a certain set of operating conditions. There are no equations that can adequately describe the complexity involved in the drilling process; therefore, the simulation of a drilling operation is not possible, unlike the given example. In other words, the performance of the drilling process can only be evaluated experimentally. Figure 4.24 shows the top level flow chart used to simulate the system. The system will continue to train or learn unsupervised until convergence in \( Qe \) is obtained. As indicated in Figure 4.25, as the number of training cycles or trials increases, the system gradually improves the predicted performance of the system, \( Qe \), and eventually converges to a value of 138.

A proper selection of the learning rate, like in exponential smoothing, is very important. As indicated in Figure 4.26, for the chosen system, the optimum learning rate
<table>
<thead>
<tr>
<th>System equations</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Te = - \frac{Qe}{18.7579} + Ta )</td>
<td>(1)</td>
</tr>
<tr>
<td>( Tc = \frac{-b \pm SQR(b^2 - 4<em>a</em>c))}{2*a} )</td>
<td>(2)</td>
</tr>
<tr>
<td>where ( a = 0.0013<em>Te - 0.00008</em>Te^2 - 0.0025 )</td>
<td></td>
</tr>
<tr>
<td>( b = 0.0082<em>Te^2 - 0.203</em>Te + 3.41 )</td>
<td></td>
</tr>
<tr>
<td>( c = 239.5 + 10.073<em>Te - 0.109</em>Te^2 - Qe )</td>
<td></td>
</tr>
<tr>
<td>( P = -2.634 - 0.3081<em>Te - 0.00301</em>Te^2 + 1.066*Tc )</td>
<td>(3)</td>
</tr>
<tr>
<td>( - 0.00528<em>Tc^2 - 0.0011</em>Te<em>Tc - 0.00031</em>Te^2*Tc )</td>
<td></td>
</tr>
<tr>
<td>( + 0.000567<em>Te</em>Tc^2 + 0.0000031<em>Te^2</em>Tc^2 )</td>
<td></td>
</tr>
<tr>
<td>( Qe = 17.99 \times (Tc - Tb) - P )</td>
<td>(4)</td>
</tr>
</tbody>
</table>

Table 4.5 System equations
Figure 4.24 Top level flow-chart used to simulate the system
Figure 4.25 Performance versus number of trials

Operating conditions
Ta=15  Tb=30
Figure 4.26 The learning curve of the system
is approximately equal to 0.17. At the two extremes, namely \( r < 0.025 \) and \( r > 0.3 \), there is an exponential increase in the number of trials required to obtain the optimum \( Q_e \).

Generally, a learning rate of between 0.1 and 0.3 is recommended.

4.7. Tool-Replacement Schema

In order to replace the cutting tool at the right time, it is necessary that the condition of the cutting tool be known at all times. In other words, continuous monitoring and assessing the condition of the cutting tool is essential. In the next two sections, the discussion will be focus on how to use the two algorithms described in chapter 4, to access the cutting tool’s condition and also to make a decision on replacing the cutting tool at the right time.

Two drills, \# B1 and \# B2, were selected in this study and their test data are included in Table 4.6. Both drills were tested under an identical set of operating conditions, on the same workpiece material, and with the same machine-tool, even though the total number of holes drilled for each was different.

As mentioned before, even though the two algorithms are derived differently they follow a common procedure and function in quite a similar manner to each other. For instance, a training stage is needed before any classification can be performed. In the classification stage, a value or grade of membership is assigned to each of the three drilling states defined. The severity of the drill bit condition is determined by the relative magnitude of these grades of membership.
<table>
<thead>
<tr>
<th>Test data of Driller # B1</th>
<th>Test data of Driller # B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 23.12 0.011</td>
<td>1 29.84 0.029</td>
</tr>
<tr>
<td>2 25.44 0.010</td>
<td>2 58.20 0.086</td>
</tr>
<tr>
<td>3 23.37 0.017</td>
<td>3 60.32 0.126</td>
</tr>
<tr>
<td>4 25.28 0.012</td>
<td>4 145.23 0.197</td>
</tr>
<tr>
<td>5 25.56 0.017</td>
<td>5 144.92 0.211</td>
</tr>
<tr>
<td>6 26.42 0.017</td>
<td>6 150.18 0.234</td>
</tr>
<tr>
<td>7 25.73 0.015</td>
<td>7 169.79 0.277</td>
</tr>
<tr>
<td>8 25.30 0.015</td>
<td>8 154.32 0.288</td>
</tr>
<tr>
<td>9 23.71 0.012</td>
<td>9 188.55 0.296</td>
</tr>
<tr>
<td>10 25.08 0.013</td>
<td>10 226.41 0.323</td>
</tr>
<tr>
<td>12 25.61 0.020</td>
<td>11 202.02 0.313</td>
</tr>
<tr>
<td>14 25.40 0.017</td>
<td>12 248.01 0.374</td>
</tr>
<tr>
<td>16 29.74 0.024</td>
<td>13 288.79 0.474</td>
</tr>
<tr>
<td>18 38.39 0.024</td>
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</tr>
<tr>
<td>20 60.02 0.087</td>
<td></td>
</tr>
<tr>
<td>22 76.39 0.111</td>
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</tr>
<tr>
<td>24 32.51 0.057</td>
<td></td>
</tr>
<tr>
<td>26 80.13 0.082</td>
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</tr>
<tr>
<td>28 84.50 0.165</td>
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<td>30 92.77 0.174</td>
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<td>32 121.81 0.181</td>
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<td>34 122.23 0.256</td>
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<td>35 134.93 0.163</td>
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</tr>
<tr>
<td>36 158.36 0.288</td>
<td></td>
</tr>
<tr>
<td>37 138.96 0.289</td>
<td></td>
</tr>
<tr>
<td>38 152.24 0.251</td>
<td></td>
</tr>
<tr>
<td>39 190.03 0.317</td>
<td></td>
</tr>
<tr>
<td>40 148.67 0.269</td>
<td></td>
</tr>
<tr>
<td>41 144.04 0.313</td>
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</tr>
<tr>
<td>42 214.51 0.393</td>
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</tr>
<tr>
<td>43 187.87 0.342</td>
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</tr>
<tr>
<td>44 174.35 0.291</td>
<td></td>
</tr>
<tr>
<td>46 201.63 0.366</td>
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</tr>
<tr>
<td>48 211.23 0.383</td>
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</tr>
<tr>
<td>50 214.10 0.369</td>
<td></td>
</tr>
<tr>
<td>52 257.71 0.451</td>
<td></td>
</tr>
<tr>
<td>54 268.26 0.482</td>
<td></td>
</tr>
<tr>
<td>56 274.01 0.413</td>
<td></td>
</tr>
</tbody>
</table>

* (Hole#, standard deviation, Bandpass RMS)

Table 4.6 Test data of drills # B1 and # B2
4.7.1. Fuzzy Clustering Algorithm

This algorithm, in the training stage, minimizes the distance between the observations and the cluster centers by successively applying equations 4.12 and 4.13. Table 4.7 shows this optimization search for the cluster centers using drill # B2. In this research, the criterion for stopping the search is when the difference between the two most recent total sums of error (last column of Table 4.7) is less than 0.01. This total sum of error is also called the control error. In fact, from Figure 4.27, the plot of grade of ‘severe’ against the control error indicates that a control error of less than 0.1 is sufficient. The resulting cluster centers for the two drills are included in Table 4.8. Even though the two drills have a significantly different number of holes drilled, their cluster centers are quite similar. Therefore, it indicates that the cluster centers obtained for one drill can be used to classify vibration signals from other drills performed under similar cutting conditions.

Using the cluster centers obtained after training the test data from drill # B1, the grade of membership (degree of belongingness) curves for the three drilling states, namely, normal, transition, and severe, for drill # B2, can be seen in Figure 4.28 and the corresponding fuzzy partition is included in Table 4.9.

In this algorithm, the grade of the membership varies from 0 to 1, with 1 as the maximum degree of belongingness. As shown in Figure 4.28, the grades of membership for normal drilling are high and close to 1 when the drill is sharp. However, the grades of membership for transition and severe increase at latter portions of the drill life, signifying that the drill is worn and drill failure is imminent. Therefore, the tool-
### Table 4.7 Iterative search for the cluster centers

<table>
<thead>
<tr>
<th>Iteration #</th>
<th>Standard deviation</th>
<th>Bandpass RMS</th>
<th>Control error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>65.34 130.95 163.18</td>
<td>0.263 0.206 0.258</td>
<td>13.1742</td>
</tr>
<tr>
<td>2</td>
<td>182.10 106.16 175.19</td>
<td>0.287 0.161 0.278</td>
<td>4.9707</td>
</tr>
<tr>
<td>3</td>
<td>201.04 65.80 176.91</td>
<td>0.311 0.106 0.281</td>
<td>5.8976</td>
</tr>
<tr>
<td>4</td>
<td>220.40 52.48 165.82</td>
<td>0.337 0.086 0.264</td>
<td>3.7056</td>
</tr>
<tr>
<td>5</td>
<td>235.96 50.40 158.63</td>
<td>0.359 0.082 0.252</td>
<td>1.4571</td>
</tr>
<tr>
<td>6</td>
<td>243.29 50.03 157.80</td>
<td>0.371 0.081 0.249</td>
<td>0.5184</td>
</tr>
<tr>
<td>7</td>
<td>246.69 49.98 158.42</td>
<td>0.377 0.081 0.250</td>
<td>0.2661</td>
</tr>
<tr>
<td>8</td>
<td>248.42 49.98 158.99</td>
<td>0.381 0.081 0.251</td>
<td>0.1530</td>
</tr>
<tr>
<td>9</td>
<td>249.35 49.97 159.35</td>
<td>0.382 0.081 0.252</td>
<td>0.0864</td>
</tr>
<tr>
<td>10</td>
<td>249.86 49.97 159.56</td>
<td>0.383 0.081 0.252</td>
<td>0.0482</td>
</tr>
<tr>
<td>11</td>
<td>250.13 49.97 159.67</td>
<td>0.384 0.081 0.252</td>
<td>0.0267</td>
</tr>
<tr>
<td>12</td>
<td>250.28 49.97 159.74</td>
<td>0.384 0.081 0.252</td>
<td>0.0147</td>
</tr>
<tr>
<td>13</td>
<td>250.37 49.97 159.77</td>
<td>0.384 0.081 0.252</td>
<td>0.0081</td>
</tr>
</tbody>
</table>

### Table 4.8 Cluster centers of drills # B1 and # B2

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>Clus. centers</th>
<th>Normal</th>
<th>Transition</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drill # B1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>34.02</td>
<td>126.28</td>
<td>223.38</td>
<td></td>
</tr>
<tr>
<td>Bandpass RMS</td>
<td>0.037</td>
<td>0.219</td>
<td>0.390</td>
<td></td>
</tr>
<tr>
<td>Drill # B2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>49.97</td>
<td>159.77</td>
<td>250.37</td>
<td></td>
</tr>
<tr>
<td>Bandpass RMS</td>
<td>0.021</td>
<td>0.252</td>
<td>0.384</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.27 Plot of grade of 'severe' versus control error
<table>
<thead>
<tr>
<th>Hole #</th>
<th>Grades of membership</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
</tr>
<tr>
<td>1</td>
<td>0.998</td>
</tr>
<tr>
<td>2</td>
<td>0.871</td>
</tr>
<tr>
<td>3</td>
<td>0.844</td>
</tr>
<tr>
<td>4</td>
<td>0.027</td>
</tr>
<tr>
<td>5</td>
<td>0.026</td>
</tr>
<tr>
<td>6</td>
<td>0.037</td>
</tr>
<tr>
<td>7</td>
<td>0.058</td>
</tr>
<tr>
<td>8</td>
<td>0.045</td>
</tr>
<tr>
<td>9</td>
<td>0.037</td>
</tr>
<tr>
<td>10</td>
<td>0.000</td>
</tr>
<tr>
<td>11</td>
<td>0.015</td>
</tr>
<tr>
<td>12</td>
<td>0.013</td>
</tr>
<tr>
<td>13</td>
<td>0.054</td>
</tr>
</tbody>
</table>

Table 4.9 Fuzzy partitions of drill # B2
Figure 4.28 Grades of membership versus hole number
replacement decision can be made when the fuzzy grade of ‘normal’ is less than 0.5 or when the grade of ‘transition’ is at a maximum. More conservatively, the cutting tool can be replaced as soon as the ‘transition’ drilling state is encountered, i.e., when the grade of ‘transition’ is the largest among the three.

4.7.2. Fuzzy Relation Algorithm

In this algorithm, the membership function selected is a normal density function. Therefore, in the training stage, the mean and standard deviation for each drilling state and each feature (descriptors) have to be determined. Table 4.10 shows the mean and standard deviation determined for the two drills chosen.

Using the mean and standard deviation, which were determined from the test data of drill # B1, the summed grades of membership were determined from equation 4.17 for drill # B2. These results are included in Table 4.11, and the corresponding plot of these summed grades of membership is shown in Figure 4.29. As illustrated in this figure, at the beginning, when the drill is sharp, the grade of ‘normal’ is greater than grades of ‘transition’ and ‘severe’. Both these grades increase to a maximum and decrease to zero in the portion when drill failure is imminent. Therefore, using this algorithm, the tool-replacement decision can be made when the grade of ‘transition’ is maximum among the three grades or when the ‘transition’ drilling state is encountered.

4.8. Tool-Life Prediction Curve

Tool-life is defined as the time frame in which the tool is producing an acceptable part. In this study, it is defined as the total number of holes drilled before tool failure occurs. In actual practise, it should be defined as the total number of holes drilled just
<table>
<thead>
<tr>
<th>Feature</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Transition</td>
</tr>
<tr>
<td><strong>Drill # B1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>55.07</td>
<td>152.46</td>
</tr>
<tr>
<td>Bandpass RMS</td>
<td>0.079</td>
<td>0.270</td>
</tr>
<tr>
<td><strong>Drill # B2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>49.46</td>
<td>158.83</td>
</tr>
<tr>
<td>Bandpass RMS</td>
<td>0.080</td>
<td>0.250</td>
</tr>
</tbody>
</table>

Table 4.10 Mean and standard deviation of drills # B1 and # B2
<table>
<thead>
<tr>
<th>Hole #</th>
<th>Summed grades of membership</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Transition</td>
<td>Severe</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4.317</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5.403</td>
<td>0.017</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4.414</td>
<td>0.184</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.493</td>
<td>2.936</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.073</td>
<td>4.107</td>
<td>0.058</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.593</td>
<td>6.006</td>
<td>0.180</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.148</td>
<td>7.521</td>
<td>1.033</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.098</td>
<td>7.169</td>
<td>1.486</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.070</td>
<td>6.691</td>
<td>1.912</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.022</td>
<td>4.558</td>
<td>3.664</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.035</td>
<td>5.453</td>
<td>2.926</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.002</td>
<td>1.070</td>
<td>6.817</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.000</td>
<td>0.004</td>
<td>2.245</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.11 Summed grades of membership of drill # B2
Figure 4.29 Summed grades of membership versus hole number
prior to the occurrence of the ‘transition’ drilling state. In addition to the basic Taylor’s equation, a more general extended Taylor’s equation is selected and it is defined by equations 4.23.

\[ L = a_0 \cdot V^{a_1} \cdot F^{a_2} \cdot d_c^{a_3} \] \[ 4.23 \]

In this study, the depth of cut is fixed at three times the diameter of the drill bit, hence, equation 4.23 can be modified and expressed in terms of the drill size as in equation 4.24.

\[ L = a_0 \cdot V^{a_1} \cdot F^{a_2} \cdot D^{a_3} \] \[ 4.24 \]

where \( a_0, a_1, a_2, a_3 \) are constants

- \( V \) is the cutting speed, [rpm]
- \( L \) is the tool-life
- \( D \) = drill size, [mm]
- \( d_c \) = depth of cut, [mm]
- \( F \) = feed rate, [mm/rev]

By taking natural logarithms on both sides of the above equations (variable transformation), the equations can be linearized. Using a linear least-square curve fitting technique, the coefficients of the equations can be determined. In this study, the two tool-life equations used are the basic Taylor’s equation defined by equation 2.3 and its extended version defined by equation 4.24. The linearization process discussed is
included in Appendix C and the listing of the computer program called ‘Toollife’, which is used to determine the coefficients of the tool-life equations, is included in Appendix A.

**4.9. Summary**

A brief summary of this chapter can be stated as follows:

1. The vibration signals obtained from the drilling operations were analyzed in two domains, namely, the time and frequency domains. Appropriate methods of analysis in the two domains were derived, respectively, through visual inspection of the time-amplitude vibration signals and the frequency spectra obtained.

2. Six statistical descriptors were selected in the time domain analysis, namely: mean, standard deviation, skew, kurtosis, RMS height of the distribution, and variance/RMS height of the distribution.

3. In the frequency domain analysis, two descriptors were selected, namely, total and bandpass RMS of the frequency spectrum.

4. The potential descriptors that could be used to develop an expert system were: standard deviation, variance/RMS height of the distribution, total and bandpass RMS of the frequency spectrum as the primary descriptors with skew and kurtosis as the secondary descriptors.

5. The vibration signals were categorized into three groups or drilling states, namely: normal, transition and severe drilling.
6. Two algorithms were selected to classify the vibration signals into the three drilling states; namely, the fuzzy clustering algorithm and the fuzzy relation algorithm.

7. Two similarity measures were selected in this study, namely: the correlation coefficient and the Bray-Curtis coefficient.

8. A smoothing technique called exponential smoothing was presented.

9. The learning schema called reinforcement learning was introduced.

10. An illustrative example of the two fuzzy algorithms was also included in section 4.7.
CHAPTER V

EXPERT SYSTEM

An expert system for condition monitoring of drill bits has been developed on the basis of the obtained experimental results and knowledge available from publications, metal cutting handbooks, etc. In this chapter, the general structure of the proposed expert system and its operations are discussed. However, an evaluation of the performance of the system or testing will be deferred until the next chapter.

The schematic diagram of the expert system is shown in Figure 5.1 and it is made up of the following five components:

1. Design,
2. Rulebase and Database,
3. Monitoring,
4. Pattern and Diagnosis, and
5. Update and Learning.

5.1. Design

This is the component which interacts with the user and the rulebase and database (knowledge base) of the system. It is the only component that carries out a dialogue with the user and is also known as the input and output module. The major function of this
Figure 5.1 Basic structure of the proposed expert system
module is to supply the user with the most favourable set of operating conditions for a particular combination of tool and workpiece. A more detailed procedure, employed to achieve the goal of this module, can be described by the following steps:

1. First, the system asks the user to supply drill bit information, such as drill size, type, etc. The system will then match the supplied drill bit information with that which exists in the database, and will provide complete dimensions of the drill bit if requested by the user. Those dimensions will include overall length, flute length, helix angle, included angle, etc.

2. Secondly, the system will request the user to supply the workpiece information, namely, the type of material used.

3. Knowing the type of drill bit and workpiece material used, the system will recommend a set of operating conditions using the information (rules) contained in the rulebase. These rules are obtained from various machining handbooks.

4. Finally, the system will ask the user to enter the actual operating speed and feed rate that is to be used. With these inputs, the system again will consult its database, the one which contains all the drill performances, and will provide the user with the predicted tool-life, if the operation is allowed to take place. The predicted tool-life is obtained from among a number of tool-life prediction curves provided by various publications. These curves were developed, modelled, and stored as part of the knowledge in the knowledge base of the system. They are improved by learning. If no
performance information is available for the drill, the system will let the user know and supply recommendations, if any.

Table 5.1 illustrates the above mentioned steps involved in the design module. The right column of the table indicates the flow of information: whether it is regarded as input to or output from the system.

<table>
<thead>
<tr>
<th>Major steps involved in the Design module</th>
<th>Informational flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT &quot;DRILL SIZE [mm] :&quot;,Drillsizex$</td>
<td>Input</td>
</tr>
<tr>
<td>INPUT &quot;DRILL MATERIAL :&quot;,Toolmat$</td>
<td>Input</td>
</tr>
<tr>
<td>PRINT &quot;RECOMMENDED SPEED AND FEED RATE&quot;;</td>
<td>Output</td>
</tr>
<tr>
<td>RecomSpeed, RecomFeedrate</td>
<td></td>
</tr>
<tr>
<td>INPUT &quot;OPERATING SPEED AND FEED RATE&quot;;</td>
<td>Input</td>
</tr>
<tr>
<td>Speed, Feedrate</td>
<td></td>
</tr>
<tr>
<td>PRINT &quot;PREDICTED NUMBER OF HOLE DRILLED&quot;;</td>
<td>Output</td>
</tr>
<tr>
<td>PredictHole</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1 Major steps involved in the design module

5.2. Knowledge Base

The rulebase and database constitute the knowledge base of the proposed expert system. They supply all the intelligent advice, solutions or recommendations to the user in order to achieve an optimum machining operation.

Generally, there are three types of information found in this module. These are static, dynamic, and temporary. Static information consists of the drill bit information,
workpiece information, and the operating condition. Information of this type is permanent and cumulative as the drilling operation progresses. Dynamic information is the knowledge used to access tool conditions so that tool replacement can be performed at the right time. Temporary information includes data from the HP35660A FFT analyzer and from the Prowler digital oscilloscope. This is being replaced as fast as a new set of data is acquired in the monitoring module.

5.2.1. Rulebase

The rulebase consists of rules (knowledge) acquired from handbooks, publications, research works, experienced operators, technicians, etc. Normally, this knowledge stays unchanged with time. In this system, the rules will provide:

1. optimum operating conditions, and
2. information regarding the tool conditions.

A sample of the rules in the two rulebases mentioned previously are presented in Table 5.2. For simplicity, the two rulebases are called ‘RecomVF’ and ‘Toolcondition’.

5.2.2. Database

There are five major databases in this system which contain information about drill dimensions, workpiece materials, learned parameters, drill performances, and descriptors’ values (results) obtained during the operation. The latter two databases will be most valuable if any post-analysis is required; for instance, to improve the parameters used through learning. The first two databases are very valuable to the design module of the system. With time and learning, the database which contains the learned parameters will
<table>
<thead>
<tr>
<th>Contents</th>
<th>Rulebase</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF Toolmat$=&quot;STEEL&quot; THEN</td>
<td>RECOMVF</td>
</tr>
<tr>
<td>IF Carbon-content &lt; 0.25 THEN</td>
<td></td>
</tr>
<tr>
<td>SFM=24</td>
<td></td>
</tr>
<tr>
<td>ELSEIF Carbon-content &lt; 0.5 THEN</td>
<td></td>
</tr>
<tr>
<td>SFM=20</td>
<td></td>
</tr>
<tr>
<td>ELSE Carbon-content &lt; 0.9 THEN</td>
<td></td>
</tr>
<tr>
<td>SFM=17</td>
<td></td>
</tr>
<tr>
<td>END IF</td>
<td></td>
</tr>
<tr>
<td>RecomFeedrate=0.057+0.011*VAL(Drillsize$)</td>
<td></td>
</tr>
<tr>
<td>END IF</td>
<td></td>
</tr>
<tr>
<td>RecomSpeed = 318.31 * SFM / VAL(Drillsize$)</td>
<td></td>
</tr>
<tr>
<td>IF State$=&quot;Transition&quot; THEN</td>
<td>TOOLCONDITION</td>
</tr>
<tr>
<td>PRINT &quot;Change the tool&quot;</td>
<td></td>
</tr>
<tr>
<td>END IF</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.2 The two rulebases in the knowledge base
be the most valuable part of this proposed system, enabling the system to be more capable and reliable. A more detailed discussion of this database will be included in the later section on ‘Update and Learning’. Table 5.3 provides an illustration of a part of each of the other four databases mentioned. The four databases are called ‘Tool’, ‘Workpiece’, ‘Performance’, and ‘Results’, signifying the functions or contents of each databases. A more detailed listing of the databases have been provided in Appendix B.

5.3. Monitoring

This module performs the very important task of continuously capturing the vibration signal from the machining process. The machine tool vibration signal is picked up by an accelerometer and it is correspondingly transformed and digitized by the HP35660A FFT analyzer and the Prowler digital oscilloscope. The resulting signals, namely, the frequency spectrum and the time-amplitude signals, are sent to the pattern and diagnosis component of the system where the condition of the tool will be assessed. Figure 5.2 shows the block diagram of the function of this module.

5.4. Pattern and Diagnosis

This is the module that implements the previous experimental findings discussed in chapter 4, namely, which descriptors are to be used for monitoring the tool’s condition, and how to use them. In general, it involves processes of feature extraction, classification, and decision making, as shown in Figure 5.3.
<table>
<thead>
<tr>
<th>Contents</th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.20,70,41</td>
<td></td>
</tr>
<tr>
<td>3.25,70,41</td>
<td></td>
</tr>
<tr>
<td>6.30,102,70</td>
<td>TOOL</td>
</tr>
<tr>
<td>6.40,105,73</td>
<td></td>
</tr>
<tr>
<td>{drill size, overall length, flute length}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WORKPIECE</td>
</tr>
<tr>
<td>Steel, Plaincarbon, 0.50, 175-225</td>
<td></td>
</tr>
<tr>
<td>Steel, Plaincarbon, 0.90, 175-225</td>
<td></td>
</tr>
<tr>
<td>Steel, Alloysteel, 0.12-0.25, 175-175</td>
<td></td>
</tr>
<tr>
<td>Steel, Alloysteel, 0.30-0.65, 175-225</td>
<td></td>
</tr>
<tr>
<td>{material drilled, workpiece, carbon content, brinell hardness}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PERFORMANCE</td>
</tr>
<tr>
<td>53.6, 40, 1100, 0.0052, 35, Okuma, 4340, Osborne, HSS</td>
<td></td>
</tr>
<tr>
<td>54.6, 40, 1100, 0.0052, 20, Okuma, 4340, Osborne, HSS</td>
<td></td>
</tr>
<tr>
<td>{Drill#, size, speed, feed rate, tool-life, machine-tool, workpiece,</td>
<td></td>
</tr>
<tr>
<td>tool manufacturer, tool material}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RESULTS</td>
</tr>
<tr>
<td>1,-44.13, 24.32, -0.49, 1.25, 2576, 32, 0.2295, 0.026, 0.041, 0.024,</td>
<td></td>
</tr>
<tr>
<td>0.010, 0.011, 0.012, 0.016, 0.015, 0.013, 0.020</td>
<td></td>
</tr>
<tr>
<td>2,-44.46, 24.54, -0.48, 1.48, 1988, 0.08, 0.3030, 0.029, 0.044, 0.037,</td>
<td></td>
</tr>
<tr>
<td>0.012, 0.016, 0.021, 0.026, 0.024, 0.022, 0.026</td>
<td></td>
</tr>
<tr>
<td>{Hole#, mean, std, skew, kur., RMS height, Var./RMS., bandpass RMS,</td>
<td></td>
</tr>
<tr>
<td>Total RMS of freq. spectrum}</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.3 The four databases in the knowledge base
Figure 5.2 Block diagram of the monitoring module
Figure 5.3 Block diagram of the pattern and diagnosis module
5.4.1. Feature Extraction

The process of determining which descriptors are to be used is called feature extraction. However, at the present time, there is no standard procedure in existence which allows selection of the best feature to be used. Commonly, features are extracted by an experienced practitioner in the field. In this system, the features or descriptors are chosen because of their unique trends as tool wear increases. For instance, when failure is imminent, standard deviation of the time-amplitude signal increases sharply, whereas skew and kurtosis tend to a small value. As stated before, the primary descriptors selected are: standard deviation, variance/RMS height of the distribution, total and bandpass RMS of the frequency spectrum; and skew and kurtosis are selected as the secondary descriptors.

5.4.2. Classification

Classification involves the assignment of the signal (time-amplitude vibration signal and frequency spectrum), via those selected descriptors, into class or cluster (drill wear states or drilling states). Due to the complexity of the drill wear states and the cutting process, more efficient and robust clustering algorithms are needed. Two algorithms from the family of fuzzy clustering algorithms were selected to perform this classification task. Even though, the two algorithms are derived differently, they both classify the unknown vibration signal and assess the tool condition in a very similar manner.

After every cut, each selected descriptor is assigned three values by the algorithms, which indicate the belongingness of the descriptors to each of the three drilling states defined, the so called grades of the membership. The dominant of these three values
determines the tool condition. A more detailed explanation of the algorithms was included in Chapter 4 and the programs that implemented the two algorithms can be found in Appendix A.

**5.4.3. Decision Making**

The rules used for decision making are derived either through pre-analysis of sample-runs (data obtained when drill is sharp until failure occurs), or post-analysis of the data stored in the databases obtained during machining.

Pre-analysis of a sample-run is a very important phase of this system. Without it the system will not function. The analysis enables the system to study the dynamics (frequency response) of the machine-tool, tool and workpiece system so that various bandpasses of the frequency spectrum that are promising can be selected. It also calculates the initial cluster centers, means and standard deviations which are needed for the clustering algorithms. In addition to studying the potential problems that may exist such as signal drop-out, tool breakage, pre-analysis also assists in distinguishing the situations (signals) when the machine is on and off without doing any cutting. Figure 5.4 shows a typical vibration signal picked-up, which includes various situations in sequential order: when the machine is off, when the machine is on, a cutting sequence by a 3.18 mm diameter drill bit, disengagement of feed, and when the machine is off again. As can be seen from the figure, each situation has its own distinct vibration level. Through pre-analysis of a sample-run, the amplitude levels corresponding to these various situations can be established and stored in the knowledge base.
Figure 5.4 A typical time-amplitude vibration signal
Out of the many potential problems and situations that may exist, as described above, the only task that is being considered in the proposed expert system is to replace the tool at the right time. The fundamental tool replacement decision is to change the tool when the drilling state is transition. From the algorithms, the drilling state is transition when the grade of ‘transition’ is the largest of the three grades.

5.5. Update and Learning

This system possesses the ability to learn and update the knowledge base, hence this will improve the reliability of the system performance with time.

After every tool change, all the machine settings, drill bit and workpiece information, operating conditions, tool-life, and the descriptors’ values, are correspondingly stored or updated in the databases called ‘Performance’ and ‘Results’.

Learning will be performed in two areas after every tool change; namely, in the two fuzzy algorithms, and the tool-life modelling. Table 5.4 presents the parameters that will be learned. The learning scheme adopted is the reinforcement scheme described in Chapter 4.

<table>
<thead>
<tr>
<th>Source of learning</th>
<th>Learned parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuzzy Clustering Algorithm</td>
<td>Cluster centers</td>
</tr>
<tr>
<td>Fuzzy relation algorithm</td>
<td>Means and standard deviations</td>
</tr>
<tr>
<td>Tool-Life Modelling</td>
<td>Coefficients of the tool-life equations</td>
</tr>
</tbody>
</table>

Table 5.4 Learned parameters of the system
To illustrate the process of learning involved; the results of five 3.2 mm diameter drill bits performed on the Okuma LS machine-tool were selected; two drilling states were defined; namely, normal and unnormal drilling. The standard deviation of the time-amplitude vibration signal was selected as the descriptor. Table 5.5 shows the cluster centers, means, standard deviations, and coefficients of tool-life equation (equation 2.3) obtained prior to and after learning the five samples mentioned. The last row of the Table gives the learned and improved parameters.

Through this type of learning, the performances of the tool-life prediction curve and the clustering algorithms will gradually be improved.

5.6. System Overview

This system is implemented using Quickbasic because it offers more flexibility in communicating with the various items of equipment used and also because of the amount of numerical computation involved. The so called AI languages, such as Prolog and Lisp, presently seem to have some problems with these specific requirements.

The proposed system is still very much restricted in its applications mainly because of the extensive amount of research still needed to cover other types of materials, larger operating ranges, etc. At this point in the development process, the machining databases used, such as ‘Tool’, ‘Workpiece’, and ‘RecomVF’, can only cope with the needs of this research. Hence, they are very limited in their scope. However, they can be easily expanded or upgraded if needed without affecting the functionality of the system. The author strongly feels that, irrespective of the type of material used, as long as the operating
<table>
<thead>
<tr>
<th>Cluster centers</th>
<th>Fuzzy clustering algorithm</th>
<th>Fuzzy relation algorithm</th>
<th>Coefficients of Basic Taylor's tool-life eqn.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>normal</td>
<td>unnormal</td>
<td>normal</td>
</tr>
<tr>
<td>Parameters prior to learning</td>
<td>44.33</td>
<td>174.18</td>
<td>33.95</td>
</tr>
<tr>
<td>Parameters of the five drills obtained through training</td>
<td>40.42</td>
<td>181.57</td>
<td>26.33</td>
</tr>
<tr>
<td></td>
<td>43.88</td>
<td>219.86</td>
<td>43.22</td>
</tr>
<tr>
<td></td>
<td>36.46</td>
<td>194.73</td>
<td>33.19</td>
</tr>
<tr>
<td></td>
<td>49.44</td>
<td>226.01</td>
<td>44.91</td>
</tr>
<tr>
<td></td>
<td>33.73</td>
<td>128.31</td>
<td>33.79</td>
</tr>
<tr>
<td>Parameters after learning</td>
<td>40.74</td>
<td>179.56</td>
<td>36.50</td>
</tr>
</tbody>
</table>

Table 5.5 The learned parameters
condition is not abusive, this system can be used. It is also not capable of monitoring the tool condition in real time yet, mainly because of the equipment involved in the data acquisition process. The HP35660A FFT analyzer and the Prowler digital oscilloscope are not well suited for on-line, in-process monitoring of tool condition. They possess too many features; most of which are not needed in this type of application. Most important of all, the computing power of the IBM PC used is inadequate in handling the large computation requirements demanded.

Many stand-alone programs were developed to satisfy the needs of this research because of the limited RAM memory available on the computer, and the functions needed to be performed in the various modules. These include capturing data from the HP35660A FFT analyzer and the Prowler digital oscilloscope, performing the data analysis, modelling the tool-life equations, and so on. Table 5.6 lists all the programs developed in this study. To overcome the mentioned drawbacks, the system was tested in three stages as illustrated in Table 5.7. Stage 1 involved the capturing of data from the HP35660A FFT analyzer and the Prowler digital oscilloscope. Stage 2 included the calculations of all the descriptors chosen in both the time and the frequency domains. Stage 3 involved the assessment of the condition of the tool; based on some of the selected descriptors.
<table>
<thead>
<tr>
<th>Program</th>
<th>Functions</th>
<th>Appendix</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANALYSIS</td>
<td>Performs the data analysis in the time and frequency domains.</td>
<td>A.5</td>
</tr>
<tr>
<td>CLUSTER</td>
<td>Implements the fuzzy clustering algorithm.</td>
<td>A.1</td>
</tr>
<tr>
<td>EXPERT</td>
<td>An expert system to monitor the tool condition.</td>
<td>A.8</td>
</tr>
<tr>
<td>HP35660A</td>
<td>Captures the frequency spectrum from the HP35660A FFT analyzer.</td>
<td>A.4</td>
</tr>
<tr>
<td>PLOTTING</td>
<td>General plotting program. Output is directed to the monitor or the HP7475A plotter.</td>
<td>A.6</td>
</tr>
<tr>
<td>PROWLER</td>
<td>Captures the digitized time-amplitude vibration signal from the Prowler digital oscilloscope.</td>
<td>A.3</td>
</tr>
<tr>
<td>RELATION</td>
<td>Implements the fuzzy relation algorithm.</td>
<td></td>
</tr>
<tr>
<td>TOOLLIFE</td>
<td>Models the tool-life prediction curves.</td>
<td>A.7</td>
</tr>
</tbody>
</table>

Table 5.6 The programs and their functions

<table>
<thead>
<tr>
<th>Stage #</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Use HP35660A and PROWLER to capture, respectively, the frequency spectrum and the time-amplitude of the vibration signal.</td>
</tr>
<tr>
<td>2</td>
<td>Use ANALYSIS to calculate the chosen descriptors.</td>
</tr>
<tr>
<td>3</td>
<td>Use CLUSTER and RELATION to assess the condition of the tool.</td>
</tr>
</tbody>
</table>

Table 5.7 The three stages involved in the testing of the system
CHAPTER VI

DISCUSSION OF RESULTS

This chapter will begin with a discussion of the observations made regarding the drilling operations performed on the selected machine tools, described in Chapter 4, in terms of the tool wear observed and the tool-life obtained. In addition, the effectiveness of the vibration-based system used to monitor the tool condition in metal cutting will be assessed. Following that, a closer examination of the vibration signals and frequency spectra obtained will be made. Finally, an evaluation on the performance of the expert system will also be presented.

6.1. Tool Wear and Tool-life

6.1.1. Tool Wear

As discussed before, there are seven dominant types of wear which may occur at the cutting edges of the drill bit. In this research, the wear at the tip of the cutting edges was selected as the performance index of the cutting process. The so called tip-wear is defined as the amount of wear along the cutting edges. In particular, the shape of the tip-wear curve obtained is affected by the two common types of wear observed in the experiments. These are chipping at the cutting edges and gradual wear along the cutting edges. The latter type of wear brings about the rounding of the cutting edges and
generally produces the familiar wear curve composed of the three portions described earlier. This is the so called normal wear curve illustrated in Figure 6.1. Chipping wear occurred in a relatively fewer cases than the gradual wear along the cutting edges. It produces a wear curve of a logarithmic type. That is, rapid wear is generated during initial use of a new drill. The wear then levels off until failure, as also shown in Figure 6.1. In this research, out of the 52 tip-wear curves available, 60 percent were of the normal type.

As mentioned in Chapter 2, there are a variety of tool-life criteria which have been used by many researchers. In this research, two drill-life criteria were used. The life of the drill was determined by the complete destruction of the cutting edges or the snapping of the drill. In this study, the majority of the 6.35 mm drill bits failed because of the high heat generated during the cutting which softened the cutting edges and eventually brought about the melting and/or fracturing at the cutting edges. On the other hand, the majority of the 3.18 mm and 2.38 mm drill bits snapped when they were too worn to drill.

Drill-life is significantly scattered even when nominally identical tools, workpieces, and operating conditions are used. Table 6.1 indicates the lowest and highest number of holes drilled for two of the drill sizes investigated. Each group in the table consists of three or more drill bits subjected to the specified cutting conditions. From the table, the maximum deviation in the holes drilled (scatterness) for the 6.35 mm and 3.18 mm drill sizes, are 189 and 99 holes, respectively. The coefficient of variation ranges from 0.24 to as high as 0.76.
Figure 6.1 Plot of the two types of wear curve observed
<table>
<thead>
<tr>
<th>Group #</th>
<th>Lowest number of hole drilled</th>
<th>Highest number of hole drilled</th>
<th>Average number of holes drilled</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>61</td>
<td>250</td>
<td>117</td>
<td>0.76</td>
</tr>
<tr>
<td>2</td>
<td>38</td>
<td>173</td>
<td>100</td>
<td>0.69</td>
</tr>
<tr>
<td>3</td>
<td>77</td>
<td>158</td>
<td>110</td>
<td>0.39</td>
</tr>
<tr>
<td>4</td>
<td>36</td>
<td>166</td>
<td>79</td>
<td>0.66</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>35</td>
<td>25</td>
<td>0.24</td>
</tr>
</tbody>
</table>

**DRILL SIZE : 6.35 mm**

<table>
<thead>
<tr>
<th>Group #</th>
<th>Lowest number of hole drilled</th>
<th>Highest number of hole drilled</th>
<th>Average number of holes drilled</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>55</td>
<td>34</td>
<td>0.56</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>115</td>
<td>76</td>
<td>0.53</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>58</td>
<td>28</td>
<td>0.55</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>35</td>
<td>24</td>
<td>0.44</td>
</tr>
</tbody>
</table>

**DRILL SIZE : 3.18 mm**

Table 6.1 The lowest and highest number of holes drilled
6.1.2. Tool-Life Prediction Curve

The development of a new tool-life equation was not one of the main objectives of this research; therefore, in some cases, the drilling data available were not adequate for the generation of a meaningful tool-life equation. For instance, on the machine-tool, Master 2500, only one drill size and one set of operational conditions was used. Out of the five machine-tools used, the tool-life equations for the Harrison M400 and Okuma LS are presentable, and they are provided in Table 6.2.

<table>
<thead>
<tr>
<th>Equation #</th>
<th>( a_0 )</th>
<th>( a_1 )</th>
<th>( a_2 )</th>
<th>( a_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Harrison M400</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>0.2125</td>
<td>3279.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.24</td>
<td>27.294</td>
<td>-0.2333</td>
<td>-0.2662</td>
<td>1.2666</td>
</tr>
<tr>
<td><strong>Okuma LS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3</td>
<td>0.3392</td>
<td>4350.612</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.24</td>
<td>111.791</td>
<td>-1.3630</td>
<td>-2.6744</td>
<td>1.4123</td>
</tr>
</tbody>
</table>

Table 6.2 Coefficients of the tool-life equations

6.2. Effectiveness of the Monitoring System

The vibration-based monitoring system, described in Chapter 4, has been used to monitor the machine-tool vibration generated during the drilling operations, both on the lathes and the milling machine. Figures 6.2 and 6.3 present the plots of the normalized standard deviation versus normalized hole number, for the 3.18 mm drill size, using the lathes and the milling machine, respectively. The values on the two axes are normalized
Figure 6.2 Plot of normalized standard deviation versus normalized hole number for a 3.18 mm drill on the lathe.

Figure 6.3 Plot of normalized standard deviation versus normalized hole number for a 3.18 mm drill on the milling machine.
purely for ease of comparison. Normalized standard deviation is defined as the standard deviation divided by the maximum standard deviation which was obtained during the test set. As can be seen in the figures, both show a similar trend with normalized hole number. Therefore, the characteristic effects of the drilling operation on both the milling machine and the lathe can be concluded to be the same.

A similar set-up had also been used by Alzner and Amicarelli[1] and Persa and Mailloux[29] to monitor the tool condition in turning and boring operations, respectively. They found that this set-up also shows promising results in monitoring the tool condition in the cases studied.

6.3. Closer Examination of the Vibration Signals

As discussed in Chapter 4, appropriate methods of data analysis were derived mainly through the visual inspection of the vibration signals and the frequency spectra obtained under various cutting conditions. In other words, they were selected on the basis of the observed differences and variations between plots. In the next two sections, the aforementioned differences and variations between plots will be discussed.

6.3.1. Time-Amplitude Vibration Signal

The vibration signals generated by a drilling operation is dependent on a number of factors. These have been discussed in Chapter 2. In this research, only a few of those factors were investigated. In this section, the discussion will focus on the time-amplitude vibration signals obtained from different machine tools, with different drill sizes, and also under different tool conditions.
Figures 6.4 and 6.5 show, respectively, the vibration signals observed at various
degrees of tip-wear for 3.18 mm and 6.35 mm drills. These figures also show that the
vibration level is higher for a 6.35 mm drill than those of a 3.18 mm drill. In addition,
the nature of the signals for a 3.18 mm drill also appears to be more uniformly distributed
(denser) than those of a 6.35 mm drill. Therefore, as drill size increases, a higher level
of vibration is expected when the cutting tool is worn but not necessarily a higher RMS
value.

The rigidity of the machine-tool also affects the vibration signals generated.
Figures 6.6 and 6.7 are, respectively, the vibration signals obtained from the machine-
tools called Harrison M400 and Okuma LS when the tool is worn. The former machine-
tool is less rigid and appears to generate a more uniformly distributed (denser) vibration
signal that also exhibits a higher overall amplitude as compared to the latter. In general,
the more rigid the machine-tool, the lower the observed level of vibration signal when the
cutting tool was worn.

In all cases, regardless of the drill sizes and rigidity of the machine-tool, the
amplitude of the vibration signal increases as wear increases.

6.3.2. Frequency Spectrum

The frequency spectrum represents the dynamic characteristic of the combined
machine-tool, tool and workpiece system. Figures 6.8 (a), (b), (c), (d) and (e), represent
these characteristics of the five machine-tools selected. Each frequency spectrum is
unique, and is particularly dependent on the type of machine-tool, but largely independent
of the drill sizes, as indicated in Figures 6.9 (a) and (b).
Figure 6.4 Vibration signals at various degrees of wear for a 3.18 mm drill
Figure 6.5 Vibration signals at various degrees of wear for a 6.35 mm drill
Figure 6.6 Vibration signal from Harrison M400

Figure 6.7 Vibration signal from Okuma LS
Figure 6.8(a) Frequency response of Harrison M400 lathe

Figure 6.8(b) Frequency response of Master 2500 lathe
Figure 6.8(c) Frequency response of Okuma LS lathe

Figure 6.8(d) Frequency response of Bridgeport milling machine
Figure 6.8(e) Frequency response of Stanko lathe
Figure 6.9(a) Frequency response of Okuma LS when the drill size was 3.18 mm

Figure 6.9(b) Frequency response of Okuma LS when the drill size was 6.35 mm
6.3.3. Primary Descriptors

The four primary descriptors selected: standard deviation, variance/RMS height of the distribution, total and bandpass RMS of the frequency spectrum, have a similar trend with wear as indicated by Figure 6.10. Moreover, they can be consistently reproduced as indicated by Figure 6.11. In addition, the trend is also preserved with different machine-tools and drill sizes, as shown, respectively, in Figures 6.12, 6.13(a), and 6.13(b).

6.3.4. Secondary Descriptors

The two secondary descriptors: skew and kurtosis, were selected because they both converge to a small value when tool failure is imminent as indicated in Figures 4.12 and 4.13. However, this unique trend is not as clearly defined with some of the machine-tools as well as with some of the drill sizes investigated. This condition is shown in Figures 6.14 (a), (b), (c), (d), (e), and 6.15 (a), (b). A more extensive investigation of the influence of machine-tool and drill size on these descriptors must be undertaken before it can be incorporated in developing the system.

6.4. Performance of the Expert System

The performance of the expert system is evaluated, based upon the number of correctly identified drilling states, if given some vibration signals. In other words, it involves the testing of the two selected algorithms: fuzzy clustering algorithm and fuzzy relation algorithm.

In this study, 773 vibration signals obtained from the drilling process, performed on five different machine-tools, by twenty-four 3.18 mm drills, five 6.35 mm drills and
Figure 6.10 Plot of the four primary descriptors versus percentage tip-wear for drill # C6
Figure 6.11 Plot of standard deviation versus normalized tip-wear for four 3.18 mm drills.
Figure 6.12 Plot of standard deviation versus normalized hole number for the five machine-tools.
Figure 6.13(a) Normalized standard deviation versus normalized hole number for a 6.35 mm drill

Figure 6.13(b) Normalized standard deviation versus normalized hole number for a 2.38 mm drill
Figure 6.14(a) Skew and kurtosis from Harrison M400

Figure 6.14(b) Skew and kurtosis from Master 2500

Figure 6.14(c) Skew and kurtosis from Okuma LS
Figure 6.14(d) Skew and kurtosis from Bridgeport

Figure 6.14(e) Skew and kurtosis from Stanko

Figure 6.15(a) Skew and kurtosis versus normalized hole number for a 6.35 mm drill
Figure 6.15(b) Skew and kurtosis versus normalized hole number for a 2.38 mm drill
four 2.38 mm drills, were used. The performance of these drills is shown in Table 6.3. They are classified into seven groups, A, B, C, D, E, F, and G, which correspond to the five machine tools and the three drill sizes used.

In this study, speed and feed rates differed from the recommended values suggested by many machining handbooks as presented in Table 6.4. In fact, most of them were at the upper extreme of the recommended operating range in order to bring about a manageable or reasonable number of holes drilled. This was, typically, around 35 holes. In some cases, the speeds and feed rates used were constrained by the settings available on the machine-tools. Because of that, the transition drilling state in a number of the test samples was difficult to locate or identify. Therefore, the performance was evaluated purely on the basis of the number of correctly identified normal and unnormal (transition and severe) drilling conditions.

Before evaluating the performance of the system, all the test samples had to be classified. This process was accomplished by first plotting the selected descriptors on the computer monitor, and then by moving the line-cursor on the monitor, the various drilling states were visually located and identified. The general plotting program used to perform such tasks has been included in Appendix A.

<table>
<thead>
<tr>
<th>Drill size [mm]</th>
<th>Speed [rpm]</th>
<th>Feed rate [mm/rev]</th>
<th>Depth of cut [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.38</td>
<td>2006 - 2407</td>
<td>0.048</td>
<td>7.14 - 11.90</td>
</tr>
<tr>
<td>3.18</td>
<td>1501 - 1802</td>
<td>0.051</td>
<td>9.54 - 15.90</td>
</tr>
<tr>
<td>6.35</td>
<td>752 - 902</td>
<td>0.089</td>
<td>19.05 - 31.75</td>
</tr>
</tbody>
</table>

Table 6.4 The recommended operating conditions
<table>
<thead>
<tr>
<th>Drill #</th>
<th>Drill size [mm]</th>
<th>Speed [rpm]</th>
<th>Feed rate [mm/rev]</th>
<th>Depth of cut [mm]</th>
<th>Number of holes drilled</th>
<th>Machine-tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>3.18</td>
<td>2000</td>
<td>0.1016</td>
<td>9.54</td>
<td>11</td>
<td>HarrisonM400</td>
</tr>
<tr>
<td>A2</td>
<td>3.18</td>
<td>2000</td>
<td>0.1016</td>
<td>9.54</td>
<td>44</td>
<td>HarrisonM400</td>
</tr>
<tr>
<td>A3</td>
<td>3.18</td>
<td>2000</td>
<td>0.1016</td>
<td>9.54</td>
<td>28</td>
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</tr>
<tr>
<td>B1</td>
<td>3.18</td>
<td>1860</td>
<td>0.1016</td>
<td>9.54</td>
<td>58</td>
<td>Master2500</td>
</tr>
<tr>
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<td>3.18</td>
<td>1860</td>
<td>0.1016</td>
<td>9.54</td>
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<tr>
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<tr>
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<td>21</td>
<td>Master2500</td>
</tr>
<tr>
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<td>3.18</td>
<td>2000</td>
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<td>9.54</td>
<td>12</td>
<td>Okuma LS</td>
</tr>
<tr>
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<td>3.18</td>
<td>2000</td>
<td>0.0711</td>
<td>9.54</td>
<td>18</td>
<td>Okuma LS</td>
</tr>
<tr>
<td>C3</td>
<td>3.18</td>
<td>2000</td>
<td>0.0711</td>
<td>9.54</td>
<td>12</td>
<td>Okuma LS</td>
</tr>
<tr>
<td>C4</td>
<td>3.18</td>
<td>2000</td>
<td>0.0711</td>
<td>9.54</td>
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</tr>
<tr>
<td>C5</td>
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<td>0.0914</td>
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<tr>
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<td>2000</td>
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<td>15</td>
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<tr>
<td>D1</td>
<td>3.18</td>
<td>1750</td>
<td>0.0381</td>
<td>9.54</td>
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<td>1750</td>
<td>0.0381</td>
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Table 6.3 The performance of the drilling process
6.4.1. Selection of the Similar Descriptors

The intent of this section is to answer the question: If the selected descriptors are similar, is it necessary to include all of them? Table 6.5 shows the resemblance matrix obtained using the correlation coefficient for drill # C6. As shown in the table, all the six descriptors are similar. This is indicated by the high values of the correlation coefficient.

Using the fuzzy clustering algorithm and drill # C6 as the training sample, the system classifies the drilling states for each of the drilling sequences of drills # C2 and # C4. The results of this investigation are summarized in Table 6.6.

Table 6.6 indicates that the system has about the same percentage of success in classifying the vibration signals irrespective of the descriptors or the combination selected. Therefore, only one (any one) out of the group of similar descriptors is needed to develop the system.

6.4.2. Smoothed Versus Unsmoothed Descriptor

As mentioned in Chapter 4, smoothing has the effect of minimizing the sudden fluctuation in the descriptor value from its characteristic trend. The question that must be addressed is whether smoothing is needed in this study. Three drills, # C2, # C4, and # C6, as before, were used in this evaluation. Table 6.7 shows the results of the evaluation, using the two algorithms described.

By comparing the corresponding entries in column 4 and column 6 of the above table, i.e., the percentage of success before and after smoothing, it is clear that the results using the fuzzy clustering algorithm are slightly improved with smoothing. On the other
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1 - Standard deviation  
2 - Bandpass RMS of the frequency spectrum [3424 - 4192 Hz]  
3 - Bandpass RMS of the frequency spectrum [2592 - 4192 Hz]  
4 - Bandpass RMS of the frequency spectrum [4192 - 7968 Hz]  
5 - Total RMS of the frequency spectrum  
6 - Variance/RMS height of the distribution

Table 6.5 The resemblance matrix of Drill # C6
<table>
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<th>Descriptors</th>
<th>Number of test samples</th>
<th>Number of misclassifications</th>
<th>% success</th>
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Table 6.6 Selection of similar descriptors
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<th>Smoothed</th>
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</table>

**FUZZY CLUSTERING ALGORITHM**

| C2  | 64 | 1  | 98 | 3  | 95 |
| C4  | 51 | 4  | 92 | 2  | 96 |
| C6  | 47 | 2  | 96 | 4  | 91 |

**FUZZY RELATION ALGORITHM**

Table 6.7 Effect of smoothed versus unsmoothed descriptor
hand, the results of the fuzzy relation algorithm were slightly degraded. Overall, since the results do not improve or degrade drastically, smoothing does not appear to be necessary. However, it is recommended if large fluctuations in the descriptor values are noticed.

6.4.3. Performance of the System

Using the findings of the last section, standard deviation was selected to be the descriptor used to evaluate the performance of the system, i.e., to test the two fuzzy algorithms.

6.4.3.1. Fuzzy Clustering Algorithm

As indicated in the previous sections, the vibration signals obtained in this type of operation are dependent on the type of machine-tool and the drill size used. Therefore, the performance of the system was evaluated individually on those seven groups indicated in Table 6.3. Within these groups, all the vibration signals were obtained from drills of the same size and the drilling operation was performed on the same machine-tool, which ensure a more meaningful study of the system performance. The testing procedure can be described as follows:

1. Select all the vibration signals corresponding to a particular drill in a group and use them as the training sample.

2. Evaluate the clustering centres for each of the drilling states of the training sample (training).

3. Use the rest of the vibration signals in the group as the test samples and determine the total number of misclassifications.
4. Repeat steps 1 to 3, for all the drills in the group.

For example, using group A, the drilling data from the Harrison M400, the outlined procedure can be summarized by the following three steps:

1. Select drill # A1 as the training sample, calculate the cluster centers, and then used drills # A2 and # A3 as the test samples.

2. Select drill # A2 as the training sample, calculate the cluster centers, and then classify the vibration signals of drills # A1 and # A3.

3. Select drill # A3 as the training sample and drills # A1 and # A2 as the test samples.

The results of this analysis are summarized in Table 6.8. As shown in the table, this algorithm is capable of determining the drilling state of the vibration signal indicated by the high values of percentage of success (column 4). In fact, the averaged percentage of success of this algorithm is greater than 83. The last two columns of the table are the cluster centres for the two drilling states, which are defined as normal and unnormal drilling.

6.4.3.2. Fuzzy Relation Algorithm

Using the same procedure described above, instead of calculating the cluster centres in the training process, the mean and standard deviation of each of the drilling states was calculated. The results of the study reveal that this algorithm also has a high percentage of success in classifying the vibration signals. These are shown in Table 6.9.
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Table 6.8 The performance of fuzzy clustering algorithm
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<td>80</td>
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</tr>
</tbody>
</table>

Table 6.9 The performance of fuzzy relation algorithm
In fact, the performance of this algorithm is comparable, and in some cases, even better than the fuzzy clustering algorithm with an averaged percentage of success of greater than 90.

6.5. Summary

The findings of this chapter can be summarized as follows:

1. The majority of the wear curves obtained were of the so called ‘normal wear curve’ type which are composed of three portions: rapid wear in the beginning, gradual or linear wear in the middle, and a very rapid wear in the final portion when tool failure is imminent.

2. In this study, the majority of the 3.18 mm and 2.38 mm drills failed by snapping whereas the 6.35 mm drills failed because of fractures at the cutting lips.

3. A significant degree of tool-life scatter was also experienced in this study. The coefficient of variation was found to range from a low of 0.24 to a high of 0.76.

4. The vibration-based monitoring system used in this study was effective and could be used for monitoring the tool condition in drilling, as well as other metal cutting operations such as turning and boring.

5. The time-amplitude vibration signal generated during drilling operations was dependent on a number of factors. The level of vibration signal increased with an increase in the drill size, an increase in the degree of tool wear, and a decrease in the rigidity of the machine-tool.
6. The frequency spectrum obtained was dependent on the machine tool and largely independent of the drill size.

7. The primary descriptors exhibited a characteristic trend composed of small values for a major portion of tool-life, followed by drastic increases in values when tool failure was imminent. This characteristic trend was consistently reproduced and also independent of the machine-tool and the drill sizes.

8. More extensive investigations of the influence of a machine-tool and drill size on the two secondary descriptors are needed before they can be incorporated in the system.

9. Since the primary descriptors selected were similar, only one (any one) was needed to develop the system. In this study, the standard deviation was the descriptor chosen.

10. Smoothing was found to be unnecessary in this study because the fluctuations in the values of the standard deviation were not significant enough to warrant the extra computational effort.

11. The two fuzzy algorithms used to classify the vibration signals: fuzzy clustering and fuzzy relation, were very effective in this application, with percentages of success greater than 83 and 90, respectively.
CHAPTER VII

CONCLUSIONS

The following conclusions were reached in this study:

1. The vibration-based monitoring system employed in this research was capable of monitoring the condition of the drill bit regardless of the types of machine-tools and the drill sizes used.

2. On the basis of initial experimental results, four primary descriptors and two secondary descriptors were selected to develop the expert system. The four primary descriptors were the standard deviation, variance/RMS height of the distribution, and total and bandpass RMS of the frequency spectrum. The two secondary descriptors were skew and kurtosis. They were selected because of their unique characteristic trend when tool failure is approached.

3. It was found that, because of their functional similarity, only one of the primary descriptors was needed to produce satisfactory performance of the expert system. Standard deviation was chosen to be the one used.
4. The two selected secondary descriptors showed some inconsistency in the trend with wear when different machine tools as well as drill sizes used. Therefore, they were not used in the development of the expert system.

5. Two fuzzy algorithms, known as fuzzy clustering and fuzzy relation, were selected to classify the vibration signals. The signals were classified as either normal or abnormal because of the difficulty encountered in judging transition drilling. The performance of the algorithms was evaluated on the basis of the number of correctly classified signals. Both algorithms were equally capable of performing the essential classification task with percentages of success greater than 83 and 90, respectively.

6. An expert system was developed which consisted of the five modules: design, monitoring, pattern and diagnosis, knowledge base, and update and learning. Experimental testing indicated that the system is capable of effectively assessing the tool condition.

7. The developed expert system provides a very satisfactory performance. Although at this stage it is not perfect, its effectiveness must be evaluated on the basis of its industrial applications. The greatest potential for its use exists with large production volume automated machining systems, such as, for example, transfer lines. The value of production can be as high as $30,000 per hour. The average down-time on these machines is approximately 25% of operating time, and is
predominantly caused by unexpected component failures. Even a partial reduction of the down-time results in significant cost reductions and improvements in productivity. Also, because of the very hostile operating environment on such machines, the monitoring system must be fully automated and capable of independent decisions.

8. The objectives of this research have been satisfied, namely, a very capable and reliable vibration-based monitoring system was developed, promising descriptors were obtained, and an intelligent tool condition monitoring system was developed.

9. The system developed can be easily extended to accommodate other metal cutting operations such as turning and boring operations.
CHAPTER VIII

RECOMMENDATIONS

The expert system developed is capable of monitoring the condition of drills. However, there are areas that can be improved. Hence, the recommendations for future researchers and those who are interested in using this system can be stated as follows:

1. In this study, the operating conditions used were at the upper extreme of those recommended. In particular, the desired number of holes drilled was around 35 whereas in actual practice a drill could last in excess of a thousand holes. The system should be tested at actual practical conditions in order to evaluate its effectiveness.

2. Because of the equipment involved, this system is not yet capable of handling, processing, and assessing the tool condition on a real-time basis. A computer with fast processing capability, larger memory, and which is equipped with an analog and digital converter is highly recommended.

3. Thus far, the system possesses a limited amount of knowledge in some of its databases and rulebases such as 'Workpiece' and 'Tool'. These should be expanded to accommodate a wider range of machinability data. Additional investigations into other types and sizes of drill bits, and types of workpiece material is also recommended.
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BIBLIOGRAPHY


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APPENDIX A

COMPUTER PROGRAMS
COMPUTER PROGRAMS

Eight major programs were developed in this study. Each handles a unique portion of the tasks involved in this research. All programs are implemented using Quickbasic version 4.5 and they run on an IBM PC. A brief functional description of each program is included in Table A.1.

The first two programs, 'Cluster' and 'Relation', handle the classification task of the system. In other words, they calculate the grades of membership of each drilling state and determine the tool condition using these grades.

'Prowler' and 'HP35660A' capture, respectively, the time-amplitude and the frequency spectrum of the vibration signal.

'Analysis' is the program used to calculate all the chosen descriptors in both domains as discussed in Chapter 4. The inputs to the program are the time-amplitude vibration signals in binary format from the Prowler digital oscilloscope and the frequency spectrum from the HP35660A FFT analyzer. The outputs from the program are the descriptors, which in turn are the inputs to 'Cluster' and 'Relation'.

'Plotting' is a general plotting routine developed to handle a variety of input data with different formats and the output of the program can be directed to the computer monitor for viewing and/or to the HP7475 plotter for hardcopy of the plot. Two main options are available: zoom and display, if the output is to the computer monitor. With the plot on the monitor, zooming a section of the plot is accomplished through the
keyboard control and the movement of the line cursor on the plot is controlled by the arrow keys. The value of the line cursor position is displayed below the plot on the monitor as well. This program also provides the feature of overlaying plots on the monitor.

‘Toollife’ is the program used to determine the coefficients of the tool-life equations using the least-square technique.

‘Expert’ is the program that implements the expert system described in Chapter 5. Because of the limited RAM memory available in the computer, it is necessary that the scope of some of the modules be reduced. For instance, instead of capturing the time-amplitude vibration signal and the frequency spectrum in the monitoring module and calculating the chosen descriptors prior to the classification of the vibration signal, this program assumes that all these tasks were already carried out and the results are stored on a diskette. In other words, the program ‘Expert’ implements only the design module, part of the pattern/diagnosis, and the update/learning module.

In order to run these program successfully, the following accessories are needed:

1. IBM PC or compatible with Hercules or CGA or EGA graphic support.
2. Quickbasic V4.5.
5. HP35660A FFT analyzer.
6. HP7475 plotter.
7. Epson LX-80 printer.
<table>
<thead>
<tr>
<th>Program</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.1. CLUSTER</td>
<td>Implements the fuzzy clustering algorithm.</td>
</tr>
<tr>
<td>A.2. RELATION</td>
<td>Implements the fuzzy relation algorithm.</td>
</tr>
<tr>
<td>A.3. PROWLER</td>
<td>Captures the time-amplitude vibration signal from the Prowler digital oscilloscope.</td>
</tr>
<tr>
<td>A.4. HP35660A</td>
<td>Captures the frequency spectrum of the vibration signal from the HP35660A FFT analyzer.</td>
</tr>
<tr>
<td>A.5. ANALYSIS</td>
<td>Performs data analysis in the time and frequency domains.</td>
</tr>
<tr>
<td>A.6. PLOTTING</td>
<td>A general plotting program which enables output onto the computer monitor or to the HP7475 plotter.</td>
</tr>
<tr>
<td>A.7. TOOLLIFE</td>
<td>Determines the coefficients of the two tool-life equations.</td>
</tr>
<tr>
<td>A.8. EXPERT</td>
<td>An expert system to monitor the tool condition in drilling.</td>
</tr>
</tbody>
</table>

Table A.1 A brief functional description of the programs
Following are the listings of the eight programs mentioned previously.

A.1. CLUSTER

```
restart: CLS: e = .01 'control error
INPUT "Number of states ": c
1 - input cluster centers, 2 - determine cluster centers
cencode$ = "2": fileext$ = "."
' == input the training data & the header file
INPUT "Drill number [Dxx] ": drill$: drillS = UCASES(drill$)
drill = VAL(RIGHTS(drill$, 2)): INPUT "drive (Header) ": headdrS
IF cencode$ = "2" THEN INPUT "drive (training) ": traindrS
IF LEFTS(drillS, 1)="P" THEN trainnam$="GROUPD.HDR": GOTO proceed
IF LEFTS(drillS, 1)="C" THEN trainnam$="GROUPC.HDR": GOTO proceed
IF drill <= 30 THEN trainnam$ = "GROUPA.HDR"
IF drill <= 51 AND drill > 44 THEN trainnam$ = "GROUPB.HDR"
IF drill <= 63 AND drill > 52 THEN trainnam$ = "GROUPC.HDR"
proceed: CLS
' == Display the header file & select descriptors for training
OPEN headdr$ + trainnam$ FOR INPUT AS #1
INPUT #1, nr, nc
REDIM xxS(nr)
FOR i=1 TO nr: INPUT #1, xxS(i): PRINT "Col# ":i," ": xxS(i): NEXT i
CLOSE #1
LOCATE 22, 5: PRINT "Select features:
   ic = 1: select$ = "0"
lhk1: LOCATE 23, 10: PRINT SPACE(50)
   LOCATE 23, 5: PRINT "Feature ": ic : INPUT select$
   IF select$ = "999" THEN GOTO lhk2
   LOCATE 22, (ic * 5 + 20): PRINT select$
   sel(ic) = VAL(select$): ic = ic + 1: GOTO lhk1
lhk2: m = ic - 1
IF cencode$ = "1" THEN
PRINT TAB(10): "input the cluster centers in ascending order"
REDIM v(c, m)
FOR i = 1 TO m: LOCATE , 10: PRINT ": Feature ": m
FOR j = 1 TO c: PRINT TAB(10): "State ": j : INPUT v(j, i): NEXT j
NEXT i
GOTO class
END IF
' == Input the training sample
OPEN traindr$ + drillS + "HRES" + fileext$ FOR INPUT AS #1
INPUT #1, n, nc
REDIM ou(c, n), u(c, n), v(c, m), x(n, m + 1), tempxx(n, n)
FOR i = 1 TO n: FOR j = 1 TO nc: INPUT #1, tempxx(i, j): NEXT j
FOR k=1 TO m: x(i, k)=tempxx(sel(k)): NEXT i: x(i, m+1)=tempxx(1): NEXT i
CLOSE #1
' == initialize the membership grades
```
Use the random number generator RND to initialize the initial grades of the membership

FOR j = 1 TO c:FOR i = 1 TO n: ou(j, i) = RND: NEXT i: NEXT j
L = 0 ' iteration counter
lop1:
  L = L + 1
  ' calculate cluster center v(i,j)
  FOR ii = 1 TO m ' features
    FOR j = 1 TO c ' clusters
      top = 0: bot = 0
      FOR i = 1 TO n
        top = top + ou(j, i) * ou(j, i) * x(i, ii)
        bot = bot + ou(j, i) * ou(j, i)
      NEXT i
      IF bot = 0 THEN
        v(j, ii) = 1
      ELSE
        v(j, ii) = top / bot
      END IF
  NEXT j
  NEXT ii

  ' calculate new membership u(i,j)
  FOR i = 1 TO n
    FOR j = 1 TO c
      sumtop = 0
      FOR ii = 1 TO m
        sumtop = sumtop + (x(i, ii) - v(j, ii))^2
      NEXT ii
      sumtop = SQR(sumtop)
      FOR k = 1 TO c
        sambot = 0
        FOR ii = 1 TO m
          sambot = sambot + (x(i, ii) - v(k, ii))^2
        NEXT ii
        sambot = SQR(sambot)
        IF sumtop = 0 AND sambot = 0 THEN
          ss = 1
        ELSEIF sambot = 0 THEN
          bot = 0: GOTO lop3
        ELSE
          ss = sumtop / sambot
        END IF
        bot = bot + (ss) ^ -1
    NEXT j
    NEXT i

  ' calculate the error
  sumerr = 0
  FOR i = 1 TO c
    FOR j = 1 TO n: sumerr = sumerr + ABS(ou(i, j) - v(j, i)): NEXT i
  NEXT i
  FOR i = 1 TO m
    PRINT "loop ": L: :LOCATE, 12
    FOR j = 1 TO c: PRINT USING "#": v(j, i): NEXT j
PRINT USING "#####"; sumerr
NEXT i
IF sumerr < c THEN
FOR i = 1 TO n
PRINT "Hole #"; x(i, m + 1); : LOCATE , 15
FOR j = 1 TO c: PRINT USING "#####"; u(j, i); : NEXT j: PRINT: NEXT i
GOTO classify
END classify
ELSE
FOR i=1 TO c: FOR j = 1 TO n: ou(i, j) = u(i, j): NEXT j: NEXT i: GOTO lop1
END IF
cls : LOCATE 5, 10: PRINT "Cluster centers are :"
FOR i = 1 TO m
LOCATE , 10: PRINT "feature "; i; " ";
FOR j = 1 TO c: PRINT USING "#####"; v(j, i); : NEXT j: PRINT NEXT i
PRINT : FOR j = 1 TO c: PRINT "i"; j; " ": INPUT s(j): NEXT j
FOR i = 1 TO m
FOR j = 1 TO c: temp(j) = v(j, i): NEXT j
FOR j = 1 TO c: v(j, i) = temp(j): NEXT j
FOR j = 1 TO c: PRINT v(j, i); " ": NEXT j: PRINT NEXT i
class:
PRINT : PRINT "**** Classification ****"
DIM name$(100)
INPUT "Drive testing (A/B/C): "; dr$
ii = 1
ii1: PRINT "Drill no. [D{x}: "; ii: INPUT name$(ii)
IF name$(ii) <> "999" THEN
name$(ii) = name$(ii) + "HMRES" + fileext$
PRINT ": "; ii; name$(ii)
ii = ii + 1
GOTO ii1
ELSE
nfile = ii - 1
GOTO retsav
END IF
retsav:
FOR j = 1 TO c: actualc(j) = 0: testc(j) = 0: errc(j) = 0: NEXT j
FOR jj = 1 TO nfile
PRINT : PRINT jj, nfile, name$(jj): PRINT
OPEN dr$ + name$(jj) FOR INPUT AS #1
INPUT #1, n, nc
REDim x(n, n), x(n, m + 2), tempxx(nc)
FOR i = 1 TO n: FOR j = 1 TO nc: INPUT #1, tempxx(j): NEXT j
FOR k = 1 TO m: x(i, k) = tempxx(sel(k)): NEXT k
IF tempxx(nc) < c THEN tempxx(nc) = c
x(i, m + 1) = tempxx(nc): x(i, m + 2) = tempxx(1)
FOR j = 1 TO c: IF tempxx(nc) = j THEN actualc(j) = actualc(j) + 1: NEXT j
NEXT i
CLOSE #1
"**** Fuzzy classification of drill wear states"
FOR i = 1 TO n
FOR j = 1 TO c
bot = 0: sumtop = 0
FOR ii = 1 TO m: sumtop = sumtop + (x(i, ii) - v(j, ii))^2: NEXT ii
sumtop = SQR(sumtop)
FOR k = 1 TO c
sbumot = 0
FOR ii = 1 TO m: sbumot = sbumot + (x(i, ii) - v(k, ii))^2: NEXT ii
sbumot = SQR(sbumot)
IF sbumot = 0 AND sumbot = 0 THEN
ss = 1
ELSEIF sbumot = 0 THEN
bot = 0: GOTO lop4
ELSE
ss = sumtop / sbumot
END IF
bot = bot + (ss)^2: NEXT k
lop4: IF bot = 0 THEN u(j, i) = 0 ELSE u(j, i) = 1 / bot: NEXT j
max = -1
FOR j = 1 TO c
IF u(j, i) > max THEN max = u(j, i): state = j
NEXT j
realst = x(i, m + 1)
IF realst <= state THEN errc(realst) = errc(realst) + 1
PRINT "i: jno: ": x(i, m + 2); : LOCATE : 15
FOR j = 1 TO c: PRINT USING "####.#### ": u(j, i); : NEXT j
PRINT state: x(i, m + 1): testc(state) = testc(state) + 1
NEXT i
NEXT ij
FOR i = 1 TO c: PRINT i, actualc(i), testc(i), errc(i): NEXT i
Endofprog: END

A.2. RELATION

<table>
<thead>
<tr>
<th></th>
<th>Fuzzy relation</th>
<th>Aug 28, 1991</th>
<th>!</th>
</tr>
</thead>
</table>

' SDYNAMIC
DECLARE SUB stat (x(:, ), xs(:, ), mS(:, ), stdS)
DIM SHARED n, m, c, ns
DIM sel(25)
rstart: CLS
INPUT "Number of states ": c
* 1 - input cluster centers, 2 - determine cluster centers
cencodeS = "2": fileextS = ".
* == Input the training data
INPUT "Drill number ": drillS: drillS = UCASES(drillS)
drill = VAL(RIGHTS(drillS, 2)): INPUT "drive (Header) ":, headdrS
IF cencodeS = "2" THEN INPUT "drive (training) ":, traindrS
IF LEFTS(drillS, 1)="P" THEN trainnamS="GROUPD.HDR": GOTO proceed
IF LEFTS(drillS, 1)="C" THEN trainnamS="GROUP.C.HDR": GOTO proceed
IF drill <= 30 AND drill >= 28 THEN trainnamS = "GROUPA.HDR"
IF drill <= 47 AND drill >= 44 THEN trainnamS = "GROUPB.HDR"
IF drill <= 63 AND drill >= 57 THEN trainnamS = "GROUPC.HDR"
proceed: CLS
OPEN head$r + trainnam$ FOR INPUT AS #1
INPUT #1, nr, nc
REDim x$x(m,n)
FOR i = 1 TO nr: INPUT #1, x$x(i): PRINT "Col# "; i; " "; x$x(i): NEXT i
CLOSE #1
' *** select features for training
   LOCATE 22, 5: PRINT "Select features:"
   ic = 1: select$ = "0"
lhk1: LOCATE 23, 10: PRINT SPACES(50)
   LOCATE 23, 5: PRINT "Feature #"; ic; : INPUT select$
   IF select$ = "999" THEN GOTO lhk2
   LOCATE 22, (ic * 5 + 20): PRINT select$
   sel(ic) = VAL(select$): ic = ic + 1: GOTO lhk1
lhk2: m = ic + 1
   IF encode$ = "$1" THEN
   PRINT TAB(10); "input the mean and standard deviation"
   REDim mS(c, m), std(c, m)
   FOR i = 1 TO c: LOCATE, 10: PRINT "== State# "; i
   FOR j = 1 TO m: PRINT TAB(10); "Feature (mean, std) "; j:
   INPUT mS(i, j), std(i, j): NEXT j
   NEXT i
   GOTO center
END IF
' *** input the training sample
OPEN train$d$ + drill$ + "HMRES" + fileext$ FOR INPUT AS #1
INPUT #1, n, nc
REDim x(n, m + 1), tempxx(nc), x$(n)
FOR i = 1 TO n
   FOR j = 1 TO nc: INPUT #1, tempxx(j): NEXT j
   FOR k = 1 TO m: x(i, k) = tempxx(sel(k)): NEXT k
   IF tempxx(nc) > c THEN tempxx(nc) = c
   x$(i) = tempxx(nc): x(i, m + 1) = tempxx(1)
   NEXT i
CLOSE #1
ns = n
L = 30 'number of sub-intervals or classes
REDim xmax(m), xmin(m), Rs(c, m, L), rgs(L), xy(L)
REDim mS(c, m), std(c, m), x$(L)
IF (ns / c) < 30 THEN CALL stats(x$, x$(o), m$(o), std$(o)): GOTO center
' find the max and min of each feature
FOR j = 1 TO m
   max = -1E+10: min = 1E+10
   FOR i = 1 TO ns
      IF x$(i, j) > max THEN max = x$(i, j)
      IF x$(i, j) < min THEN min = x$(i, j)
   NEXT i
   xmax(j) = max: xmin(j) = min
NEXT j
' find the frequency of occurence
FOR i = 1 TO c
   FOR j = 1 TO m: FOR k = 1 TO L: Rs(i, j, k) = 0: NEXT k: NEXT j
NEXT i
FOR j = 1 TO m
   PRINT "Feature (occurrence): "; j
   inc = (xmax(j) - xmin(j)) / L: rgs(0) = xmin(j)
FOR k = 1 TO L
   rg(k) = rg(k - 1) + inc
NEXT k
FOR k = 1 TO L: xx(k) = (rg(k) + rg(k - 1)) / 2. NEXT k
FOR k = 1 TO L: xy(k) = 0: NEXT k
FOR i = 1 TO ns
   IF x(i, j) = xmax(j) THEN
      ic% = L
   ELSE
      ic% = INT((x(i, j) - xmin(j)) / inc) + 1
   END IF
   xy(ic%) = xy(ic%) + 1
FOR kk = 1 TO c
   IF xx(i) = kk THEN R(kk, j, ic%) = R(kk, j, ic%) + 1
   NEXT kk
NEXT i
NEXT j

* determine mean and standard deviation
FOR i = 1 TO c: FOR j = 1 TO m: mS(i, j) = 0: std(i, j) = 0: NEXT j: NEXT i
FOR j = 1 TO m
   FOR i = 1 TO c
      ss = 0
      FOR k = 1 TO L
         mS(i, j) = mS(i, j) + R(i, j, k) * xx(k); ss = ss + R(i, j, k)
      NEXT k
      mS(i, j) = mS(i, j) / ss
      FOR k = 1 TO L
         std(i, j) = std(i, j) + R(i, j, k) * (xx(k) - mS(i, j)) ^ 2
      NEXT k
      std(i, j) = SQR(std(i, j) / ss)
   NEXT i
   NEXT j
   center:
   FOR j = 1 TO c: FOR j = 1 TO m: PRINT mS(i, j), std(i, j): NEXT j: NEXT i
   classify:
   PRINT : PRINT "***** Classification *****"
   DIM name$(100)
   INPUT "Drive testing (A:,B:,C:): " : dS
   ii = 1
   ii1: PRINT "Drill no. [Dxx]: " : ii1 : INPUT name$(ii)
      IF name$(ii) <> "999" THEN
         name$(ii) = name$(ii) + "HMRES" + fileext5
         PRINT "# " : ii1 : name$(ii); ii = ii + 1: GOTO ii1
      ELSE
         nfile = ii - 1: GOTO resav
      END IF
      resav:
      FOR j = 1 TO c: actual(j) = 0: test(j) = 0: errc(j) = 0: NEXT j
      FOR ij = 1 TO nfile
         PRINT : PRINT ij, nfile, name$(ij): PRINT
         OPEN dS$ + name$(ij) FOR INPUT AS #1
         INPUT #1, n, nc
         REDIM x(n, m + 2), tempxx(nc), F(c, m), S(c)
         FOR i = 1 TO n
            FOR j = 1 TO nc: INPUT #1, tempxx(j): NEXT j
            FOR k = 1 TO m: x(i, k) = tempxx(k): NEXT k
         NEXT i
         FOR i = 1 TO m: next
IF tempx(nc) > c THEN tempx(nc) = c
x(i, m + 1) = tempx(nc): x(i, m + 2) = tempx(1) " hole#
FOR j = 1 TO c: IF tempx(nc) = j THEN actualc(j) = actualc(j) + 1: NEXT j
NEXT i
CLOSE #1
' === start the classification process
ns = n
FOR ii = 1 TO ns: FOR i = 1 TO c: FOR j = 1 TO m
qij = 1 / (SQR(2 * 3.141592) * std(i, j))
F(i, j) = qij * EXP(-(x(iii, i) - mS(i, j))^2 / (2*std(i, j)*std(i, j)))
NEXT j: NEXT i: NEXT ii
FOR i = 1 TO c: S(i) = 0: NEXT i
FOR i = 1 TO c: FOR j = 1 TO m: S(i) = S(i) + F(i, j): NEXT j: NEXT i
temp = -1E+10
FOR i = 1 TO c
IF S(i) > temp THEN state = i: temp = S(i)
NEXT i
realst = x(ii, m + 1)
IF realst <> state THEN
    IF x(ii, 1) < mS(1, 1) THEN state = 1
    IF x(ii, 1) > mS(1, 1) THEN state = c
END IF
IF realst <> state THEN errc(realst) = errc(realst) + 1
testc(state) = testc(state) + 1: PRINT "Hole#": x(ii, m + 2):
FOR kk = 1 TO c: PRINT USING "###.#####"; S(kk); : NEXT kk
PRINT state, realst
NEXT ii
NEXT jj
FOR i = 1 TO c: PRINT i, actualc(i), testc(i), errc(i): NEXT i
Endo(prop): END
REM SSTATIC
SUB stat(xO, xs(), mS(), std()) STATIC
' ===== calculate mean and standard deviation using ungrouped data
DIM tmnc(0), stdc(0), nsc(0)
FOR ii = 1 TO m
    FOR j = 1 TO c: tmean(j) = 0: tstd(j) = 0: nst(j) = 0: NEXT j
    FOR i = 1 TO ns
        FOR k = 1 TO c
            IF xs(i, k) THEN
                nst(k) = nst(k) + 1: tmean(k) = tmean(k) + x(i, ii): GOTO lsp1
            END IF
        NEXT k
    NEXT i
    NEXT j
lsp1:
    NEXT i
    FOR k = 1 TO c: tmean(k) = tmean(k) / nst(k): NEXT k
    FOR i = 1 TO ns
        FOR k = 1 TO c
            IF xs(i, k) THEN
                tstd(k) = tstd(k) + (x(i, ii) - tmean(k))^2: GOTO lsp2
            END IF
        NEXT k
    NEXT i
lsp2:
    NEXT k
    FOR k = 1 TO c
        mS(k, ii) = tmean(k): std(k, ii) = SQR(tstd(k) / (nst(k) - 1))
        NEXT k
NEXT ii
END SUB
A.3. PROWLER

Program used to capture signal from Prowler, these binary data signal can be stored, retrieved and converted to real numbers.

OPTION BASE 1
COMMON SHARED IBSTA%, IBERR%, IBCNT%
REM沈阳
DIM xy(16384), rdAS(8), rdBS(8)
bind$ = "0"; deode$ = "0"

=== Setting up the Prowler
DIM ProwlerIDS(15, 2)
TraceAS = "A"; TraceBS = "": nsegA$ = 0; nsegB$ = 0; IDsegmentA% = 2
IDsegmentB% = 0
ProwlerIDS(1, 1) = ".1. [1/1]"; ProwlerIDS(1, 2) = "]@"
ProwlerIDS(2, 1) = ".2. [1/2]"; ProwlerIDS(2, 2) = "]B"
ProwlerIDS(3, 1) = ".3. [2/2]"; ProwlerIDS(3, 2) = "]D"
ProwlerIDS(4, 1) = ".4. [14]"; ProwlerIDS(4, 2) = "]F"
ProwlerIDS(5, 1) = ".5. [24]"; ProwlerIDS(5, 2) = "]G"
ProwlerIDS(6, 1) = ".6. [34]"; ProwlerIDS(6, 2) = "]J"
ProwlerIDS(7, 1) = ".7. [4/4]"; ProwlerIDS(7, 2) = "]L"
ProwlerIDS(8, 1) = ".8. [1/8]"; ProwlerIDS(8, 2) = "]A"
ProwlerIDS(9, 1) = ".9. [2/6]"; ProwlerIDS(9, 2) = "]C"
ProwlerIDS(10, 1) = ".10. [3/8]"; ProwlerIDS(10, 2) = "]E"
ProwlerIDS(11, 1) = ".11. [4/8]"; ProwlerIDS(11, 2) = "]G"
ProwlerIDS(12, 1) = ".12. [5/8]"; ProwlerIDS(12, 2) = "]I"
ProwlerIDS(13, 1) = ".13. [6/8]"; ProwlerIDS(13, 2) = "]K"
ProwlerIDS(14, 1) = ".14. [7/8]"; ProwlerIDS(14, 2) = "]M"
ProwlerIDS(15, 1) = ".15. [8/8]"; ProwlerIDS(15, 2) = "]O"

menu: CLS
LOCATE 3, 15: PRINT "CAPTURE, STORE, & RETRIEVE RAW DATA (PROWLER)"
LOCATE 5, 20: PRINT "1. Capture raw data (binary) ?"
LOCATE 6, 20: PRINT "2. Convert binary data ?"
LOCATE 7, 20: PRINT "3. Store raw data ?"
LOCATE 8, 20: PRINT "4. Retrieve raw data ?"
LOCATE 9, 20: PRINT "5. Quit ?"

reenter: LOCATE 11, 20: INPUT "Selection (1-5) ":; sel$
IF sel$ = "1" OR sel$ = "5" THEN GOTO reenter
IF sel$ = "5" THEN GOTO Elp
IF sel$ = "4" THEN CLS

lp7: LOCATE 4, 19: INPUT "Filename : "; namS
LOCATE 5, 19: INPUT "Drive (a/b/c or path) ":; dirS

lp6: LOCATE 7, 19: INPUT "Satisfy (y/n) ":; aa$: aa$ = UCASE$(aa$)
IF aa$ = "Q" THEN GOTO Elp
IF NOT (aa$ = "Y" OR aa$ = "N") THEN GOTO lp6
IF aa$ = "N" THEN GOTO lp7
OPEN dir$ + namS FOR INPUT AS #1: INPUT #1, nsegA%, nsegB%
IF nsegA% > 8 THEN
np = nsegA%; deode$ = "1": FOR i% = 1 TO np: INPUT #1, xy(i%): NEXT i%
ELSE
bind$ = "1"
FOR i% = 1 TO nsegA%: rdAS(i%) = INPUT$(4132, #1)
PRINT i%; " A "; LEFT$(rdAS(i%), 55): NEXT i%
FOR i% = 1 TO nsegB%: rdBS(i%) = INPUT$(4132, #1)
PRINT i%; " B "; LEFT$(rdBS(i%), 55): NEXT i%
END IF
CLOSE #1: INPUT " 
END IF
IF selS = "2" THEN
cdata: CLS
IF bindats = "0" THEN PRINT "No binary data": GOTO menu
LOCATE 2, 10: PRINT "1. Convert Trace A 
"LOCATE 3, 10: PRINT "2. Convert Trace B 
"c11: LOCATE 5, 10: INPUT "Selection (1/2/Q)":, cselS
IF cselS = "Q" OR cselS = "q" THEN RETURN
IF cselS = "1" THEN
IF nsegA% = 0 THEN
LOCATE 10, 10: PRINT "Trace A is not available.. 
"FOR i = 1 TO 10000: NEXT i: GOTO cdata
ELSE
nseg = nsegA%: GOTO c12
END IF
END IF
END IF
IF cselS = "2" THEN
IF nsegB% = 0 THEN
LOCATE 10, 10: PRINT "Trace B is not available.. 
"FOR i = 1 TO 10000: NEXT i: GOTO cdata
ELSE
nseg = nsegB%: GOTO c12
END IF
END IF
END IF
IF NOT (cselS = "1" OR cselS = "2") THEN GOTO c11
c12:
FOR i% = 1 TO nseg
IF cselS = "1" THEN rdS = rdAS(i%) ELSE rdS = rdBS(i%)
GOSUB ExitFor
LOCATE 5, 10: PRINT "Segment ": i%; " "; LEFT$(rdS, 55)
st = stloc + 32: ij% = (i% - 1) * 2048
FOR j% = 1 TO 2048
$MID$(rdS, st, 2): aa = $ASC($MID$(tempS, 1, 1)): ab = $ASC($MID$(tempS, 2, 1))
abc = (aa + ab * 256) - 32768: xy(j%+ij%)=(FF01(1) * abc + FF02(2)) * 1000: st = st + 2
IF j% < 10 THEN PRINT j%, xy(j% + ij%)
NEXT j%
np = nseg * 2048: decdata% = "1": CLOSE #1
END IF
IF selS = "3" THEN
CLS
lop2: LOCATE 5, 15: INPUT "Filename to store raw data ":, namS
LOCATE 6, 15: INPUT "Drive (a/b/c or path )":, cdS
lop3: LOCATE 7, 15: INPUT "Satisfy \( y/n \) ": anS
IF NOT (anS = "N" OR anS = "n" OR anS = "Y" OR anS = "y") THEN GOTO lop3
IF anS = "N" OR anS = "n" THEN GOTO lop2
LOCATE 9, 15: PRINT "1. Binary data 
"LOCATE 10, 15: PRINT "2. Real data (Y values ) 
"lop34: LOCATE 12, 15: INPUT "Selection (1-2 )":, cselS
IF cselS = "1" AND bindats = "0" THEN GOTO lop34
IF cselS = "2" AND decdataS = "0" THEN GOTO lop34
LOCATE 10, 15: PRINT "Wait, Saving......"; nam$  
OPEN do$ + nam$ FOR OUTPUT AS #1  
IF ssel$ = "1" THEN  
  PRINT #1, nsegA%, nsegB%  
  FOR i=1 TO nsegA%; PRINT #1, LEFT$(rdA$(i),4130); NEXT i  
  FOR i=1 TO nsegB%; PRINT #1, LEFT$(rdb$(i),4130); NEXT i  
ELSE  
  PRINT #1, np: FOR i%= 1 TO np: PRINT #1, x%(i%); NEXT i%  
END IF  
CLOSE #1
END IF
IF sel$ = "1" THEN  
  bdbname$ = "prowler"  
  capture: CLS : LOCATE 2, 20: PRINT "Capture data from PROWLER"  
  IF TraceA$ = "A" THEN  
    LOCATE 4,10: PRINT "Trace A";RIGHT$(ProwlerIDS(1DsegmentA%, 1),.5)  
  END IF  
  IF TraceB$ = "B" THEN  
    LOCATE 5,10: PRINT "Trace B";RIGHT$(ProwlerIDS(1DsegmentB%, 1),.5)  
  END IF  
s11: LOCATE 7, 10: INPUT "Any changes (Y/N)?", setup$n  
  setup$n$ = UCASE$(setup$n$)  
  IF NOT (setup$n$ = "Y" OR setup$n$ = "N") THEN GOTO s11  
  IF setup$n$ = "Y" THEN GOSUB Prowlersetup: GOTO capture  
    id% = 1  
    IF TraceA$ = "A" THEN  
      strA$ = ".KCCA" + ProwlerIDS(1DsegmentA%, 2) + CHR$(255)  
      id% = id% + 1  
    END IF  
    IF TraceB$ = "B" THEN  
      strB$ = " KCCC" + ProwlerIDS(1DsegmentB%, 2) + CHR$(255)  
      id% = id% + 1  
    END IF  
    numberoftrace% = id% - 1  
LOCATE 10,10: PRINT "Get the signal ready to transfer in PROWLER"  
  s12: IF INKEYS <> CHR$(13) THEN GOTO s12  
    LOCATE 10, 1: PRINT SPACE$(80)  
    . Initialize the device  
    CALL ibfind(bdbname$, bd%); CALL ibsib(bd%); v% = 1: CALL ibser(bd%, v%)  
    . To capture the data from Prowler  
    nsegA% = 0: nsegB% = 0  
    IF TraceA$ = "A" THEN  
      length% = 12: CALL ibtmob(bd%, length%)  
    END IF  
    LOCATE 10, 1: PRINT SPACE$(75): LOCATE 10,10  
    PRINT "Press RESET on the prowler.....ENTER to capture..."  
  s13: IF INKEYS <> CHR$(13) THEN GOTO s13  
LOCATE 10,10:PRINT "Please....wait...Capturing Trace A..."  
    temp% = 1DsegmentA%; GOSUB detsegment: nsegA% = nseg%  
    wrt$=strA$: CALL ibwrt(bd%, wrt$): FOR i=1 TO 5000: NEXT i  
    length% = 11: CALL ibtmob(bd%, length%)  
    FOR ii = 1 TO nsegA%  
      rdA$(ii) = SPACE$(4130)  
      IF ii = nsegA% THEN rdA$(ii) = SPACE$(4132)  
      FOR jk = 1 TO 2000: NEXT jk  
      CALL ibrd(bd%, rdA$(ii))  
      IF ii<> nsegA% THEN rdA$(ii)=rdA$(ii)+CHR$(13)+ CHR$(10)
PRINT ii,LEFT$(rdAS$(ii), 35);" "+MIDS(rdAS$(ii),4000,32)
NEXT ii
END IF

IF TraceBS = "B" THEN
length% = 12: CALL ibtsmo(bd%, length%)
LOCATE 10, 1: PRINT SPACES(75);LOCATE 10,10
PRINT "Press RESET on the prowlser...& ENTER to capture..."

ELSE: IF INKEY$ <> CHR$(13) THEN GOTO std3
LOCATE 10,10: PRINT "Please.....wait...Capturing Trace B..."
   temp% = IDsegmentB%; GOSUB Detsegment: nsegB% = nseg%
   wrt$=rdBS$: CALL ibwrt(bd%,wrt$): FOR i=1 TO 5000: NEXT i
   length% = 11: CALL ibtsmo(bd%, length%)
   FOR ii = 1 TO nsegB%
      rdBS$(ii) = SPACES$(4130)
      IF ii = nsegB% THEN rdBS$(ii) = SPACES$(4132)
      FOR jk = 1 TO 2000: NEXT jk: CALL ibrd(bd%, rdBS$(ii))
   IF ii <> nsegB% THEN rdBS$(ii)=rdBS$(ii)+CHR$(13)+CHR$(10)
   PRINT LEFT$(rdBS$(ii),35);" "+MIDS(rdBS$(ii),4000,32)
   NEXT ii
END IF
END IF
bindata$ = "1"

loc1: IF INKEY$ <> CHR$(13) THEN GOTO loc1
END IF

GOTO menu
Eloop: END
GOTO menu
Detsegment:
IF temp% = 1 THEN nseg% = 8
IF temp% = 2 AND temp% = 3 THEN nseg% = 4
IF temp% > 3 AND temp% <= 7 THEN nseg% = 2
IF temp% > 7 AND temp% <= 15 THEN nseg% = 1
RETURN
Prowlersetup:
CLS : cc = 3: FOR ik = 1 TO 15 STEP 3: LOCATE cc, 10
PRINT ProwlerIDS$(ik,1);TAB(25);ProwlerIDS$(ik+1,1);TAB(40);ProwlerIDS$(ik+2,1)
cc = cc + 1: NEXT ik
pl1: LOCATE 9,10: INPUT "Number of Trace(s) to transfer <1/2> ": numberoftrace%
   IF NOT (numberoftrace% = 1 OR numberoftrace% = 2) THEN GOTO pl1
   IF numberoftrace% = 1 THEN
   LOCATE 11,10: INPUT "Which Trace (A/B) ?": TraceS:TraceS=UCASE$(TraceS)
   IF TraceS = "A" THEN
      TraceBS = "A": TraceBS = "": LOCATE 12,10
      INPUT "Which segment of trace A to transfer ":, IDsegmentA%
   ELSE
      TraceBS = "B": TraceBS = "": LOCATE 13, 10
      INPUT "Which segment of trace B to transfer ":, IDsegmentB%
   END IF
   ELSE
      TraceBS = "A": TraceBS = "B": LOCATE 12, 10
      INPUT "Which segment of trace A to transfer ":, IDsegmentA%
      LOCATE 13, 10: INPUT "Which segment of trace B to transfer ":, IDsegmentB%
END IF
RETURN
COMMON SHARED IBSTA%, IBERR%, IBCNT%
DIM RD(401), rd(1024)
Numpoints=401: XSTART=0; XSTOP=12800; xunit$ = "Hz"; yunit$ = "EU"
CLS: LOCATE 3, 5: PRINT "Number of point "; Numpoint
LOCATE 4, 5: PRINT "X-axis starting value "; XSTART
LOCATE 5, 5: PRINT "X-axis last value "; XSTOP
LOCATE 6, 5: PRINT "X-axis unit "; xunit$
LOCATE 7, 5: PRINT "Y-axis unit "; yunit$
sp1: LOCATE 9, 5: INPUT "Satisfy (Y/N) ", ANS: ANS = UCASE$(ANS)
IF NOT (ANS = "Y" OR ANS = "N") OR ANS = "Q") THEN GOTO sp1
IF ANS = "Q" THEN GOTO ENDOFFROG
IF ANS = "Y" THEN GOTO sp2
FOR I = 3 TO 9: LOCATE I, 1: PRINT SPACES(70): NEXT I
LOCATE 3, 5: INPUT "Number of point "; Numpoint
LOCATE 4, 5: INPUT "X-axis starting value "; XSTART
LOCATE 5, 5: INPUT "X-axis last value "; XSTOP
LOCATE 6, 5: INPUT "X-axis unit "; xunit$
LOCATE 7, 5: INPUT "Y-axis unit "; yunit$
GOTO sp1
sp2: INPUT "Drill name (prefix) ", nam$ INPUT "Drive to save data (a/b/c/d/path) ", DR$
capdata: CLS
bdname$ = "HP35660"; CALL ibfind(bdname$, bd%); v% = 1; CALL IRSRD(bd%, v%)
v% = &H7: CALL ibpad(bd%, v%); v% = 0; CALL ibmxt(bd%, v%)
LOCATE 5, 5: PRINT "Press 'ENTER' to capture data ..."
Wait2: IF INKEYS <> CHR$(13) THEN GOTO Wait2
LOCATE 5, 5: PRINT "Wait, capturing data... "; SPACES(20)
IF Numpoint = 401 THEN
  AAS = SPACES(3000) "bytes=7*401+3"
  FOR I = 1 TO 3000: NEXT I: CALL ibrdA(bd%, AAS): mask% &= &H4100
  CALL ibwai(bd%, mask%)
  LOCATE 7, 2: PRINT "T1": LEFT$(AAS, 70)
ELSE
  AAS = SPACES(7300): CALL ibrdA(bd%, AAS): mask% &= &H4100
  CALL ibwai(bd%, mask%)
  LOCATE 7, 2: PRINT "T2": LEFT$(AAS, 70)
END IF
LB% = 1
SP3: IF MID$(AAS, LB%, 1) <> " " THEN LB% = LB% + 1: GOTO SP3
TB% = LEN(AAS)
SP6: IF MID$(AAS, TB%, 1) = " " THEN TB% = TB% - 1: GOTO SP6
PRINT LB%, TB%, MID$(AAS, TB% - 10, 25)
sp8: LOCATE 12, 5: INPUT "Want to save data [Y/N, (P)lot] ", ANS
ANS = UCASE$(ANS)
IF ANS = "Q" THEN GOTO ENDOFFROG
IF ANS = "P" THEN GOSUB PLOTDATA: GOTO sp8
IF NOT (ANS = "Y" OR ANS = "N" OR ANS = "Q") THEN GOTO sp8
IF ANS = "Q" THEN GOTO ENDOFFROG
IF ANS = "N" THEN GOTO SP4
LOCATE 11, 5: PRINT hole$: : INPUT "Hole ":, hole$
IF LEN(hole$) = 1 THEN hole$ = "0" + hole$
name$ = nam$ + hole$
OPEN DRS + name$ FOR OUTPUT AS #1
LOCATE 13, 5: PRINT "Saving data ..."; name$; SPACES(20)
WRITE #1, Numpoint, XSTART, XSTOP, xunit$, yunit$
PRINT #1, MIDS(AAS, LB%, TB% - LB% + 1)
CLOSE #1
SP4: LOCATE 15, 5: INPUT "Another run (y/n)?", ANS: ANS = UCASES(ANS$)
IF NOT (ANS = "Y" OR ANS = "N") OR ANS = "Q") THEN GOTO SP4
IF ANS = "Y" THEN GOTO capdata
ENDOFPROG: END
* ========= Plot the captured data
PLODATA: SCREEN 9: CLS: LOCATE 5, 10: PRINT "Wait...extracting values..."
OPEN DRS + "TEMPDUMP" FOR OUTPUT AS #3
PRINT #3, MIDS(AAS, LB%, TB% - LB% + 1); CLOSE #3
OPEN DRS + "TEMPDUMP" FOR INPUT AS #3
INPUT #3, YMIN, YMAX: FOR I = 1 TO 401
INPUT #3, RD1(I): NEXT I: CLOSE #3
* ========= START PLOTTING
VIEW (130, 30)-(532, 275)
WINDOW (1, 0)-(401, 10000): LINE (1, 0)-(401, 10000), B
PSET (1, RD1(I)): FOR I% = 1 TO 401: LINE -(1%, RD1(I%)): NEXT 1%
LOCATE 21, 16: PRINT XSTART; LOCATE 21, 62: PRINT XSTOP
LOCATE 20, 11: PRINT YMIN; LOCATE 3, 11: PRINT YMAX
LOCATE 22, 29: PRINT "Press 'ENTER' to continue..."
Loop3: IF INKEYS = CHR$(13) THEN GOTO Loop3
VIEW: WINDOW
RETURN

A.5. ANALYSIS

* =============

* | Data analysis in time and frequency domains | Dec 10, 1990 |
* =============

DECLARE SUB srflit (xl$, nl$, nl)
DECLARE SUB strates (rd$[, rg, dvs, NP])
OPTION BASE 1
DIM SHARED mean, std, sk, kur, rmsrd, rmsfd, xx(500), yy(500), sdr(500)
REM SDYNAMIC
DIM SHARED rd(8192), rdAS$(4), rdBS$(4), x(8192), Y(1024)
DIM SHARED name$(100), HOLE$(100), LB(10), UB(10), SBP(10)
bindat$ = "0": decode$ = "0"
MENU: CLS
LOCATE 3, 15: PRINT "RETRIEVE RAW DATA & ANALYZE"
LOCATE 5, 20: PRINT "0. Fast data analysis ?"
LOCATE 6, 20: PRINT "1. Retrieve raw data ?"
LOCATE 7, 20: PRINT "2. Convert binary data ?"
LOCATE 8, 20: PRINT "3. Data analysis ?"
LOCATE 9, 20: PRINT "4. Store data ?"
LOCATE 10, 20: PRINT "5. Quit ?"
retent: LOCATE 12, 20: INPUT "Selection (0-5) ?", sel$;
IF sel$ < "0" OR sel$ > "5" THEN GOTO retent
IF sel$ = "5" THEN GOTO clop
IF sel$ = "0" THEN
CLS
INPUT "Drill name [DXXH] ": nam$m$
INPUT "Drive (A/B/C): ": drr$
II = 1
ELSE IF PRINT "Hole ": II; : PRINT HOLE$1)
IF LEN(HOLE$1) = 1 THEN HOLE$1 = "0" + HOLE$1
IF HOLE$1 <> "999" THEN
   name$II = nam$m$ + HOLE$1: PRINT "; ": name$II
   II = II + 1: GOTO ii1
ELSE
tohole = II - 1: GOTO rtsav
END IF
rtsav: CLS
LOCATE 3, 7: PRINT "DATA ANALYSIS"
LOCATE 5, 7: PRINT "1. Time domain ?"
LOCATE 6, 7: PRINT "2. Frequency domain ?"
LOCATE 7, 7: PRINT "3. Exit ?"
LOCATE 9, 7: INPUT "selection (1-3) ": DASELS: DASEL = VAL(DASELS)
IF DASEL = 3 THEN GOTO MENU
IF DASEL = 2 THEN
   PRINT "1. FREQUENCY SPECTRUM ?"
   PRINT "2. BANDPASS RMS ?"
SP5: INPUT "SELECTION (1/2) ": FSSEL$S
   IF NOT (FSSEL$ = "1" OR FSSEL$ = "2") THEN GOTO SP5
   IF FSSEL$ = "2" THEN
      PRINT "INPUT THE FREQUENCY BANDS ": II = 1
   PRINT "LOWER BOUND ": II; : INPUT LB(II)
   PRINT "UPPER BOUND ": II; : INPUT UB(II)
   IF LB(II) = 999 THEN GOTO SP7
   II = II + 1: GOTO SP6
SP7: NBP = II - 1
   END IF
END IF
LOCATE 10, 7
INPUT "Want to save results (Y/N) ": asav$: asav$UCASE$(asav$)
IF asav$ = "Y" THEN
   LOCATE 11, 7: INPUT "Drive (a/b/c/e): ": drrsav$
END IF
IF DASEL = 1 THEN
   LOCATE 5, 45: INPUT "Amplitude range ": rg
   LOCATE 6, 45: INPUT "Number of class ": divs
END IF
FOR II = 1 TO tohole
   LOCATE 3, 45: PRINT name$II)
   IF FSSEL$ = "2" THEN GOTO SP10
   OPEN drr$ + name$II FOR INPUT AS #1
   INPUT #1, nsegA%, nsegB%
   FOR I% = 1 TO nsegA%: rdA$(I%) = INPUT$(4134, #1)
   IF LEFT$(rdA$(I%), 1) <> "7" THEN rdA$(I%) = MID$(rdA$(I%), 2, 4133)
   NEXT I%
   FOR I% = 1 TO nsegB%: rdB$(I%) = INPUT$(4134, #1): NEXT I%
   CLOSE #1
   numtrace% = 2
IF nsegA% = 0 OR nsegB% = 0 THEN numtrace% = 1
FOR f1% = 1 TO numtrace%
    IF numtrace% = 1 THEN
        IF nsegA% = 0 THEN nseg = nsegB% ELSE nseg = nsegA%
    ELSE
        IF f1% = 1 THEN nseg = nsegA% ELSE nseg = nsegB%
    END IF
END IF
FOR f1% = 1 TO nseg
    IF numtrace% = 2 THEN
        IF f1% = 1 THEN rdS = rdAS(1%) ELSE rdS = rdBS(1%)
    ELSE
        IF nsegA% = 0 THEN rdS = rdBS(1%) ELSE rdS = rdAS(1%)
    END IF
    GOSUB ExtFFot
    LOCATE 5; PRINT "Segment #": f1%; " "; LEFT$(rdS, 35)
    st = stloc + 32; ij% = (f1% - 1) * 2048
    FOR f1% = 1 TO 2048
        tempS = MIDS(rdS, st, 2); AA = ASC(MIDS(tempS, 1, 1))
        ab = ASC(MIDS(tempS, 2, 1)); abc = (AA + ab * 256) - 32768
        rd%(1%) + ij% = (FFot(1%) * abc + FFot(2%)) * 1000; st = st + 2
    NEXT f1%
    NEXT f1%
    NP = nseg * 2048
    IF f1% = 1 THEN codetrace$ = ".A" ELSE codetrace$ = ".B"
    GOTO SPI1
SPI1:
OPEN drs$ + name$(I) FOR INPUT AS #1
INPUT #1, NP, XMIN, XMAX, XUNITS, YUNITS, YMIN, YMAX
YDIFF = YMAX - YMIN
FOR f1% = 1 TO NP
    INPUT #1, Y(%): Y(%!) = YDIFF * Y(%) / 10000 + YMIN
NEXT f1%
CLOSE #1
SPI1:
IF DASEL = 1 THEN
    CALL states(rd(), rg, divs, NP)
    IF assav$ = "Y" THEN
        OPEN drsav$ + namm$ + "SR" + codetrace$ FOR APPEND AS #1
        PRINT #1, HOLE$(II), divs, mean, std, sk, kur, rmsrd, rmsfd
        CLOSE #1
        OPEN drsav$ + name$(II) + "SD" + codetrace$ FOR OUTPUT AS #1
        PRINT #1, divs, 2
        FOR jj% = 1 TO divs: PRINT #1, xx(jj%), yy(jj%): NEXT jj%
        CLOSE #1
    END IF
END IF
IF DASEL = 2 AND FSSEL$ = "1" THEN
    LOCATE 11, 45; PRINT "Please, wait ...."
    REDIM x(NP)
    FOR f1% = 1 TO NP: x(f1%) = rd(f1%) = x(f1%) = x(f1%) * 5 *(1 - COS((6.283185 * (f1% + .5)) / NP))
    NEXT f1%
    no = 1: IK = 0
    c12: no = no + no: IK = IK + 1: IF no < NP THEN GOTO c12
m = 1K: CALL srftt(x(), NP, m)
FOR i% = 1 TO NP / 2 - 1
x(i%) = (SQR(x(i% + 1) ^ 2 + x(NP - i% + 1) ^ 2) * 2) / NP
NEXT i%
spectnp = NP / 2
OPEN dsn8$ + name$2) + "FS" + caderec$ FOR OUTPUT AS #1
PRINT #1, spectnp, 1
FOR i% = 1 TO spectnp: PRINT #1, x(i%): NEXT i%
CLOSE #1
ELSE
FOR i% = 1 TO NBP: SBP(i%) = 0: FOR j% = LB(i%) TO UB(i%)
SBP(i%) = SBP(i%) + Y(j%) ^ 2: NEXT j%
SBP(i%) = SQR(SBP(i%)): PRINT i%, LB(i%), UB(i%), SBP(i%): NEXT i%
OPEN dsn8$ + name$2) + "BP" FOR OUTPUT AS #1
PRINT #1, NBP
FOR i%=1 TO NBP: PRINT #1, LB(i%), UB(i%), SBP(i%): NEXT i%
CLOSE #1
END IF
NEXT i%: NEXT II: BEEP
END IF

IF sel$ = "I" THEN
CLS
lsp7: LOCATE 4, 19: INPUT "Filename : ": nam$
LOCATE 5, 19: INPUT "Drive (a/b/c) or path ": dr$
lsp6: LOCATE 7,19: INPUT "Satisfy (y/n) ?", AAS: AAS=UCASES(AAS)
IF AAS = "Q" THEN GOTO clop
IF NOT (AAS = "Y" OR AAS = "N") THEN GOTO lsp6
IF AAS = "N" THEN GOTO lsp7
PRINT "1. BINARY RAW DATA [Prowler] ?"
PRINT "2. FREQUENCY SPECTRUM ?"
PRINT "3. SELECTION (1/2) ?", RSELS
PRINT "4. EXIT ":
IF NOT (RSELS = "1" OR RSELS = "2") THEN GOTO SP4
OPEN dr$ + nam$ FOR INPUT AS #1

IF RSELS = "1" THEN
INPUT #1, nsegA%, nsegB%
IF nsegA% > 8 THEN
REDIM rd$(nsegA%)
NP = nsegA%: dectar$ = "I"
FOR i% = 1 TO NP: INPUT #1, rd%(i%): NEXT i%
ELSE
IF nsegA%<=0 AND nsegB%<=0 THEN REDIM rd$(nsegA%),rdBS(nsegB%)
IF nsegA% = 0 THEN REDIM rdBS(nsegB%)
IF nsegB% = 0 THEN REDIM rd$(nsegA%)
bindat$ = "I"
PRINT "Number of segments (A,B) :", nsegA%, nsegB%
FOR i% = 1 TO nsegA%: rd$(i%) = INPUT$(4132, #1)
IF LEFT$(rd$(i%),1)="Y" THEN rd$(i%) = MID$(rd$(i%), 2, 4133);
PRINT i%, "A", LEFT$(rd$(i%), 55); NEXT i%
FOR i% = 1 TO nsegB%: rdBS(i%) = INPUT$(4132, #1)
PRINT i%, "B", LEFT$(rdBS(i%), 55); NEXT i%
END IF
ELSE
INPUT #1, NP, XMIN, XMAX, XUNITS, YUNITS, YMIN, YMAX
YDIFF = YMAX - YMIN
FOR I% = 1 TO NP
INPUT #1, Y(I%) = YDIFF + Y(I%) / 10000 + YMIN: NEXT I%
END IF
CLOSE #1
lsp1: IF INKEYS <> CHR$(13) THEN GOTO lsp1
END IF

IF sel$ = "2" THEN
cdata: CLS
  IF bindata$ = "0" THEN PRINT "No binary data": GOTO MENU
  LOCATE 2, 10: PRINT "1. Convert Trace A ?"
  LOCATE 3, 10: PRINT "2. Convert Trace B ?"
c11: LOCATE 5, 10: INPUT "Selection (1/2/Q) ": cse1$
  IF cse1$ = "Q" OR cse1$ = "q" THEN RETURN
  IF cse1$ = "1" THEN
    IF nsegA% = 0 THEN
      LOCATE 10, 10: PRINT "Trace A is not available..."
      FOR I = 1 TO 10000: NEXT I: GOTO cdata
    ELSE
      REDIM rd(nsegA% * 2048): nseg = nsegA%: GOTO cl2
    END IF
  END IF
  END IF
  IF cse1$ = "2" THEN
    IF nsegB% = 0 THEN
      LOCATE 10, 10: PRINT "Trace B is not available..."
      FOR I = 1 TO 10000: NEXT I: GOTO cdata
    ELSE
      REDIM rd(nsegB% * 2048): nseg = nsegB%: GOTO cl2
    END IF
  END IF
  END IF
  IF NOT (cse1$ = "1" OR cse1$ = "2") THEN GOTO c11
cl2:
  FOR I% = 1 TO nseg
    IF cse1$ = "1" THEN rd$ = rdA$(I%) ELSE rd$ = rdB$(I%)
    GOSUB ExtFot: LOCATE , 5: PRINT "Segment #": I%; ";": LEFT$(rd$, 55)
    st = stloc + 32: ij% = (I% - 1) * 2048
    FOR J% = 1 TO 2048
      temp$ = MID$(rd$, st, 2): AA = ASC(MID$(temp$, 1, 1))
      ab = ASC(MID$(temp$, 2, 1)): abc = (AA + ab * 256) - 32768
      rd(1%-ij%) = (FFloat(1) * abc + FFloat(2)) * 1000: st = st + 2
    IF J% < 10 THEN PRINT J%, rd(1% + ij%)
    NEXT J%
    NEXT I%
NP = nseg * 2048: decdata$ = "1"
CLOSE #1
END IF

IF sel$ = "4" THEN  ' store data
AAS(1) = "Prowler raw data"
AAS(2) = "Frequency spectrum"
AAS(3) = "Statistical results"
AAS(4) = "Bandpass RMS"
dstl: CLS: LOCATE 3, 7: PRINT "DATA STORAGE"
LOCATE 5, 7: PRINT "1. Prowler raw data ?"
  LOCATE 6, 7: PRINT "2. Frequency spectrum ?"
  LOCATE 7, 7: PRINT "3. Statistical results ?"

LOCATE 8, 7: PRINT "4. Band pass RMS ?"
LOCATE 9, 7: PRINT "5. Exit ?"
LOCATE 10, 7: INPUT "selection (1-5) ": DSTSELS: DSTSEL = VAL(DSTSELS)
IF DSTSEL < 1 OR DSTSEL > 5 THEN GOTO dstl1
IF DSTSEL = 5 THEN GOTO MENU
IF DSTSEL = 1 THEN
   LOCATE 12, 7: PRINT "1. Binary data ?"
   LOCATE 13, 7: PRINT "2. Real data (Y values) ?"
   lop34: LOCATE 15, 7: INPUT "Selection (1-2) ":, sselS
   IF sselS = "1" AND bindatS = "3" THEN GOTO lop34
   IF sselS = "2" AND decdatS = "0" THEN GOTO lop34
END IF

LOCATE 6, 45: PRINT "Storing << "; AAS(DSTSEL): " >>"
dstl: LOCATE 8, 45
INPUT "Want to store data (y/n) ":; anS: anS = UCASES(anS)
   IF anS = "Q" THEN GOTO dstes
   IF NOT (anS = "Y" OR anS = "N") THEN GOTO dstl1
   IF anS = "Y" THEN
   dst2: LOCATE 8, 45: PRINT SPACE(30): LOCATE 8, 45
   INPUT "Filename to store data ":, namS
   LOCATE 9, 45: INPUT "Drive (A/B/C: or Path ): "; drS
   LOCATE 22,10: PRINT "<<< Data will be stored on ";, namS;
   PRINT "\ in Drive ";, drS, 1: >>>"
   dst3: LOCATE 11, 45
   INPUT "OK to save now (Y/N) ":, sanS: sanS = UCASES(sanS)
   IF sanS = "Q" THEN GOTO dstes
   IF NOT (sanS = "Y" OR sanS = "N") THEN GOTO dstl3
   IF sanS = "N" THEN GOTO dstl2
   ELSE
   GOTO dstes
   END IF
   LOCATE 13, 45: PRINT "Please wait....."
   OPEN drS+namS FOR OUTPUT AS #1
IF DSTSEL = 1 THEN
   IF sselS = "1" THEN
      PRINT #1, nsegA%, nsegB%
      FOR I = 1 TO nsegA%: PRINT #1, LEFTS(rdAS(I), 4132): NEXT I
      FOR I = 1 TO nsegB%: PRINT #1, LEFTS(rdBS(I), 4132): NEXT I
      ELSE:
      PRINT #1, NP, 1
      FOR NP = 1 TO NP: PRINT #1, rd(NP): NEXT NP
      END IF
ELSEIF DSTSEL = 2 THEN
   WRITE #1, spectnp, 1
   FOR NP = 1 TO spectnp: WRITE #1, x(NP): NEXT NP
ELSEIF DSTSEL = 3 THEN
   WRITE #1, mean, std, sk, kur, rmsd, rmsfd
ELSE
   WRITE #1, NBP
   FOR NP=1 TO NBP
      WRITE #1, LB(NP), UB(NP), SBP(NP): NEXT NP
END IF
CLOSE #1
dstes: END IF
### Data analysis

```plaintext
IF sel$ = "3" THEN
IF decdat$ = "0" THEN PRINT "No real data available."
FOR I = 1 TO 10000: NEXT I: GOTO MENU
CLS
LOCATE 3, 7: PRINT "DATA ANALYSIS"
LOCATE 5, 7: PRINT "1. Time domain ?"
LOCATE 6, 7: PRINT "2. Frequency domain ?"
LOCATE 7, 7: PRINT "3. Exit ?"
LOCATE 9, 7: INPUT "selection (1-3) :": DASELS: DASEL = VAL(DASELS)
IF DASEL = 3 THEN GOTO MENU
IF DASEL = 1 THEN
LOCATE 6, 45: PRINT "STATISTICAL ANALYSIS"
LOCATE 8, 45: INPUT "Amplitude range :"; rg
LOCATE 9, 45: INPUT "Number of class :"; divs
CALL statres(rg, divs, NP)
PRINT mean, std, sk, kur, rmsrd, rmsfd
d1: IF INKEY$ <> CHR$(13) THEN GOTO d1
END IF
IF DASEL = 2 THEN
PRINT "1. FREQUENCY SPECTRUM ?"
PRINT "2. PASSBAND RMS ?"
SPI: INPUT "SELECTION (1/2) :": ASEL$;
IF NOT (ASELS = "1" OR ASEL$ = "2") THEN GOTO SPI
IF ASEL$ = "1" THEN
LOCATE 11, 45: PRINT "Please, wait ...."
REDIM x(NP)
FOR I% = 1 TO NP: x(I%) = rd(I%)
x(I%) = x(I%) * .5 * (1 - COS((6.283185 * (I% + .5)) / NP))
NEXT I%
no = 1: II = 0
c11: no = no + no: II = II + 1: IF no < NP THEN GOTO c11
m = II
CALL srfft(x(), NP, m)
FOR I% = 1 TO NP / 2 - 1
x(I%) = (SQR(x(I% + 1) ^ 2 + x(NP - I% + 1) ^ 2) * 2) / NP
NEXT I%
spectmp = NP / 2
ELSE
PRINT "INPUT THE FREQUENCY BANDS."
II = 1
SP2: PRINT "LOWER BOUND :": II = II + 1: IF LB(II) = 999 THEN GOTO SP3
IF LB(II) = 999 THEN GOTO SP3
II = II + 1
GOTO SP2
SP3: NBF = II - 1
FOR I% = 1 TO NBP: SBP(I%) = 0
FOR I% = LB(II) TO UB(II): SBP(I%) = SBP(I%) + Y(I%) ^ 2: NEXT I%
SBP(I%) = SQR(SBP(I%)): PRINT I%, LB(II), UB(II), SBP(I%): NEXT I%
END IF
END IF
END IF
GOTO MENU
cllop: END
```

***** END OF THE PROGRAM *****
REM SSTATIC  'Split-radix FFT
SUB sfft (x(), n, m) STATIC
    J% = 1: n1 = n - 1
    FOR I% = 1 TO n1
        IF I% >= J% THEN GOTO 2
        xt = x(I%); x(I%) = x(J%); x(J%) = xt
    K = n / 2
    IF K >= J% THEN GOTO 4
        J% = J% - K; K = K / 2: GOTO 3
    J% = J% + K
    NEXT I%
    js = 1: id = 4
    FOR i0% = js TO n STEP id
        i1 = i0% + 1: r1 = x(i0%): x(i0%) = r1 + x(i1): x(i1) = r1 - x(i1): NEXT i0%
        js = 2 * id - 1: id = 4 * id: IF js < n THEN GOTO 70
    n2 = 2
    FOR K% = 2 TO m
        n2 = n * n2 / 4: n8 = n2 / 8: e = 6.283185309 / n2
        js = 0: id = n2 * 2
    FOR I = js TO n - 1 STEP id
        i1 = I + 1: i2 = i1 + n4: i3 = i2 + n4: i4 = i3 + n4
        t1 = x(i4) + x(i3): x(i4) = x(i4) - x(i3): x(i3) = x(i1) - t1
        x(i1) = x(i1) + t1: IF n4 = 1 THEN GOTO 38
        i1 = i1 + n8: i2 = i2 + n8: i3 = i3 + n8: i4 = i4 + n8
        t1 = x(i3) + x(i4) / SQR(2): t2 = x(i3) - x(i4) / SQR(2)
        x(i4) = x(i2) - t1: x(i3) = -x(i2) - t1: x(i2) = x(i1) - t2
        x(i1) = x(i1) + t2
    NEXT I
    js = 2 * id - n2: id = 4 * id: IF js < n THEN GOTO 40
    a = e
    FOR J% = 2 TO n8
        a3 = a * e: ccl = COS(a): s1 = SIN(a): cc3 = COS(a3): ss3 = SIN(a3)
        a = J% * e: js = 0: id = 2 * n2
    FOR I = js TO n - 1 STEP id
        i1 = I + 1: i2 = i1 + n4: i3 = i2 + n4: i4 = i3 + n4
        i5 = I + n4 - J% + 2: i6 = i5 + n4: i7 = i6 + n4: i8 = i7 + n4
        t1 = x(i3) + x(i7) * ss1: t2 = x(i7) * cc1 - x(i3) * ss1
        t3 = x(i4) + x(i8) * ss3: t4 = x(i8) * cc3 - x(i4) * ss3
        t5 = t1 + t3: t6 = t2 + t4: t3 = t1 - t3: t4 = t2 - t4
        t2 = x(i6) + x(i3): x(i3) = x(i6) - x(i3): x(i6) = x(i2) - t3
        x(i7) = x(i2) + t3: x(i4) = t2: t1 = x(i1) + t5: t5 = x(i1) - x(i5)
        x(i1) = t1: t1 = x(i5) + t4: x(i5) = x(i5) - t4: t4 = t1
    NEXT I
    js = 2 * id - n2: id = 4 * id: IF js < n THEN GOTO 36
    NEXT J%
    NEXT K%
END SUB

SUB.states (rd0, rg, divs, NP) STATIC
DIM sum(5)
LOCATE 13, 45: PRINT "Please wait ........."
' statistical analysis
'--- set the boundary & mid-point x-values
inc = (2 * rg) / divs: sdr(1) = 0
FOR I = 2 TO divs + 1
    sdr(I) = sdr(1 - 1) + inc: xx(I - 1) = (sdr(I) + sdr(1 - 1)) / 2
NEXT I
'--- start the statistical analysis
sumrms = 0: FOR I = 1 TO 5: sum(I) = 0: NEXT I
FOR I = 1 TO NPs: sumrms = sumrms + rol(I) * :rk(I): NEXT I
rmsrd = SQR(sumrms / NPs)
'--- grouping
FOR I = 1 TO divs: yy(I) = 0: NEXT I: crg = 0
FOR I = 1 TO NPs: xy = INT((rk(I) + rg) / inc)
  IF xy < 0 OR xy > divs THEN crg = crg + 1
  IF xy <= 0 THEN xy = 1
  IF xy > divs THEN xy = divs
  yy(xy) = yy(xy) + 1: NEXT I
IF crg <> 0 THEN LOCATE 13, 45: PRINT "Number of point out of range"; crg
FOR I = 1 TO divs
  sum(I) = sum(I) + yy(I): sum(2) = sum(2) + xx(I) * yy(I)
  sum(3) = sum(3) + yy(I) * yy(I): NEXT I
rmsfd = SQR(sum(3)/divs): mean=sum(2)/sum(1): sum(2)=0: sum(3)=0
FOR I = 1 TO divs
dx=xx(I)/mean: FOR J=2 TO 4: sum(J) = sum(J) + dx ^ J * yy(I): NEXT I
NEXT I
FOR I = 2 TO 4: sum(I) = sum(I) / sum(1): NEXT I
std = SQR(sum(2)): sk = sum(3) / std ^ 3: kur = sum(4) / std ^ 4
'PRINT mean, std, sk, kur, rmsrd, rmsfd
mean = mean - rg
END SUB

A.6. PLOTTING

` 1  GENERAL PLOTTING PROGRAM  8/8/91 1`

* OPTION BASE 1
DECLARE SUB winbox (px1, py1, px2, py2)
DECLARE SUB CENSTR (row, STRGS)
DECLARE SUB plot (x0, y0, np)
DECLARE SUB ploter (x0, y0, np)
DIM SHARED n,p,g%,SBOLS(10),dset$,$TRPLOTS, OFFILE, ijk%, overlay$ 
DIM SHARED ibeta%, iberr%, ibent%
DIM SHARED ploter$,.xx,.ys,GT$.x1,.yl,.x2,.y2,.ngraph,.ss,.lts, LLS, LB$ 
' SYDYNAMIC
DIM SHARED gst%(10), icc, sb%, cb%, gstl%(10), GLINE%(10)
DIM SHARED XMIN,MAX,ymin,ymax,xdiv,ydiv,a,b,x7,x8,y7,y8, yfact
DIM SHARED NAMES(70)
  SBOLS(1) = "N3 NF3 NG3 NH3": SBOLS(2) = "NU3 NL3 ND3 NR3"
  SBOLS(3) = "BH2 R4 D4 U4 BF2": SBOLS(4) = "BNU0"
* === Select a graphic card
CLS : LOCATE 1, 2: PRINT STRINGS(78, "**");
FOR i=2 TO 24
LOCATE i:2: PRINT "**": LOCATE i:79: PRINT "**": NEXT i
LOCATE 25, 2: PRINT STRINGS(78, "**");
STRGS = "<<< GENERAL PLOTTING PROGRAM >>>": CALL CENSTR(3, STRGS)
STRGS = "BY: THOMAS LAU": CALL CENSTR(5, STRGS)
STRGS = "DATED : August 8, 1991";
CALL CENSTR(6, STRGS)
STRGS = "UNIVERSITY OF WINDSOR";
CALL CENSTR(7, STRGS)
LOCATE 9, 2: PRINT STRINGS(78, "*");
LOCATE 12, 28: PRINT "Graphic card selection: ";
LOCATE 13, 28: PRINT "----------------------";
LOCATE 15, 28: PRINT "Hercules graphic card ?";
LOCATE 16, 28: PRINT "Color graphic card (CGA)?";
LOCATE 17, 28: PRINT "EGA ?";
LOCATE 18, 28: PRINT "None ?"

lsp3: LOCATE 20, 28: INPUT "Selection (1/2/3/4) ": , gssel$ 
    gssel$ = VAL(gssel$)
    IF gssel$ < 1 OR gssel$ > 4 THEN GOTO lsp3
    IF gssel$ = 4 THEN GOTO ENDOFPROG
    cb% = 1
    IF gssel$ = 1 THEN pg% = 3
    IF gssel$ = 2 THEN pg% = 2
    IF gssel$ = 3 THEN pg% = 9: cb% = 2

Restart:
CLS:VIEW PRINT 1 TO 25:GOSUB LOGO: LINE (10, 5)-(490, 445), 0, BF
LOCATE 6, 5: PRINT "SELECTION OF DATA"
LOCATE 8, 3: PRINT "1. General data [NP,NC],[x1,y1],.. ?"
LOCATE 9, 3: PRINT "2. Raw data [NP] [y1,y2,...] ?"
del1: LOCATE 13, 3: INPUT "Selection (1/2/3/4) ": , dsel$ 
    IF dsel$ = "Q" THEN GOTO ENDOFPROG
    IF dsel$ < "1" OR dsel$ > "4" THEN GOTO del1

IF dsel$ = "1" THEN
    LINE (10, 5)-(490, 445), 0, BF
    LOCATE 6, 5: PRINT "GENERAL DATA :
    LOCATE 8, 5: PRINT "1. Statistical data ?"
    LOCATE 9, 5: PRINT "2. Statistical results ?"
    LOCATE 10, 5: PRINT "3. Bandpass RMS ?"
    LOCATE 11, 5: PRINT "4. Others ?"
    LOCATE 13, 5: INPUT "Selection (1/2/3/4) ", dsel$ 
    IF dsel$ = "Q" THEN GOTO Restart

END IF
'
— Define filenames and their location
LINE (510, 5)-(490, 445), 0, BF
FILENAME:
    IF dsel$ = "1" OR dsel$ = "2" THEN
    LSP11: LOCATE 6, 43: INPUT "Drive (a:b:c: or path) ": ; DRS
    lsp10: LOCATE 7, 43: INPUT "Satisfy (y/n) ": , as$; as$ = UCASES(as$)
    IF as$ = "Q" THEN GOTO Restart
    IF NOT (as$ = "Y" OR as$ = "N") THEN GOTO lsp10
    IF as$ = "N" THEN GOTO LSP11
ELSE
    lsp7: LOCATE 5, 43: INPUT "Filename (PREFIX) ": ; NAMS
    LOCATE 6, 43: INPUT "Drive (a:b:c: or path) ": ; DRS
    lsp6: LOCATE 7, 43: INPUT "Satisfy (y/n) ": , as$ 
    as$ = UCASES(as$)
    IF as$ = "Q" THEN GOTO Restart
    IF NOT (as$ = "Y" OR as$ = "N") THEN GOTO lsp6
    IF as$ = "N" THEN GOTO lsp7
END IF
II = 1: ST = 9: LOCATE 7, 43: PRINT SPACES(25)
IF dsel$ = "$" OR dsel$ = "2" THEN
SP4: LOCATE 7, 43: PRINT "NAME ": II; SPACES(15)
    LOCATE 7, 53: INPUT NAMES(II)
    IF NAMES(II) = "$999" THEN GOTO SP11
ELSE
SP10: LOCATE 7, 45: PRINT "HOLE ": II; SPACES(15)
    LOCATE 7, 55: INPUT ": HOLE$ 
    IF HOLE$ = "$999" THEN GOTO SP11
    IF LEN(HOLE$) = 1 THEN HOLE$ = "0" + HOLE$
    NAMES(II) = NAMES + HOLE$
END IF
III = (II - 1) MOD 10
IF dsel$ = "$" THEN
    LOCATE ST + III, 43: PRINT "FILE NAME ": II; NAMES(II)
ELSE
    LOCATE ST + III, 45: PRINT "HOLE ": II; " FROM FILE ": NAMES(II)
END IF
II = II + 1: IF dsel$ = "$" THEN GOTO SP4 ELSE GOTO SP10
SP11: NFILE = II - 1: IF NFILE = 0 THEN GOTO Rstart
ngraph = 0

MENU:
VIEW PRINT 1 TO 25: GOSUB LOGO: LINE (10, 5)-(490, 445), 0, BF
LOCATE 6, 15; PRINT "MAIN MENU": LOCATE 7, 13
PRINT "************
LOCATE 10, 7: PRINT "1. PLOTTING (SCREEN ") ?"
LOCATE 11, 7: PRINT "2. PLOTTING (PLOTTER ) ?"
LOCATE 12, 7: PRINT "3. VIEW PLOT ?"
LOCATE 13, 7: PRINT "4. RESTART ?"
LOCATE 14, 7: PRINT "5. QUIT ?"
rent: LOCATE *16, 7: INPUT "selection (1-5) ": SELS: SEL = VAL(SELS)
IF SEL < 1 OR SEL > 5 THEN GOTO rent
IF SEL = 5 THEN GOTO ENDOPROG
IF SEL = 4 THEN GOTO Rstart
IF SEL = 3 THEN
    IF ngraph = 0 THEN
        CALL windbox(20, 20, 980, 140)
        STRGS = "No plots available. Go back and pick Plotting": CALL CENSSTR(21, STRGS)
        STRGS = "Press 'ENTER' to go back ...": CALL CENSSTR(23, STRGS)
lkp3: IF INKEYS <> CHR$(13) THEN GOTO lkp3
            LINE (20, 20)-(980, 140), 0, BF: PUT (20, 20), gst1%
        ELSE
            GOSUB imgput
        END IF
    END IF
FOR jk% = 1 TO NFILE
' ---- Read data from file
OPEN DRS = NAMES(jk%) FOR INPUT AS #1
IF dsel$ = "1" THEN
    INPUT #1, np, NC
    REDIM X(np), y(np), XY(np, NC + 1)
    STROW% = 1
    IF dsel$ = "3" THEN
STROW% = 3
FOR i%= 1 TO 2: FOR j%= 1 TO NC: INPUT #1, XY(i%, j%)
NEXT j%; NEXT i%
FOR i%=STROW% TO np: FOR j%=1 TO NC + 1: INPUT #1, XY(i%, j%)
NEXT j%; NEXT i%
IF dsel1$ = "3" THEN np = np - STROW% + 1
ELSE
FOR i%=STROW% TO np: FOR j%=1 TO NC: INPUT #1, XY(i%, j%); NEXT j%; NEXT i%
END IF
ELSEIF dsel1$ = "2" THEN
NC = 1
INPUT #1, np
REDIM y(np)
FOR i%= 1 TO np: INPUT #1, y(i%): NEXT i%
ELSEIF dsel1$ = "4" THEN
INPUT #1, np, XX7, XX8, XUNITS, YUNITS, YY7, YY8
REDIM y(np)
NC = 1: ydiff = YY8 - YY7
FOR i%= 1 TO np: INPUT #1, y(i%)
  y(i%) = INT((ydiff * y(i%) / 10000 + YY7) * 1000)
NEXT i%
ELSEIF dsel1$ = "3" THEN
INPUT #1, nsegas%, nsegb%
NSEG = 2: IF nsegas% = 0 OR nsegb% = 0 THEN NSFG = 1
IF NSEG = 2 THEN
  LOCATE 18, 7: PRINT "1. Trace A?"
  LOCATE 19, 7: PRINT "2. Trace B?"
SP2: LOCATE 21, 7: INPUT "Which Trace to Plot (1/2) ?:", TRPLOTS
  IF NOT (TRPLOTS = "1" OR TRPLOTS = "2") THEN GOTO SP2
END IF
IF nsegas% <> 0 THEN
  REDIM RDAS(nsegas%), (nsegas% * 2048)
FOR i% = 1 TO nsegas%: RDAS(i%) = INPUT$(4132, #1): NEXT i%
IF TRPLOTS = "1" THEN NSEG = nsegas%: GOSUB EXTINARY: GOTO SP15
ERASE RDAS
END IF
IF nsegb% <> 0 THEN
  REDIM RDBS(nsegb%), (nsegb% * 2048)
FOR i% = 1 TO nsegb%: RDBS(i%) = INPUT$(4132, #1): NEXT i%
IF TRPLOTS = "2" THEN NSEG = nsegb%: GOSUB EXTINARY: GOTO SP15
ERASE RDBS
END IF
END IF
SP15: CLOSE #1
SP22: LOCATE 18, 7: PRINT "1. Single plot ?"
  LOCATE 19, 7: PRINT "2. Overlay plot ?"
  LOCATE 20, 7: PRINT "3. Next data set ?"
  LOCATE 21, 7: INPUT "Choice (1/2/3) :", overlay$
  IF NOT (overlay$ = "1" OR overlay$ = "2" OR overlay$ = "3") THEN GOTO SP22
  FOR i% = 18 TO 21: LOCATE i%, 7: PRINT SPACES(30): NEXT i%
  IF overlay$ = "3" THEN GOTO SP21
  IF dsel$ = "1" THEN
    IF NC > 2 THEN
      CALL windbox(200, 50, 800, 200)
    END IF
  END IF
le1: LOCATE 17, 30: INPUT "X-axis: column# :, XX%
  LOCATE 19, 30: INPUT "Y-axis: column# :, YY%
CALL CENSTR(21, STRGS)

l2:
  INPUT "", ANS: ANS = UCASES(ANS)
  IF NOT (ANS = "R" OR ANS = "C") THEN GOTO l2
  IF ANS = "R" THEN GOTO l1
  LINE (200, 50)-(800, 200), 0, BF: PUT (200, 50), gs11%
END IF
GOSUB xyaxis
IF dseq$ = "1" THEN
  ssocc = 0
  FOR i% = 1 TO np: ssocc = ssocc + y(i%); NEXT i%
  FOR i% = 1 TO np: y(i%) = y(i%) / ssocc * 100; NEXT i%
END IF
END IF
IF dseq$ = "1" THEN
  x7 = 1E+07: x8 = -1E+07: y7 = 1E+07: y8 = -1E+07
  FOR i% = 1 TO np
    IF y(i%) > y8 THEN y8 = y(i%)
    IF y(i%) < y7 THEN y7 = y(i%)
    IF x(i%) > x8 THEN x8 = x(i%)
    IF x(i%) < x7 THEN x7 = x(i%)
    NEXT i%
ELSE
  x7 = 1: x8 = np: y7 = 1E+07: y8 = -1E+07
  FOR i% = 1 TO np
    IF y(i%) > y8 THEN y8 = y(i%)
    IF y(i%) < y7 THEN y7 = y(i%)
    NEXT i%
ENDIF
IF overlay$ = "2" AND ngraph <> 0 THEN GOTO sp12
LINE (510, 5)-(990, 445), 0, BF: LOCATE 5, 45: PRINT "Input plotting data:
LOCATE 7, 45:PRINT "Xmin, Xmax =": TAB(59); USING "####.##": x7; TAB(70); x8
LOCATE 8, 45:PRINT "Ymin, Ymax =": TAB(59); USING "####.##": y7; TAB(70); y8
xmino = x7: xmaxo = x8
lsp9: LOCATE 9, 45: INPUT "Xmin, Xmax =": XMIN, XmAX
LOCATE 10, 45: INPUT "Ymin, Ymax =": ymin, ymax
IF SEL = 2 THEN LOCATE 11, 45: INPUT "Xsep, Ysep =": xsep, ysep
  LOCATE 13, 45: INPUT "Satisfy (y/n) ?", ANS
  IF ANS = "q" OR ANS = "Q" THEN GOTO MENU
  IF ANS = "a" OR ANS = "N" THEN GOTO lsp9
sp12: 'START PLOTTING
IF SEL = 1 THEN
  IF overlay$ = "2" AND ngraph <> 0 THEN
    IF xmino < x7 OR xmaxo < x8 THEN
      PRINT "Mismatch in the x-axis"
      FOR i = 1 TO 5000: NEXT i
      GOTO SP22
    END IF
  END IF
ELSE
  ' normalized value between 0 to yfact
  IF jk% = 1 OR overlay$ = "1" THEN
    IF ABS(y7) > 100 OR ABS(y8) > 100 THEN yfact=1 ELSE yfact= 10
    END IF
    IF yfact = 10 THEN
      ydiff = (y8 - y7)
FOR inom% = 1 TO np
  y(nom%) = (y(nom%) - y7) / ydiff * yfact
NEXT inom%

IF y1 = y7 * yfact: y8 = y8 * yfact: ymin = ymin * yfact
  ymax = ymax * yfact: y5 = y5 * yfact
END IF
END IF

LOCATE 18, 45: PRINT "symbol ;"
LOCATE 19, 45: INPUT "(1,2,3,4,5,6-line) :", sb%
IF SEL = 1 THEN CALL plot(X0, y0, np); ngraph = ngraph + 1
IF SEL = 2 THEN CALL ploter(X0, y0, np); ngraph = ngraph + 1
GOTO SP2
SP21: NEXT ijk%
GOTO MENU
ENDOFPROG: CLS : END

* ===== BELOW ARE ALL THE SUBROUTINES USED =====

LOGO:
SCREEN pg%; WINDOW (0,0)-(1000,500): LINE (0,0)-(1000,500),0,BF
LINE (0,0)-(1000,500), B
STRGS = "<<< GENERAL PLOTTING PROGRAM >>>": CALL CENSTR(2, STRGS)
LINE (0,450)-(1000,450): LINE (500,0)-(500,450)
LOCATE 2, 72: PRINT "V10 HK"
RETURN

EXTBINARY: 'CONVERT BINARY VALUE TO DECIMAL [PROWLER]
FOR i% = 1 TO NSEG
  IF TRPLOTS = "1" THEN rd$ = RDAS(i%) ELSE rd$ = RDBS(i%)
  GOSUB ExtFFot
  LOCATE , 5: PRINT "Segment #" ; i%; " "; LEFTS(rd$, 55)
  ST = stloc + 32: ij% = (i% - 1) * 2048
  FOR j% = 1 TO 2048
    TEMPS = MIDS(rd$, ST, 2); aa = ASC(MIDS(TEMPS, 1, 1))
    ab = ASC(MIDS(TEMPS, 2, 1)); abc = (aa + ab * 256) - 32768
    y(f% + ij%) = (FFot(1) * abc + FFot(2)) * 1000: ST = ST + 2
  NEXT j%
  NEXT i%
  np = NSEG * 2048
RETURN

ExtFFot: 'extract factor, offset, time scale, & time index
stloc = 1
e11: IF MIDS(rd$, stloc, 1) = "" THEN stloc = stloc + 1: GOTO e11
stl = stloc: s0 = st1 + 8: st3 = st2 + 8: st4 = st3 + 8
FFot(1) = MIDS(rd$, st1, 8); FFot(2) = MIDS(rd$, st2, 8)
FFot(3) = MIDS(rd$, st3, 8); FFot(4) = MIDS(rd$, st4, 8)
FOR f% = 1 TO 3
  FOR f% = 1 TO 8
    tempww = ASC(MIDS(FFot(f%), f%, 1))
    IF tempww < 58 THEN tempww = tempww + 48
    IF tempww > 64 THEN tempww = tempww - 55
  NEXT f%
  NEXT f%
WW(i%) = tempww
NEXT i%
  w1 = 2 ^ (WW(1) * 16 + WW(2) * 128); WW$ = ""
FOR i% = 3 TO 8: GOSUB decbin: WW$ = WW$ + binstr$: NEXT i%
FOR i% = 1 TO 24
  IF i% = 1 THEN
    w234 = 2 ^ -1
  ELSE
    w234 = w234 + VAL(MID$(WW$, i%, 1)) * 2 ^ (-i%)
  END IF
NEXT i%
FFoN(i%) = w1 * w234
NEXT i%
RETURN

decbin:
  IF WW(i%) = 0 THEN binstr$ = "0000"
  IF WW(i%) = 1 THEN binstr$ = "0001"
  IF WW(i%) = 2 THEN binstr$ = "0010"
  IF WW(i%) = 3 THEN binstr$ = "0011"
  IF WW(i%) = 4 THEN binstr$ = "0100"
  IF WW(i%) = 5 THEN binstr$ = "0101"
  IF WW(i%) = 6 THEN binstr$ = "0110"
  IF WW(i%) = 7 THEN binstr$ = "0111"
  IF WW(i%) = 8 THEN binstr$ = "1000"
  IF WW(i%) = 9 THEN binstr$ = "1001"
RETURN

xyaxis:
  IF NC = 2 THEN
    FOR i% = 1 TO np: X(i%) = XY(i%, 1): y(i%) = XY(i%, 2): NEXT i%
    ELSE
    IF dscfl$ = "3" THEN STROW% = 3 ELSE STROW% = 1
    FOR i% = STROW% TO np
      X(i% - STROW% + 1) = XY(i%, XX%)
      y(i% - STROW% + 1) = XY(i%, YY%)
    NEXT i%
    IF dscfl$ = "3" THEN np = np - STROW% + 1
  END IF
RETURN

imgput:
SCREEN pg%: CLS : VIEW: WINDOW
TS = SPACES(75 - 5)
LOCATE 2, 3: PRINT CHRS(218); STRINGS(70, 196); CHRS(191)
FOR i = 3 TO 22
  LOCATE 1, 3: PRINT CHRS(179); TS; CHRS(179)
NEXT i
LOCATE 23, 3: PRINT CHRS(192); STRINGS(70, 196); CHRS(217)
IF pg% = 2 THEN PUT (30, 50), got%
IF pg% = 9 THEN PUT (30, 95), got%
IF pg% = 5 THEN PUT (80, 95), got%
la3: IF INKEY$ <> CHRS(13) THEN GOTO la3
CLS
RETURN
REM :STATIC
SUB CENSTR (row, STRGS) STATIC
STRGS = LTRIM$(STRGS); STRGS = RTRIM$(STRGS); length = LEN(STRGS)
col = 40 - length / 2: LOCATE row, col: PRINT STRGS:
END SUB

SUB plot (X(), y0, np)
SCREEN pg%
IF overlay$ = "1" OR oggraph = 0 THEN
WINDOW (0, 0)-(500, 500): LINE (0, 0)-(500, 500), 0, BF: VIEW
END IF
IF pg% = 2 THEN VIEW (130, 15)-(532, 90)
IF pg% = 9 THEN VIEW (130, 30)-(532, 160)
IF pg% = 3 THEN VIEW (143, 20)-(605, 258)
IF pg% = 2 THEN
xrange = 630 - 50 + 1: yrange = 103 - 10 + 1
size=INT(xrange/8+1)*yrange*cb% / 2 + 4: REDIM gstr%(size)
SS = 4 * (95 - 10) * cb% / 2 + 4
ELSE IF pg% = 9 THEN
xrange = 630 - 50 + 1: yrange = 180 - 25 + 1
size=INT(xrange/8+1)*yrange * cb% + 4: REDIM gstr%(size)
SS = 4 * (180 - 25) * cb% / 2 + 4
ELSE
xrange = 610 - 100 + 1: yrange = 170 - 25 + 1
size=INT(xrange/8+1)*yrange * cb% / 2 + 4: REDIM gstr%(size)
SS = 4 * (258 - 20) * cb% / 2 + 4
END IF
REDim Gline%(SS), GLineu%(SS), GLineu%(SS)
IF overlay$ = "2" AND oggraph <> 0 THEN GOTO Plot!
LOCATE 12, 12: PRINT ymin: LOCATE 3, 12: PRINT ymax
LOCATE 13, 16: PRINT ymin: LOCATE 13, 65: PRINT ymax
WINDOW (0, 0)-(500, 500): LINE (0, 0)-(500, 500), 0, BF
LINE (0, 0)-(500, 500), , B
FOR i = 1 TO 5
FOR jy% = 0 TO 500 STEP 10: PSET (i * 100, jy%): NEXT jy%
FOR jx% = 1 TO 500 STEP 5: PSET (jx%, i * 100): NEXT jx%
NEXT i
Plot1: LB = 1: UB = np: UBFLAGS = "0": LBFLAGS = "0"
Y77 = ymin: Y88 = ymax: x7 = xmin: x8 = xmax

DATAPLOT:
IF LBFLAGS = "1" AND UBFLAGS = "1" THEN
IF LBL > UBR THEN TEMP = UBR: UBR = LBL: LBL = TEMP
LB = LBL: UB = UBR: LBL = 0: UBR = 0
IF REPlots$="1" THEN REPlots$ = "0": y7 = Y77: y8 = Y88: GOTO SP6
y7 = 1000000: y8 = -1000000!
FOR i% = LB TO UB
IF y(i%) < y7 THEN y7 = y(i%)
IF y(i%) > y8 THEN y8 = y(i%)
NEXT i%
SP6: LOCATE 18, 20:
PRINT "Ymin, Ymax =": TAB(32); USING "##.##": y7; TAB(50); y8
LOCATE 19, 5
PRINT Spaces$: LOCATE 19, 20: INPUT "Ymin, Ymax ":, ymin, ymax
IF dset$ = "1" THEN
XMIN = X(LB): XMAX = X(UB)
ELSE
   XMIN = LB; XMAX = UB
END IF
LOCATE 11, 11: PRINT SPACES(5); : LOCATE 3, 11: PRINT SPACES(5);
LOCATE 12.16: PRINT SPACES(10); LOCATE 12.64: PRINT SPACES(10);
LOCATE 11, 11: PRINT ymin; : LOCATE 3, 11: PRINT ymax;
LOCATE 12, 16: PRINT XMIN; : LOCATE 12, 64: PRINT XMAX;
WINDOW (0, 0)-(500, 500); LINE (0, 0)-(500, 500), 0, BF
LINE (0, 0)-(500, 500), B
FOR i = 1 TO 5
   FOR jy% = 0 TO 500 STEP 8: PSET (i * 100, jy%); NEXT jy%
   FOR jx% = 1 TO 500 STEP 5: PSET (jx%, i * 100); NEXT jx%
NEXT i
WINDOW (XMIN, ymin)-(XMAX, ymax)
GOTO SP1
END IF

WINDOW (XMIN, ymin)-(XMAX, ymax)

SP1:
PSET (XMIN, ymin)
FOR J% = LB TO UB
IF dsetS = "1" THEN
   IF sb% = 6 THEN
      LINE (X(J%), Y(J%))
   ELSEIF sb% = 5 THEN
      PSET (X(J%), Y(J%))
   ELSE
      PSET (X(J%), Y(J%)); DRAW SBOLS(sb%)
   END IF
ELSE
   IF sb% = 6 THEN
      LINE (J%, Y(J%))
   ELSEIF sb% = 5 THEN
      PSET (J%, Y(J%))
   ELSE
      PSET (J%, Y(J%)); DRAW SBOLS(sb%)
   END IF
END IF
END IF
NEXT J%

LBFLAGS = "0"; UBFLAGS = "0"
LOCATE 15.20: PRINT "X value :"; LOCATE 15.45: PRINT "Y value :";
LOCATE 23.20: PRINT "1=>(R/2) 2=>(R/4) 3=>(R/8) 0=>(1) 9=> EXIT"
XX = INT((UB - LB) / 2) + 1; inxx = XX; inx = XX
LI:
IF dsetS = "1" THEN
   XXX = X(XX + LB)
ELSE
   XXX = INT(XX + LB)
END IF
YXX = y(XX + LB)
GET YXX, ymin + .1 * ymin)-(XXX, ymax - .1 * ymax), GLINE%
LINE (XXX, ymin + .1 * ymin)-(XXX, ymax - .1 * ymax), 7
LOCATE 15.29: PRINT SPACES(15); LOCATE 15.54: PRINT SPACES(15);
LOCATE 15.29: PRINT XXX; : LOCATE 15.54: PRINT YXX;
LL1: DO
  CHAR$ = INKEYS
  LOOP WHILE CHAR$ = ""
  IF LEN(CHAR$) < 2 THEN
    CHAR$ = UCASE$(CHAR$)
    IF CHAR$ = "9" THEN GOTO LLOUT
    IF CHAR$ = "1" THEN inx = inxx / 2
    IF CHAR$ = "2" THEN inx = inxx / 4
    IF CHAR$ = "3" THEN inx = inxx / 8
    IF CHAR$ = "0" THEN inx = 1
  IF CHAR$ = "L" AND LBL <= INT(XX + LB) THEN
    IF LBFLAGS = "1" THEN
      LINE (LBL, ymin + .1 * ymin)-(LBL, ymax - .1 * ymax), 0
      PUT (LBL, ymin + .1 * ymin), GLINE%
    END IF
    LBL = INT(XX + LB); LBFLAGS = "1"
    GET (LBL, ymin + .1 * ymin)-(LBL, ymax - .1 * ymax), GLINE%
    LINE (LBL, ymin + .1 * ymin)-(LBL, ymax - .1 * ymax), 10
    GET (LBL, ymin + .1 * ymin)-(LBL, ymax - .1 * ymax), GLINE%
  END IF
  IF CHAR$ = "R" AND UBR <= INT(XX + LB) THEN
    IF UBFLAGS = "1" THEN
      LINE (UBR, ymin + .1 * ymin)-(UBR, ymax - .1 * ymax), 0
      PUT (UBR, ymin + .1 * ymin), GLINE%
    END IF
    UBR = INT(XX + LB); UBFLAGS = "1"
    GET (UBR, ymin + .1 * ymin)-(UBR, ymax - .1 * ymax), GLINE%
    LINE (UBR, ymin + .1 * ymin)-(UBR, ymax - .1 * ymax), 10
    GET (UBR, ymin + .1 * ymin)-(UBR, ymax - .1 * ymax), GLINE%
  END IF
  IF CHAR$="5" THEN
    LBL=1: UBR=up: LBFLAGS="1": UBFLAGS="1": REPLOTS="1"
  END IF
  IF LBFLAGS = "1" AND UBFLAGS = "1" THEN
    IF (UBR - LBL) <= 0 THEN
      GOTO DATAPLOT
    ELSE
      LOCATE 20, 25: PRINT "NO RANGE WAS SELECTED ..."
      LBFLAGS = "0": UBFLAGS = "0": XXX = LBL
      PUT (XXX, ymin + .1 * ymin), GLINE%
      sp7: IF INKEYS <> CHR$(13) THEN GOTO sp7
      LOCATE 20, 25: PRINT SPACES(50)
      GOTO LL
    END IF
  END IF
  GOTO LL1
ELSE
  ch$ = RIGHTS(CHARS, 1)
  IF ch$ = CHR$(77) THEN XX = XX + inx
  IF ch$ = CHR$(75) THEN XX = XX - inx
  XX = INT(XX)
  IF (XX + LB) <= LB THEN XX = 0
  IF (XX + LB) >= UB THEN XX = INT(UB - LB)
  LINE (XXX, ymin + .1 * ymin)-(XXX, ymax - .1 * ymax), 0
  PUT (XXX, ymin + .1 * ymin), GLINE%
  GOTO LL
LLOUT:

WINDOW: VIEW
IF pg% = 2 THEN GET (50, 10)-(630, 103), gts%
IF pg% = 9 THEN GET (50, 25)-(630, 180), gts%
IF pg% = 3 THEN GET (100, 25)-(610, 170), gts%
END IF
IF jk% = NFILE THEN ERASE GLINE%, GLINEL%, GLINER%
END SUB

SUB plotter (XO, yo, np)
WRTS = "": NPP% = 512
IF jk% = 1 THEN
OPEN "TEMPIMG" FOR OUTPUT AS #3
ELSE
OPEN "TEMPIMG" FOR APPEND AS #3
END IF
IF jk% = 1 THEN
IF np > NPP% THEN
NSEG% = INT(np / NPP%)
IF (np / NPP%) <> NSEG% THEN
NSEG% = NSEG% + 1
END IF
WRITE #3, NSEG% * NFILE
ELSE
WRITE #3, NFILE
END IF
END IF
END IF
IF overlay$ = "2" AND ngraph <> 0 THEN GOTO I.PLOT
CLS: LOCATE 2, 15: PRINT "Graph type :"
LOCATE 3, 17: PRINT "1). Vertical ?"
LOCATE 4, 17: PRINT "2). Horizontal ?"
LSP20: LOCATE 5, 15: INPUT "** Selection (1/2) :", GTS
IF NOT (GTS = "1" OR GTS = "2") THEN GOTO LSP20
LOCATE 7, 15: PRINT "X label :", LBS
LOCATE 8, 15: PRINT "Y label :", LLS
LOCATE 9, 15: PRINT "Title :", LTS
LSP21: LOCATE 11, 15
INPUT "Satisfy (y/n) :", ANS: ANS = UCASES(ANS)
IF NOT (ANS = "Y" OR ANS = "N") THEN GOTO LSP21
IF ANS = "Y" THEN GOTO LSP22
LOCATE 7, 15: INPUT "X label :", LBS
LOCATE 8, 15: INPUT "Y label :", LLS
LOCATE 9, 15: INPUT "Title :", LTS
GOTO LSP21
LSP22: CX = LEN(LBS) / 2: CY = LEN(LLS) / 2
IF GTS = "2" THEN GOTO LSP23
LSP23: LOCATE 13, 15: INPUT "p1 (x,y) :", x1, y1
LOCATE 14, 15: INPUT "p2 (x,y) :", x2, y2
LSP24: LOCATE 15, 15
INPUT "Satisfy (y/n) :", ANS: ANS = UCASES(ANS)
IF NOT (ANS = "Y" OR ANS = "N") THEN GOTO LSP24
IF ANS = "N" THEN GOTO LSP25
LSP25: 'Real plotting routine start here
IF GTS = "1" THEN
WRTS = WRTS+"Yo90;ip;iwp;sp1;VS20;ip"+STR$(x1)+".","+STR$(y1)+":"
WRTS = WRTS + STRS(x2) + "." + STRS(y2)
ELSE
WRTS = WRTS + "r0;insp1;VS20;ip2300.000.8000.6100"
END IF
END IF
WRTS = WRTS + "se+STRS(XMIN)+","+STRS(XMAX)+","+STRS(ymin)
WRTS = WRTS + "," + STRS(ymax)
WRTS = WRTS + "s0.2.0.28;11.5.0;"
WRTS = WRTS + "pu+STRS(XMIN) + "," + STRS(ymin) + ":pS_"
+ STRS(YMAX) + "," + STRS(YMIN) + ",";
WRTS = WRTS + STRS(XMAX)+"," + STRS(YMAX)+"," + STRS(YMIN) + ",";
WRTS = WRTS + STRS(YMAX)+"," + STRS(YMIN) + "," + STRS(XMIN)+ ",";
FOR i = XMIN TO XMAX STEP xs
WRTS = WRTS + "pa+STRS(i) + "," + STRS(YMIN) + ",xt"
DX = LEN(STRS(i)) / 2
WRTS = WRTS + "cp" + STRS(DX) + ",-1.2;lb" + STRS(i) + CHR$(3)
NEXT i
FOR y = ymin TO ymax STEP ys
IF yfact = 10 THEN iy = INT(y / yfact) * 1000 / 1000 ELSE iy = y
WRTS = WRTS + "pa+STRS(YMIN) + "," + STRS(y) + ",yt"
IF iy <= 1 THEN WRTS = WRTS + "cp-5.0-25;lb" + STRS(y) + CHR$(3): GOTO i14
IF y < 0 AND ABS(y) > 9999 THEN WRTS = WRTS + "cp-7.0-25;lb" + STRS(y) + CHR$(3): GOTO i14
IF y < 0 AND ABS(y) > 999 THEN WRTS = WRTS + "cp-6.0-25;lb" + STRS(y) + CHR$(3): GOTO i14
IF y > 0 AND ABS(y) > 999 THEN WRTS = WRTS + "cp-6.0-25;lb" + STRS(y) + CHR$(3): GOTO i14
IF ABS(y) < 100 THEN WRTS = WRTS + "cp-4.0-25;lb" + STRS(y) + CHR$(3): GOTO i14
IF ABS(y) > 99 THEN WRTS = WRTS + "cp-5.0-25;lb" + STRS(y) + CHR$(3)
i14: NEXT y
WRTS = WRTS + "pa+STRS(XMIN) + "," + STRS(ymin + ymax) / 2 + "s0.2.0.3;di0.1;cp" + STRS(-CY) + ",3"
WRTS = WRTS + "lb+LLS+CHR$(3): CX = LEN(LLS) / 2"
WRTS = WRTS + "di+pa+STRS(XMIN+XMAX)/2","+STRS(YMIN) + "s0.2.0.3;cp" + STRS(-CX)+",-2.5"
WRTS = WRTS + "lb+LBS+CHR$(3): CX = LEN(LBS) / 2"
WRTS = WRTS + "pa+STRS(XMIN+XMAX)/2","+STRS(YMAX) + "cp" + STRS(-CX)+",2"
WRTS = WRTS + "lb+LTS+CHR$(3)
IPLTS: *plotting
LOCATE 17. 20: PRINT "wait............"; ijk%
WRTS = WRTS + "PA+STRS(XMIN) + "," + STRS(ymin)
IF s% = 6 THEN WRTS = WRTS + ":Pd_"
IF yfact = 10 THEN
y7 = y7 / yfact: y8 = y8 / yfact: ydiff = y8 - y7
END IF
FOR x = 1 TO np
IF yfact = 10 THEN y%(i) = (y7 + (y%(i) * ydiff / yfact)) * 10
y%(i) = INT(y%(i) * 1000) / 1000
IF dysel$ = "1" THEN
IF X%(i) < XMIN OR X%(i) >= XMAX THEN GOTO i31
IF y%(i) <= ymin OR y%(i) >= ymax THEN GOTO i31
ELSE
IF (y%(i) <= ymin) OR (y%(i) >= ymax THEN
IF s% = 6 THEN
IF y%(i) <= ymin THEN y%(i) = ymin
IF y%(i) >= ymax THEN y%(i) = ymax
GOTO i47
ELSE
GOTO i31
END IF
END IF
END IF
I47:
IF dselS = "1" THEN
IF sb% = 6 THEN
  WRTS = WRTS + "ps" + STRS(x(i%)) + ":" + STRS(y(i%))
ELSE
  WRTS = WRTS + "ps" + STRS(x(i%)) + ":" + STRS(y(i%))
  COSUB SUBSYM
END IF
ELSE
IF sb% = 6 THEN
  WRTS = WRTS + "PA" + STRS(i%) + ":" + STRS(y(i%))
ELSE
  WRTS = WRTS + "ps" + STRS(i%) + ":" + STRS(y(i%))
  COSUB SUBSYM
END IF
END IF
IF (i% MOD NPP%) = 0 AND i% <= np THEN
  WRITE #3, WRTS
  WRTS = ""
END IF
I31: NEXT i%
WRTS = WRTS + ":PU;"
IF ijk% = NFILE THEN
  WRTS = WRTS + "SP;PA" + STRS(XMAX) + ":" + STRS(YMAX) + ":PU;"
END IF
WRITE #3, WRTS
CLOSE #3, GOTO IESUB
SUBSYM:
ON sb% GOTO i22, i24, i26, i28, i30
i22: WRTS = WRTS + "uc-3.299,6.0,-3.4,-4.4;": GOTO I40
i24: WRTS = WRTS + "uc-2.299,4.0,0.4,-4.0,0.4;": GOTO I40
i26: WRTS = WRTS + "uc0.0,3.99,6.0,-9.3,-3.99,6.0;": GOTO I40
i28: WRTS = WRTS + "uc0.0,3.993,3.3,-3.3,-3.3,3;": GOTO I40
i30: WRTS = WRTS + ".
I40: RETURN
IESUB:
IF ijk% = NFILE THEN
PRINT "1. PLOT ?"
PRINT "2. SAVE PLOT FILE ?"
PRINT "3. RETURN ?"
I41: INPUT "SELECTION (1/2/3) ?", SELS
IF NOT (SELS = "1" OR SELS = "2" OR SELS = "3") THEN GOTO I41
IF SELS = "3" THEN GOTO I42
IF SELS = "2" THEN
  INPUT "FILENAME (SAVE IMAGE) ?", NMS
  INPUT "DRIVE (A/...)?", DDS
  OPEN DDS + NMS FOR OUTPUT AS #2
END IF
OPEN "TEMPIMG" FOR INPUT AS #3
INPUT #3, NFILE
FOR JK% = 1 TO NFILE
  INPUT #3, WRTS
END IF
INPUT "PRESS ANY KEY TO PLOT...", WWS
BDNAMES = "GPIB0": CALL ibfind(BDNAMES, ploter%)
CALL ibsic(pltcr%); V% = 1: CALL ibstr(pltcr%, V%)
CMDS = "@S": CALL IBCMD(pltcr%, CMDS)
CALL IBWRTA(pltcr%, WRTS)
mask% = &H4100: CALL ibwait(pltcr%, mask%)
INPUT "PRESS ANY KEY FOR NEXT PLOT ": WW$ CMDS = ".?": CALL IBCMD(pltcr%, CMDS)
ELSE
IF JK% = 1 THEN WRITE #2, NFILE
WRITE #2, WRTS
END IF
NEXT JK%
CLOSE #3: CLOSE #2: GOTO 141
END IF
142: END SUB

SUB windbox (px1, py1, px2, py2) STATIC
VIEW: WINDOW (0, 0)-(1000, 500)
pxr = px2 - px1 + 1: pyr = py2 - py1 + 1
REDIM gst1%/(INT(px / 8 + 1) * py * er% / 2 + 4)
GET (px1, py1)-(px2, py2), gst1%
LINE (px1, py1)-(px2, py2), 0, BF
LINE (px1, py1)-(px2, py2), B
END SUB

A.7. TOOLLIFE

*========================================================================*
* 1 Tool life prediction equations  Sept 8, 1991    *
*========================================================================*

DIM xyperf(200, 10) 'array to store drill performance
DIM xy(200, 10), x(200), y(200), a(10), 10, b(10), p(10)
CLS
OPEN "xyperf.dat" FOR INPUT AS #1
INPUT #1, nr, nc
FOR ii = 1 TO nr
FOR j = 1 TO nc: INPUT #1, xyperf(ii, j); NEXT j
FOR j = 1 TO nc: PRINT xyperf(ii, j); : NEXT j: PRINT
NEXT ii
CLOSE #1

usdef: 'user defined routine (least square)
    L - tool life in term of Hole#
    V - operating speed [RPM]
    F - Feed rate [in/Rev]
    d - drill size [mm]
    a0,a1,a2,a3 - coefficient constants to be determined

CLS
LOCATE 5, 5: PRINT "1. Harrison M400 
LOCATE 6, 5: PRINT "2. M300 
LOCATE 7, 5: PRINT "3. Master 2500 
LOCATE 8, 5: PRINT "4. Okuma LS 
LOCATE 9, 5: PRINT "5. Bridgeport 
LOCATE 10, 5: PRINT "6. Quit ?
LOCATE 12, 5: INPUT "Selection (1-6) ": mc$ IF mc$ = "6" THEN GOTO Endofpgm
IF mcs = "1" THEN mcs = "HarrisonM400"
IF mcs = "2" THEN mcs = "M300"
IF mcs = "3" THEN mcs = "Master2500"
IF mcs = "4" THEN mcs = "Okuma"
IF mcs = "5" THEN mcs = "Bridgeport"

s1: '====== L= a0+a1*F+a2+d+a3
n = 4
FOR i = 1 TO n: FOR j = 1 TO n: a(i, j) = 0: NEXT j: r(i) = 0: NEXT i
ic = 1
FOR i = 1 TO nr
IF mcs = xypeFS(i, 6) AND xypeFS(i, nc) <> "**" THEN
xy(ic, 1) = LOG(VAL(xypeFS(i, 3)))
xy(ic, 2) = LOG(VAL(xypeFS(i, 4)) * 25.4)
xy(ic, 3) = LOG(VAL(xypeFS(i, 2)))
xy(ic, 4) = LOG(VAL(xypeFS(i, 5)))
ic = ic + 1
END IF
NEXT i
np = ic - 1: a(1, 1) = np
FOR i = 1 TO np
a(1, 2) = a(1, 2) + xy(i, 1)
a(1, 3) = a(1, 3) + xy(i, 2)
a(1, 4) = a(1, 4) + xy(i, 3)
a(2, 2) = a(2, 2) + xy(i, 1) ^ 2
a(3, 3) = a(3, 3) + xy(i, 2) ^ 2
a(4, 4) = a(4, 4) + xy(i, 3) ^ 2
a(2, 3) = a(2, 3) + xy(i, 1) * xy(i, 2)
a(2, 4) = a(2, 4) + xy(i, 1) * xy(i, 3)
a(3, 4) = a(3, 4) + xy(i, 2) * xy(i, 3)
r(1) = r(1) + xy(i, 4)
r(2) = r(2) + xy(i, 4) * xy(i, 1)
r(3) = r(3) + xy(i, 4) * xy(i, 2)
r(4) = r(4) + xy(i, 4) * xy(i, 3)
NEXT i
a(2, 1) = a(1, 2): a(3, 1) = a(1, 3): a(4, 1) = a(1, 4)
a(2, 2) = a(2, 2): a(4, 2) = a(2, 4): a(4, 3) = a(3, 4)
GOSUB simcox
PRINT "a0 =", EXP(r(1)): PRINT "a1 =", r(2): PRINT "a2 =", r(3)
PRINT "a3 =", r(4): GOSUB oput

s2: '====== V^L^a0 = a1
n = 2
FOR i=1 TO n: FOR j=1 TO n: a(i, j)=0: NEXT j: r(i) = 0: NEXT i
ic = 1
FOR i = 1 TO nr
IF mcs = xypeFS(i, 6) AND xypeFS(i, nc) <> "**" THEN
xy(ic, 1) = LOG(VAL(xypeFS(i, 5)))
xy(ic, 2) = LOG(VAL(xypeFS(i, 5)))
ic = ic + 1
END IF
NEXT i
np = ic - 1: a(1, 1) = np
FOR i = 1 TO np
a(1, 2) = a(1, 2) + xy(i, 1)
a(2, 2) = a(2, 2) + xy(i, 1) ^ 2

r(1) = r(1) + xy(i, 2)
\n\n\nNEXT i
\n\ns(2, 1) = a(1, 2)
\n\n\nGOSUB simeqn
\n\nPRINT "s0 =", -v(2); PRINT "s1 =", EXP(v(1))
\n\nGOSUB oput: GOTO usdef
\n\nEndofpgm: END
\n\n\nsimeqn: IF n = 1 THEN v(1) = r(1) / a(1, 1): RETURN
\n\n1830 FOR k = 1 TO n - 1: i = k + 1: l = k
\n\n1860 IF ABS(a(i, k)) > ABS(a(l, k)) THEN l = i
\n\n1870 IF i < n THEN i = i + 1: GOTO 1860
\n\n1880 IF l = k THEN 1920
\n\n1890 FOR j = k TO n: q = a(j, k): a(j, k) = a(j, l): a(l, j) = q: NEXT
\n\n1910 q = r(k): r(k) = r(l): r(l) = q
\n\n1920 i = k + 1
\n\n1930 q = a(i, k) / a(k, k): a(i, k) = 0
\n\n1940 FOR j = k + 1 TO n: a(i, j) = a(i, j) - q * a(k, j): NEXT
\n\n1950 r(i) = r(i) - q * r(k): IF i < n THEN i = i + 1: GOTO 1930
\n\n1960 NEXT
\n\n1970 v(n) = r(n) / a(n, n): FOR i = n - 1 TO 1 STEP -1: q = 0:
\n\n1980 FOR j = i + 1 TO n
\n\n1990 q = q + a(i, j) * v(j): v(i) = (r(i) - q) / a(i, i): NEXT: NEXT
\n\n2000 RETURN
\n\n\noput:
\n\nus2: IF INKEYS <> CHRS(13) THEN GOTO us2
\n\nRETURN

A.8. EXPERT

*---------------------------------------------------------------*
* 1 ******* EXPERT SYSTEM ****** Sept 10, 1991 1*
*---------------------------------------------------------------*
* For Straight shank, jobber length, 2-flutes HSS twist drill
*
'SDYNAMIC
DECLARE SUB drilllength (drillsize!, overlen!, flutelen!)
DECLARE SUB ToolLifePredict (speed!, feed!, Depth!, Predicthole!)
DECLARE SUB recomVF(drillsize!,toolmat$,steeltype,Workcarbon,speed!),
feed)
DIM speed(2), feed, Depthofcut(2)
CLS
* >>>> design module <<<<<
\n\nr1 = 2: C1 = 5: r2 = 20: c2 = 40
\ntitles = "Drill information ": GOSUB wcree
\n\nLOCATE 4, 8: INPUT "Drill size [mm] ":, drillsize
\n\nLOCATE 5, 8: INPUT "Drill material [HSS] ":, toolmat$
\n\nLOCATE 6, 8: INPUT "Drill manufacturer":, drillman$
\n\nCALL drilllength(drillsize, overlen, flutelen)
\n\nLOCATE 7, 8: PRINT "Overall length [mm] ":, overlen
\n\nLOCATE 8, 8: PRINT "Flute length [mm] ":, flutelen
\n\nLOCATE 9, 8: PRINT "Point angle [degree] ":, 118
\n\nLOCATE 10, 8: PRINT "Helix angle [degree] : 25-35"
LOCATE 12, 8: INPUT "Machine tool ":, mc$  
LOCATE 13, 8: INPUT "Drill Number ":, drillnumber  
LOCATE 22, 8: INPUT "Press ENTER to continue "; z$  

CLS: r1 = 2: C1 = 5: r2 = 20: c2 = 40  
title$ = " Workpiece Information ": GOSUB wcreate  
LOCATE 4, 8: PRINT "1. Plain carbon steel ":"  
LOCATE 5, 8: PRINT "2. Alloy steel ":"  
LOCATE 6, 8: INPUT "Selection (1/2 )":, stectype  
LOCATE 8, 8: PRINT "Carbon content in the material ":"  
IF stectype = 1 THEN  
  LOCATE 9, 8: PRINT "1. to 0.25 C":"  
  LOCATE 10, 8: PRINT "2. to 0.50 C":"  
  LOCATE 11, 8: PRINT "3. to 0.90 C":"  
ELSE  
  LOCATE 9, 8: PRINT "1. Low carbon (0.12 - 0.25 )":"  
  LOCATE 10, 8: PRINT "2. Medium carbon (0.30-0.65 )":"  
END IF  
LOCATE 12, 8: INPUT "Selection ":, Workcarbon  
IF stectype = 1 THEN  
  Workmat$ = "Plain carbon steel"  
  IF Workcarbon = 1 THEN Workmat$ = Workmat$ + "(0.25 C) ":"  
  IF Workcarbon = 2 THEN Workmat$ = Workmat$ + "(0.50 C) ":"  
  IF Workcarbon = 3 THEN Workmat$ = Workmat$ + "(0.90 C)":"  
ELSEIF stectype = 2 THEN  
  Workmat$ = "Alloy steel"  
  IF Workcarbon = 1 THEN Workmat$ = Workmat$ + "(Low C)":"  
  IF Workcarbon = 1 THEN Workmat$ = Workmat$ + "(Medium C)":"  
END IF  
CALL recomVF(drillsize, toolmat$, stectype, Workcarbon, speed(), feed)  
FOR i = 1 TO 2: speed(i) = 318.31 * speed(i) / drillsize: NEXT i  

CLS: r1 = 2: C1 = 5: r2 = 20: c2 = 60  
title$ = " Operating conditions ": GOSUB wcreate  
IF speed(1) = speed(2) THEN  
  LOCATE 4, 8: PRINT "Recommended speed ":; speed(1)  
ELSE  
  LOCATE 4, 8: PRINT "Recommended speed ":; speed(1); ";; speed(2)  
END IF  
LOCATE 5, 8: PRINT "Recommended feed ":; feed  
LOCATE 8, 8: PRINT "Please enter actual ":"  
  LOCATE 10, 8: INPUT "Operating speed ":, speed  
LOCATE 11, 8: INPUT "Operating feed ":, feedrate  

CALL ToolLifePredict(speed, feedrate, Depth, Predicthole)  
LOCATE 14, 8: PRINT "Predicted number of ":"  
LOCATE 15, 10: PRINT "Hole drilled ":, Predicthole  
LOCATE 22, 8: INPUT "Press ENTER to continue "; z$  

lop2:  
**************  
* Assumptions:  
* 1. This system selects "standard deviation" as the descriptor.  
* 2. There are only two drilling states (Normal versus Unnormal).
This program will not simulate the process of monitoring, namely, capturing the time-amplitude signal the from Prowler digital oscilloscope or the frequency spectrum from the HP35660A FFT analyzer. Instead, the program will simulate the classification process, assuming that the vibration signals have been analyzed and the results are stored in a file called “Results” which is one of the many databases of this system.

c = 2
m = 1
 sel(1) = 4

>>> monitoring module <<<

>n = total number of hole drilled
x(i, j) = array used to store those descriptors values

OPEN “a:Results” FOR INPUT AS #1
INPUT #1, n, nc
REDIM u(c, 1), x(n, m + 2), tempxx(nc)
REDIM F(c, m), S(c)
FOR i = 1 TO n
FOR j = 1 TO nc: INPUT #1, tempxx(j): NEXT j
FOR k = 1 TO m: x(i, k) = tempxx(sel(k)): NEXT k
x(i, m + 1) = tempxx(nc): x(i, m + 2) = tempxx(1)
NEXT i
CLOSE #1

>>> Pattern/diagnosis module <<<

Assuming that the learned parameters are stored with the following format in a file called “Lparam”
field#1 - cluster center for “Normal” drilling
field#2 - cluster center for “Unnormal” drilling
field#3 - Mean value for “Normal” drilling
field#4 - standard deviation for “Normal” drilling
field#5 - Mean value for “Unnormal” drilling
field#6 - standard deviation for “Unnormal” drilling
field#7 and field#8 - coefficients of basic Taylor’s equation

OPEN “a:Lparam” FOR INPUT AS #1
FOR i = 1 TO 8: INPUT #1, param(i): NEXT i
CLOSE #1

REDIM v(c, m), ms(c, m), std(c, m)
v(1, 1) = param(1): v(1, 2) = param(2)
ms(1, 1) = param(3): ms(1, 2) = param(5)
std(1, 1) = param(4): std(1, 2) = param(6)

FOR ijk = 1 TO n
FOR j = 1 TO m + 2: xx(1, j) = x(ijk, j): NEXT j

* Fuzzy Clustering Algorithm
FOR j = 1 TO e
    bot = 0 : sumtop = 0
    FOR ii = 1 TO m
        sumtop = sumtop + (xx(1, ii) - v(j, ii))^2
    NEXT ii
    sumtop = SQR(sumtop)
FOR k = 1 TO c
  sumbot = 0
  FOR ii = 1 TO m
    sumbot = sumbot + (xx(1, ii) - v(k, ii))^2
  NEXT ii
  sumbot = SQRT(sumbot)
  IF sumtop = 0 AND sumbot = 0 THEN
    ss = 1
  ELSEIF sumbot = 0 THEN
    bot = 0; GOTO lop4
  ELSE
    ss = sumtop / sumbot
  END IF
  bot = bot + (ts)^2
NEXT k

lop4: IF bot = 0 THEN u(j, 1) = 0 ELSE u(j, 1) = 1 / bot
NEXT j

max = -1
FOR j = 1 TO c
  IF u(j, 1) > max THEN max = u(j, 1); state1 = j
NEXT j

* Fuzzy Relation algorithm
FOR i = 1 TO c
  FOR j = 1 TO m
    qj1 = 1 / (SQRT(2 * 3.141592) * std(i, j))
    F(i, j) = qj1 * EXP(-(xx(i, j) - ms(i, j))^2 / (2 * std(i, j)^2))
  NEXT j
  NEXT i

FOR i = 1 TO c: S(i) = 0; NEXT i
FOR i = 1 TO c
  FOR j = 1 TO m: S(i) = S(i) + F(i, j); NEXT j
NEXT i

temp = -1E+10
FOR i = 1 TO c
  IF S(i) > temp THEN state2 = i: temp = S(i)
NEXT i

* State1 & State2 are, respectively, the results of the classification
* from fuzzy clustering and fuzzy relation algorithms
* State1 = 1 => Normal drilling
* State1 = 2 => Unnormal drilling

PRINT "Fuzzy Clustering Algorithm, drilling state ="; USING "##"; state1
PRINT "Fuzzy Relation Algorithm, drilling state ="; USING "##"; state2

IF state1 = 2 AND state2 = 2 THEN
  PRINT "Tool replacement is necessary at this time 
  GOTO Update
END IF

NEXT ijk
Update:

' >>>> update & learning module <<<
'Two important tasks that are performed after tool change occurs,
'namely,
'1. Update the knowledge base (store all operating conditions, tool and
   * workplace, material, descriptors values, etc... in a file or database
   * called "Performat")
'2. Use reinforcement scheme to relearn the parameters used in the two
   * fuzzy algorithms and also the coefficients of the tool-life equation

' * = Bad drilling, "" = good drilling
drillcodeS = ""
Numberofhole = n
OPEN "aPerformat" FOR APPEND AS #1
PRINT #1, HoleNumber, drillsize, speed, feedrate, Numberofhole, mcS, WorkmatS, drillmanS, toolmatS, drillcodeS
CLOSE #1

'Note: New parameters are obtained from the programs "Cluster" and
"Relation", Coefficients of tool-life equations are obtained from
"Toollife". Assuming these new parameters and coefficients are stored
in a file called "Newparam".

' Use reinforcement scheme to relearn those parameters and coefficients
OPEN "aNewparam" FOR INPUT AS #1
FOR i = 1 TO 8: INPUT #1, newparam(i): NEXT i
CLOSE #1

alpha = .3  'Learning parameter
FOR k = 1 TO 8
param(k) = alpha * newparam(k) + (1 - alpha) * param(k)
NEXT k

OPEN "aLparam" FOR OUTPUT AS #1
FOR j = 1 TO 8: PRINT #1, "####.##### ": param(j): NEXT j
CLOSE #1

Endofprog: END

wcreate:
s$ = SPACES((c2 - C1) - 1)
LOCATE r1, C1: PRINT CHR$(218); STRINGS((c2 - C1) - 1, 196); CHR$(191)
FOR x = r1 + 1 TO r2 - 1
LOCATE x, C1: PRINT CHR$(179); s$; CHR$(179)
NEXT x
LOCATE r2, C1: PRINT CHR$(192); STRINGS((c2 - C1) - 1, 196); CHR$(217)
IF LEN(title$) <> 0 THEN
LOCATE r1, ((c2 - C1) - LEN(title$)) / 2 + C1: PRINT title$
END IF
RETURN

REM $STATIC
SUB drilllength (drillsize, overlen, flutelen) STATIC
IF drillsize < .15 OR drillsize > 17.5 THEN
   CLS : LOCATE 5, 5: PRINT "Drill size ".; drillsize: " is not available..."
   LOCATE 20, 5: INPUT "Press ENTER to continue ...", z$ END IF

OPEN "adrillen.dat" FOR INPUT AS #1
Dlop1: INPUT #1, Drize, Olen, Flen
IF Drize = drillsize THEN
  ovelen = Olen
  flutelen = Flen
  GOTO Dlop2
ELSE
  GOTO Dlop1
END IF
Dlop2: CLOSE #1
END SUB

SUB recomVF (drillsize, toolmatS, stecltype, Workcarbon,speed(), feed) STATIC
IF stecltype = 1 THEN
  IF Workcarbon = 1 THEN speed(1) = 24; speed(2) = 24
  IF Workcarbon = 2 THEN speed(1) = 20; speed(2) = 20
  IF Workcarbon = 3 THEN speed(1) = 17; speed(2) = 17
  feed = .057 + .011 * drillsize
ELSE
  IF Workcarbon = 1 THEN
    speed(1) = 21; speed(2) = 21
    feed = .025 + .018 * drillsize
  ELSE
    speed(1) = 15; speed(2) = 18
    feed = .024 + .01 * drillsize
  END IF
END IF
IF drillsize = 3.2 THEN Depthofcut(1) = .002: Depthofcut(2) = .006
IF drillsize = 6.4 THEN Depthofcut(1) = .004: Depthofcut(2) = .01
END SUB

SUB ToolLifePredict (speed, feed, Depth, Predicthole) STATIC
OPEN "aLparam" FOR INPUT AS #1
INPUT #1, ct, cun, mct, mn, sidun, s0, a1
CLOSE #1
Predicthole = INT(EXP((LOG(a1 / speed) / s0)))
END SUB
APPENDIX B

KNOWLEDGE BASE
APPENDIX B

This appendix will provide a listing of the databases and the rulebases used in this research. More specifically, it includes the following:

1. Database called ‘Tool’.
2. Database called ‘Workpiece’.
3. Database called ‘Performance’.
4. Database called ‘Results’.

B.1. TOOL

This database, as shown in Table B.1, provides the overall and flute lengths for jobber length, high speed steel (HSS), two-flutes twist drill. Given the diameter of the drill bit, the program ‘Expert’ will open this database as an input, sequentially retrieve the data record by record, and match the first field in the record with the size given. The process will terminate if a match is found.

B.2. WORKPIECE

Since all the workpiece materials used are steel, only materials with the five grades shown in Table B.2 are considered. However, this database can be easily expanded to accommodate other type of materials without any restriction. The right side of the table shows the knowledge used to establish the rules needed to provide the recommended speed and feed rate. Feed rate is dependent on the diameter of the drill bit, as indicated
in Table B.3. Since only five feed rates corresponding to five drill sizes are provided, it is necessary to curve-fit these data so that any drill size in-between can have an estimated feed rate. The plot of the three feed rate curves, X, Y, and Z, versus drill size are shown in Figure B.1 and the equations of the curves are presented in Table B.4.

<table>
<thead>
<tr>
<th>Drill Size</th>
<th>Feed Rate (X)</th>
<th>Feed Rate (Y)</th>
<th>Feed Rate (Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15, 19.125</td>
<td>0.16, 19.125</td>
<td>0.17, 19.125</td>
<td>0.18, 19.125</td>
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<tr>
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<td>0.32, 19.500</td>
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<tr>
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<td>0.42, 22.500</td>
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<td>0.55, 28.500</td>
<td>0.60, 29.800</td>
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<td>0.75, 35.13</td>
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<td>0.95, 38.16</td>
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<td>6.20, 102.70</td>
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<tr>
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<td>6.80, 105.73</td>
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<td>7.80, 114.81</td>
<td>7.90, 114.81</td>
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<tr>
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</tr>
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<td>8.40, 127.87</td>
<td>8.75, 124.89</td>
<td>8.80, 124.89</td>
<td>8.90, 124.89</td>
</tr>
<tr>
<td>9.20, 127.92</td>
<td>9.50, 130.95</td>
<td>9.60, 130.95</td>
<td>9.70, 130.95</td>
</tr>
<tr>
<td>9.50, 130.95</td>
<td>9.80, 130.95</td>
<td>9.90, 130.95</td>
<td>10.00, 130.95</td>
</tr>
<tr>
<td>9.80, 130.95</td>
<td>10.10, 133.98</td>
<td>10.20, 133.98</td>
<td>10.30, 133.98</td>
</tr>
<tr>
<td>10.10, 133.98</td>
<td>10.30, 133.98</td>
<td>10.50, 137.100</td>
<td>10.60, 137.100</td>
</tr>
</tbody>
</table>

Table B.1 Database 'Tool'

Format of record:
(Drill Size, Overall length, Flute length)
### Table B.2 Database 'Workpiece'

<table>
<thead>
<tr>
<th>Material drilled</th>
<th>Peripheral speed, sfm (m/min)</th>
<th>Feed rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>steel, plain carbon, to 0.25 C, 125-175</td>
<td>24</td>
<td>Y</td>
</tr>
<tr>
<td>steel, plain carbon, to 0.50 C, 175-225</td>
<td>20</td>
<td>Y</td>
</tr>
<tr>
<td>steel, plain carbon, to 0.90 C, 175-225</td>
<td>17</td>
<td>Y</td>
</tr>
<tr>
<td>steel, alloy steel, 0.12-0.25 C, 175-225</td>
<td>21</td>
<td>Z</td>
</tr>
<tr>
<td>steel, alloy steel, 0.30-0.65 C, 175-225</td>
<td>15-18</td>
<td>X</td>
</tr>
</tbody>
</table>

### Table B.3 Recommended feed rates at various drill sizes

<table>
<thead>
<tr>
<th>Feed rate (mm/rev)</th>
<th>Drill diameter (mm)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.2</td>
<td>6.4</td>
<td>12.7</td>
<td>19.1</td>
<td>25.4</td>
</tr>
<tr>
<td>X</td>
<td>0.05</td>
<td>0.089</td>
<td>0.15</td>
<td>0.216</td>
<td>0.257</td>
</tr>
<tr>
<td>Y</td>
<td>0.08</td>
<td>0.13</td>
<td>0.20</td>
<td>0.267</td>
<td>0.317</td>
</tr>
<tr>
<td>Z</td>
<td>0.08</td>
<td>0.15</td>
<td>0.25</td>
<td>0.394</td>
<td>0.483</td>
</tr>
</tbody>
</table>

### Table B.4 Equations of the feed rate curves

<table>
<thead>
<tr>
<th>Feed rate (mm/rev)</th>
<th>Correlation coefficient (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
</tr>
<tr>
<td>X</td>
<td>0.024</td>
</tr>
<tr>
<td>Y</td>
<td>0.057</td>
</tr>
<tr>
<td>Z</td>
<td>0.026</td>
</tr>
</tbody>
</table>
B.3. PERFORMANCE

This database accumulates all the tool and workpiece information, tool-life, speed, feed rate, etc., when the machine-tool is in operation. The 'Performance' data for the five machine-tools used in this research are shown in Tables B.5 to B.9. The asterisk in the right most field of a record indicates that some problems were encountered during the drilling operation. The format of each record is defined as follows:

{Drill#, drill size, speed, feed rate, tool-life, machine-tool, workpiece material, drill manufacturer, drill material, flag}
### Table B.5 Performance of Harrison M400

<table>
<thead>
<tr>
<th>No.</th>
<th>Mach.</th>
<th>Feed</th>
<th>Depth of Cut</th>
<th>Tool Life</th>
<th>Tool Code</th>
<th>Tool Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.40</td>
<td>.400</td>
<td>.0.229</td>
<td>.90</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>2</td>
<td>6.40</td>
<td>.400</td>
<td>.0.178</td>
<td>.92</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>3</td>
<td>6.40</td>
<td>.500</td>
<td>.0.178</td>
<td>.47</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>4</td>
<td>6.40</td>
<td>.500</td>
<td>.0.160</td>
<td>.260</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>5</td>
<td>6.40</td>
<td>.100</td>
<td>.0.127</td>
<td>.40</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>6</td>
<td>6.40</td>
<td>.125</td>
<td>.0.127</td>
<td>.61</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>7</td>
<td>6.40</td>
<td>.125</td>
<td>.0.102</td>
<td>.68</td>
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<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
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<td>.0.102</td>
<td>.250</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>9</td>
<td>6.40</td>
<td>.125</td>
<td>.0.102</td>
<td>.90</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>10</td>
<td>6.40</td>
<td>.500</td>
<td>.0.160</td>
<td>.240</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>11</td>
<td>6.40</td>
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<td>.0.160</td>
<td>.255</td>
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<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
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<td>6.40</td>
<td>.500</td>
<td>.0.160</td>
<td>.182</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>13</td>
<td>6.40</td>
<td>.125</td>
<td>.0.127</td>
<td>.48</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>14</td>
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<td>.0.127</td>
<td>.100</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
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<td>.125</td>
<td>.0.127</td>
<td>.22</td>
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<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
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<td>.0.127</td>
<td>.36</td>
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<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
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<td>.144</td>
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<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
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<td>.100</td>
<td>.0.127</td>
<td>.173</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
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<td>.100</td>
<td>.0.127</td>
<td>.44</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>20</td>
<td>6.40</td>
<td>.160</td>
<td>.0.133</td>
<td>.142</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>21</td>
<td>6.40</td>
<td>.160</td>
<td>.0.178</td>
<td>.86</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>22</td>
<td>6.40</td>
<td>.200</td>
<td>.0.178</td>
<td>.94</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
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<td>.77</td>
<td>HarrisonM400</td>
<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
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<td>6.40</td>
<td>.200</td>
<td>.0.178</td>
<td>.158</td>
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<td>.D2 .Osborne .HSS.</td>
</tr>
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<td>.200</td>
<td>.0.051</td>
<td>.80</td>
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<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
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<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
<td>27</td>
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<td>.200</td>
<td>.0.102</td>
<td>.55</td>
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<td>.D2 .Osborne .HSS.</td>
</tr>
<tr>
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<td>.200</td>
<td>.0.102</td>
<td>.11</td>
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<td>.D2 .Osborne .HSS.</td>
</tr>
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<td>.200</td>
<td>.0.102</td>
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<td>.D2 .Osborne .HSS.</td>
</tr>
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<td>.200</td>
<td>.0.102</td>
<td>.28</td>
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<td>.D2 .Osborne .HSS.</td>
</tr>
</tbody>
</table>

### Table B.6 Performance of Master 2500

<table>
<thead>
<tr>
<th>No.</th>
<th>Mach.</th>
<th>Feed</th>
<th>Depth of Cut</th>
<th>Tool Life</th>
<th>Tool Code</th>
<th>Tool Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>3.20</td>
<td>.1860</td>
<td>.0.102</td>
<td>.58</td>
<td>Master2500</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
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<td>3.20</td>
<td>.1860</td>
<td>.0.102</td>
<td>.14</td>
<td>Master2500</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
<td>B3</td>
<td>3.20</td>
<td>.1860</td>
<td>.0.102</td>
<td>.21</td>
<td>Master2500</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
<td>B4</td>
<td>3.20</td>
<td>.1860</td>
<td>.0.102</td>
<td>.21</td>
<td>Master2500</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
<td>B5</td>
<td>3.20</td>
<td>.1860</td>
<td>.0.102</td>
<td>.26</td>
<td>Master2500</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
<td>B6</td>
<td>3.20</td>
<td>.1860</td>
<td>.0.102</td>
<td>.26</td>
<td>Master2500</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
<td>B7</td>
<td>3.20</td>
<td>.1860</td>
<td>.0.102</td>
<td>.26</td>
<td>Master2500</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
<td>B8</td>
<td>3.20</td>
<td>.1860</td>
<td>.0.102</td>
<td>.26</td>
<td>Master2500</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
<td>B9</td>
<td>3.20</td>
<td>.1860</td>
<td>.0.102</td>
<td>.26</td>
<td>Master2500</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
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<td>.1860</td>
<td>.0.102</td>
<td>.26</td>
<td>Master2500</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
</tbody>
</table>

### Table B.7 Performance of Okuma LS

<table>
<thead>
<tr>
<th>No.</th>
<th>Mach.</th>
<th>Feed</th>
<th>Depth of Cut</th>
<th>Tool Life</th>
<th>Tool Code</th>
<th>Tool Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>6.40</td>
<td>.1100</td>
<td>.0.133</td>
<td>.23</td>
<td>Okuma</td>
<td>.4340 .Osborne .HSS.</td>
</tr>
<tr>
<td>F2</td>
<td>6.40</td>
<td>.1100</td>
<td>.0.133</td>
<td>.23</td>
<td>Okuma</td>
<td>.4340 .Osborne .HSS.</td>
</tr>
<tr>
<td>F3</td>
<td>6.40</td>
<td>.1100</td>
<td>.0.133</td>
<td>.23</td>
<td>Okuma</td>
<td>.4340 .Osborne .HSS.</td>
</tr>
<tr>
<td>F4</td>
<td>6.40</td>
<td>.1100</td>
<td>.0.133</td>
<td>.23</td>
<td>Okuma</td>
<td>.4340 .Osborne .HSS.</td>
</tr>
<tr>
<td>F5</td>
<td>6.40</td>
<td>.1100</td>
<td>.0.133</td>
<td>.23</td>
<td>Okuma</td>
<td>.4340 .Osborne .HSS.</td>
</tr>
<tr>
<td>F6</td>
<td>6.40</td>
<td>.1100</td>
<td>.0.133</td>
<td>.23</td>
<td>Okuma</td>
<td>.4340 .Osborne .HSS.</td>
</tr>
<tr>
<td>F7</td>
<td>6.40</td>
<td>.1100</td>
<td>.0.133</td>
<td>.23</td>
<td>Okuma</td>
<td>.4340 .Osborne .HSS.</td>
</tr>
<tr>
<td>F8</td>
<td>6.40</td>
<td>.1100</td>
<td>.0.133</td>
<td>.23</td>
<td>Okuma</td>
<td>.4340 .Osborne .HSS.</td>
</tr>
<tr>
<td>F9</td>
<td>6.40</td>
<td>.1100</td>
<td>.0.133</td>
<td>.23</td>
<td>Okuma</td>
<td>.4340 .Osborne .HSS.</td>
</tr>
<tr>
<td>C1</td>
<td>3.20</td>
<td>.2000</td>
<td>.0.079</td>
<td>.12</td>
<td>Okuma</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
<td>C3</td>
<td>3.20</td>
<td>.2000</td>
<td>.0.079</td>
<td>.12</td>
<td>Okuma</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
<td>C4</td>
<td>3.20</td>
<td>.2000</td>
<td>.0.079</td>
<td>.12</td>
<td>Okuma</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
<td>C5</td>
<td>3.20</td>
<td>.2000</td>
<td>.0.079</td>
<td>.12</td>
<td>Okuma</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
<td>C6</td>
<td>3.20</td>
<td>.2000</td>
<td>.0.079</td>
<td>.12</td>
<td>Okuma</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
<tr>
<td>C7</td>
<td>3.20</td>
<td>.2000</td>
<td>.0.079</td>
<td>.12</td>
<td>Okuma</td>
<td>.4340 .Clevedon .HSS.</td>
</tr>
</tbody>
</table>
### Table B.8 Performance of Bridgeport

<table>
<thead>
<tr>
<th>MACHINE TOOL: BRIDGEPORT</th>
</tr>
</thead>
<tbody>
<tr>
<td>64</td>
</tr>
<tr>
<td>65</td>
</tr>
<tr>
<td>D2</td>
</tr>
<tr>
<td>67</td>
</tr>
<tr>
<td>D5</td>
</tr>
<tr>
<td>D4</td>
</tr>
</tbody>
</table>

### Table B.9 Performance of Stanko

<table>
<thead>
<tr>
<th>MACHINE TOOL: STANKO</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
</tr>
<tr>
<td>E1</td>
</tr>
<tr>
<td>E2</td>
</tr>
<tr>
<td>E3</td>
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<td>E4</td>
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</tr>
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<td>G3</td>
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<td>G4</td>
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<tr>
<td>82</td>
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<tr>
<td>84</td>
</tr>
</tbody>
</table>

### B.4. RESULTS

The thirty-three 'Results' are divided into the seven groups mentioned in Chapters 5 and 6. These results are included in the next few pages. The format of each record is defined as follows: hole number, followed by the six statistical parameters: namely, mean, standard deviation, skew, kurtosis, RMS height, variance/RMS height, and finally, the various bandpass RMS of the frequency spectrum, as indicated in Table 4.1.

The 'Results' are presented in the order, as shown in Table 6.8, from group A to group F.

#### B.4.1. Group A

<table>
<thead>
<tr>
<th>MACHINE TOOL: Harrison M400</th>
<th>DRILL NUMBER</th>
<th>AI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>24.32</td>
</tr>
<tr>
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<td>44.46</td>
<td>26.54</td>
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<td>3</td>
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<tr>
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</tr>
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<td>10</td>
<td>47.41</td>
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</tr>
</tbody>
</table>
### B.4.6. Group F

#### MACHINE Tool: Okuma LS

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<th>E2</th>
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<td>1.1 - 1.626</td>
<td>1.319</td>
</tr>
<tr>
<td>2.1 - 1.626</td>
<td>1.319</td>
</tr>
<tr>
<td>3.1 - 1.626</td>
<td>1.319</td>
</tr>
<tr>
<td>4.1 - 1.626</td>
<td>1.319</td>
</tr>
<tr>
<td>5.1 - 1.626</td>
<td>1.319</td>
</tr>
</tbody>
</table>

#### MACHINE Tool: Stanko

<table>
<thead>
<tr>
<th>DRILL NUMBER</th>
<th>E3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 - 1.626</td>
<td>1.319</td>
</tr>
<tr>
<td>2.1 - 1.626</td>
<td>1.319</td>
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<tr>
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APPENDIX C
APPENDIX C

C.1. The Number of Averages Needed in HP35660A FFT Analyzer

In this study, the time taken to perform a drilling operation or the duration of a vibration signal is known. In order to get the maximum number of averaged frequency spectra in that duration, the time taken to perform the averages must be known. This time taken is dependent on two variables: the number of averages desired, and the update-rates used. An update means a display of the averaged frequency spectrum on the analyzer’s monitor.

The HP35660A FFT analyzer is a very sophisticated piece of equipment. The only drawback that the author found while using it is that there is no way of knowing how long it takes to perform averages and also no way of stopping it while averaging is underway. Because of that, an experimental study was performed to determine the time required to perform averages with different update-rates and the results can be seen in Table C.1 and in Figure C.1. The four curves, corresponding to the four update-rates, have the same slope of 0.09 but with different y-intercepts, as indicated in Table C.2. The equations shown in Table C.2 are obtained using the linear, least-square curve fitting technique. By plotting the y-intercept, $a$, versus the update-rate, $u$, a linear relationship is observed, as indicated by Figure C.2. The slope of this plot indicates that the time required for an update is equal to 0.32 seconds.
Figure C.1 Time required to perform averages with different update-rates for the HP35660A FFT analyzer

Figure C.2 Plot of Y-intercept versus update-rate
<table>
<thead>
<tr>
<th>Number of averages</th>
<th>Update-rates</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>2.11*</td>
</tr>
<tr>
<td>20</td>
<td>3.04</td>
</tr>
<tr>
<td>30</td>
<td>3.91</td>
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<td>40</td>
<td>4.88</td>
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<td>50</td>
<td>5.70</td>
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<td>60</td>
<td>6.60</td>
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<td>70</td>
<td>7.56</td>
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<tr>
<td>80</td>
<td>8.45</td>
</tr>
<tr>
<td>100</td>
<td>10.29</td>
</tr>
</tbody>
</table>

* units in second.

Table C.1 Time required to perform different number of averages with different update-rates

<table>
<thead>
<tr>
<th>Update-rates ( U )</th>
<th>( T_s = a + b \times N_i )</th>
<th>Correlation coefficient ( r )</th>
</tr>
</thead>
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<tr>
<td></td>
<td>( a )</td>
<td>( b )</td>
</tr>
<tr>
<td>Curve A</td>
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<td>1.203</td>
</tr>
<tr>
<td>Curve B</td>
<td>2</td>
<td>1.575</td>
</tr>
<tr>
<td>Curve C</td>
<td>3</td>
<td>1.900</td>
</tr>
<tr>
<td>Curve D</td>
<td>4</td>
<td>2.154</td>
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</table>

Table C.2 Equations of time required with different update-rates

From the above study, if the time required to perform a drilling sequence and the number of updates desired are known, equation C.2 can be used to determine the maximum number of averages attainable in the HP35660A FFT analyzer.
\[ T_s(N_s, U) = 0.913 + 0.318U + 0.09N_s \]  \hspace{1cm} \text{(C.1)}

\[ N(T_s, U) = 1.11T_s - 30.14 - 3.53U \]  \hspace{1cm} \text{(C.2)}

Where \( T_s \) = time required, [s]

\( N_s \) = number of averages

\( U \) = update-rates

\textbf{C.2. Determine the Coefficients of the Tool-life Equations}

The two tool-life equations selected in the study are the basic Taylor's equation and its extended version as shown below:

\[ VL^{a_0} = a_1 \]  \hspace{1cm} \text{(C.3)}

\[ L = a_0V^{a_2}f^{a_3}D^{a_4} \]  \hspace{1cm} \text{(C.4)}

where \( a_0, a_1, a_2, a_3 \) are the coefficients

\( V \) = cutting speed, [rpm]

\( L \) = tool-life, [Total number of holes drilled]

\( D \) = drill size, [mm]

\( f \) = feed rate, [mm/rev]
C.2.1. Linearizing the Equations

Linearization of the two tool-life equations shown previously can be achieved by taking natural logarithms on both sides of the equations. Equations C.5 and C.6 are the linearized tool-life equations obtained.

\[
\begin{align*}
\ln V + a_0 \cdot \ln L &= \ln a_1 \quad \text{C.5} \\
\ln L &= \ln a_0 + a_1 \cdot \ln V + a_2 \cdot \ln f + a_3 \cdot \ln D \quad \text{C.6}
\end{align*}
\]

These two equations can be expressed as linear polynomial equations with some necessary variable transformations: namely, by setting \(Y=\ln V\), \(X=\ln L\), \(b_0=\ln a_1\), and \(b_1=\ln a_0\) in equation C.5; and \(Y=\ln L\), \(X_1=\ln V\), \(X_2=\ln f\), \(X_3=\ln D\), \(b_0=\ln a_0\), \(b_1=\ln a_1\), \(b_2=\ln a_2\), \(b_3=\ln a_3\) in equation C.6. The resulting polynomial equations are given as follows:

\[
\begin{align*}
Y &= b_0 + b_1 \cdot X \quad \text{C.7} \\
Y &= b_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + b_3 \cdot X_3 \quad \text{C.8}
\end{align*}
\]

C.2.2. Least-Square Curve Fitting Technique

The least-square curve fitting technique aims at minimizing the sum of square error of the transformed function, in this case, the following two equations are applicable:

\[
\begin{align*}
Z_1 &= (Y - b_0 - b_1 \cdot X)^2 \\
Z_2 &= (Y - b_0 - b_1 \cdot X_1 - b_2 \cdot X_2 - b_3 \cdot X_3)^2
\end{align*}
\]

By differentiating the above two equations with respect to its coefficients, the two matrix equations given by equations C.9 and C.10 are obtained; and they can be solved for the unknown coefficients, \(\{b_0, b_1, b_2, b_3\}\). The coefficients of the tool-life equations can be then obtained by following the transformations given in Table C.3.
\[
\begin{bmatrix}
\sum X & \sum X^2 \\
\sum X & \sum X^2
\end{bmatrix}
\begin{bmatrix}
b_0 \\
b_1
\end{bmatrix}
= 
\begin{bmatrix}
\sum Y \\
\sum XY
\end{bmatrix}
\]

C.9

\[
\begin{bmatrix}
\sum X_1 & \sum X_2 & \sum X_3 \\
\sum X_1 & \sum X_2^2 & \sum X_1X_2 & \sum X_1X_3 \\
\sum X_2 & \sum X_2X_1 & \sum X_2^2 & \sum X_2X_3 \\
\sum X_3 & \sum X_3X_1 & \sum X_3X_2 & \sum X_3^2
\end{bmatrix}
\begin{bmatrix}
b_0 \\
b_1 \\
b_2 \\
b_3
\end{bmatrix}
= 
\begin{bmatrix}
\sum Y \\
\sum X_1Y \\
\sum X_2Y \\
\sum X_3Y
\end{bmatrix}
\]

C.10

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<th></th>
<th></th>
<th></th>
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<td>(a_0)</td>
<td>(-b_1)</td>
<td>(e^{b_0})</td>
</tr>
<tr>
<td>(a_1)</td>
<td>(e^{b_0})</td>
<td>(b_1)</td>
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<tr>
<td>(a_2)</td>
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</tr>
<tr>
<td>(a_3)</td>
<td></td>
<td>(b_3)</td>
</tr>
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Table C.3 Coefficients of the tool-life equations
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1961  Born in Sibu, Sarawak, Malaysia.
1976  Received Sarawak Junior School Certificate, Malaysia.
1978  Received Senior Cambridge Certificate, Malaysia.
1980  Received Grade 13 diploma, Toronto, Ontario, Canada.
1985  Received the Degree of Bachelor of Applied Science at the University
      Windsor, Windsor, Ontario, Canada.
1987  Received the Degree of Master of Applied Science at the University of
      Windsor, Windsor, Ontario, Canada.