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Statistical assessment of vibration data in drilling.

Hui Kong. Lau
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STATISTICAL ASSESSMENT
OF
VIBRATION DATA IN DRILLING

by
Hui Kong Lau

A Thesis
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 Master of Applied Science at
the University of Windsor

Windsor, Ontario, Canada
1987
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ABSTRACT

A tool wear monitoring procedure, using the vibration signals generated from the drilling process, was developed. The signals were assessed statistically by grouping the time-amplitude signals into frequency distributions and describing the characteristics of the distributions in terms of their central tendency, dispersion, asymmetry and peakedness. Five statistical parameters were used, these being: mean, standard deviation, skew, kurtosis and RMS or height of the distribution. Two different drill sizes; 3.18 mm and 6.35 mm were used and experiments were performed on three machine-tools with operating conditions as close to the recommended values as possible.

Statistical results obtained were machine dependent and to some extent influenced by the type of drill wear taking place at the cutting edges. The results for the 3.18 mm diameter drill bits were promising and were reproducible. For the 6.35 mm diameter drill bits, the results were not very good.

The standard deviation, RMS of the distribution and kurtosis were found to be useful as potential descriptors for drill wear monitoring.
Dedicated to

my parents and sisters
ACKNOWLEDGEMENTS

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NOMENCLATURE

A = Real area of contact between the tool and workpiece.
A/D = Analog to digital conversion.
Acc. = Accelerometer.
attn. = Signal attenuation.
BUE = Built-up edge.
C = Chisel edge length.
Cw = Crater wear.
Cew = Chisel edge wear.
D = Drill diameter.
Ds = Sampling interval delay.
d = Unworn portion of the drill along the cutting lips.
EU" = Engineering unit.
F_i = Frequency of occurrence in i_th class. (i=1,2,...N)
Fw = Flank wear.
Fz = Principal cutting force.
HSS = High speed steel.
Hb = Material hardness.
h = Sampling interval.
M = Torque.
Mr = r_th moment of the distribution.
Mw = Margin wear.
N = Total number of classes in a statistical distribution.
RMS = Root mean square height of the distribution.
RPM = Spindle speed.
SD = Statistical/raw data.
SR = Statistical results.
s = Feed rate.

ST. DEV. = Standard deviation.
T = Thrust.
V = Drill speed.

Vib. = Vibration.

\( X \) = Mean value of the statistical distribution.
\( X_i \) = Classes. \((i=1,2,\ldots,N)\)
\( \gamma \) = Included angle.
\( \theta \) = Chip-tool interface temperature.
\( \mu_3 \) = Skewness of the statistical distribution.
\( \mu_4 \) = Kurtosis of the statistical distribution.
\( \sigma \) = Standard deviation.
Chapter I

INTRODUCTION

Drilling is the most widely used manufacturing operation and the most economical method of hole production in industry today. It is the type of manufacturing operation which is absolutely indispensable for production of machine parts and many other components [52]. Billions of holes are drilled each year and it is estimated that the cost of circular hole cutting tools in the United States alone exceeds $200 million annually and accounts for about one-third of all metal-cutting operations [2]. It is, however, also one of the most troublesome operations due to the complex tooling used and the cutting mechanics involved at the cutting zones. Therefore, in order to improve the productivity and quality of the manufacturing processes and the automation of the machine, a fundamental need is to have accurate and continuous knowledge of the tool's condition (on-line information).

The drill, the basic hole-producing tool, is of 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

* Numbers in parentheses refer to cited references.
machine-made twist drills were not produced until about 1860, and truly modern twist-drill development begins with the invention of high speed steel around 1900 [51,60].

Because of its importance in nearly all production operations, twist-drills have been the subject of research for years. The basic design and the general configuration of a twist-drill, as shown in Figure 1.1, has remained virtually unchanged. The cutting elements consist 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.

Twist drills are manufactured in a variety of styles and in many different sizes. Figure 1.2 illustrates some of the more commonly used conventional and special-purpose twist drills. Based on sales of more than 50 million standard twist drills, the statistics compiled by National Twist Drill shows that a median of 90% of all sales fall between 1.27 and 10.16 mm in diameter and with 3.2 mm diameter being the most popular type [12,19].

The geometrical shape of the drill point is not efficient in cutting due to lack of centering, poor cutting action at the centre and also varying load along the cutting edges. Those basic problems have long been recognized and have been the subject of numerous investigations [4,8,20,31,41,43,63].

In this research, the main emphasis is not on finding a new concept in the drill point geometry but on monitoring the
Figure 1.1 Standard terms used to describe elements of twist drills.

Figure 1.2 Some conventional and special-purpose twist drills.
drill conditions during the process of drilling ("in-process") and to predict tool-life through statistical means. However, some of the findings concerning the effect of drill geometry, operating conditions (speed and feed rate), and the tool and workpiece selection on the performance of the drill will be reviewed in the literature survey. These findings will help in a better understanding of the mechanism of the drilling process.

The need for such an "in-process" system has traditionally resulted from the desire to cut down on downtime which may arise either due to unexpected tool failure or routine inspection for wear. In recent years, with the increased use of expensive, high volume, multiple tool machining systems like transfer lines and automatic machining centers, it has become essential to have a system that could monitor and predict tool failure in order to increase machine-tool efficiency and stay competitive in this high technology computer-based world. An added need for research in this area is due to advances in adaptive control and Computer-Aided-Manufacturing. It is to those machining systems at which this research is aimed.

The common practise with the tool-replacement in industry is often based on the following criteria:

1). After a predetermined number of cuts or certain time; or

2). Replace all at the time of the shortest-lived tool.

The above practices are by no means efficient and lead to severe under-utilization of tools in most cases due to the fact that significant differences in tool life exist even in nominally identical new tools. The large scatter of tool life has
been shown to be due to the production tolerances in manufacturing [32,34]. If a tool is changed before the end of its economical life, it will not only increase the tool-change time but will also increase capital cost. In summary, it can be stated that an effective wear monitoring procedure will significantly increase, particularly in untended manufacturing, productivity and quality control.

Machine-tool vibration was chosen as the parameter for tool wear monitoring, mainly because it was proven to be reliable, easy to implement and also cost effective [2,49,75]. Monitoring of tool wear, generally, will give invaluable information about the tool's condition and it is the extent of wear on the cutting edges which determines the tool life.

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 conditions, such as speed and feed rate, workpiece hardness, microstructural changes, lubricant, etc [6,19]. In drilling operations, generally there are seven dominant types of wear taking place at the active cutting zone of the drill, namely, tip wear, outer corner wear, flank wear, crater wear, margin wear, chisel edge wear and chipping at the cutting edges [34]. These are shown in Figure 1.3. The severity of each type of wear is significantly influenced by the speed of operation, feed rate, and tool and workpiece configuration.

Knowing that drilling is the most popular hole-production method used in industry today, and the importance
in the development of a reliable and efficient tool wear monitoring system for use in high volume, multiple tool machining systems, and in a Computer-Integrated-Manufacturing environment, the objective of this research is:

To study the feasibility of developing a tool wear monitoring system based on the evaluation of statistical descriptors applied to the vibration signal generated during the drilling operation.
Corner wear:
Tip wear = D - d

Flank Wear

Chisel Edge Wear
Chipping at cutting edge

Crater Wear
Margin Wear

Figure 1.3 Different types of wears.
Chapter II

LITERATURE SURVEY

The objectives of this chapter are to give an overview of the drilling process, the mechanisms and factors affecting tool wear, and finally, available methods of tool-wear sensing.

2.1. Drilling.

Drilling is generally applied where precision work is not the prime concern. Its main advantages are a high penetration rate and longer tool life.

As mentioned in Chapter I, drilling is the most important machining operation in metal-cutting industry today, however, it involves the use of a tool, for which not only the basic mechanics of the cutting action are complex but are also not adequately understood. Because of the geometrical shape of the twist drill, complicated cutting action takes place at the drill point, with different radii of the cutting edges subjected to different cutting conditions.

The basic cutting action 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 ejected through the flutes, and finally the drill is guided in the hole already produced by the margin.

The drill geometry represents a compromise of several conflicting requirements, which include:
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.

Less obvious compromises are associated with the choice of the geometric parameters that influence the effective rake and relief angle.

2.2. Mechanics of the drilling process.

Oxford and Shaw [51], using the quick-stop technique, were able to freeze the cutting action through a rapid stop of the relative motion between the drill and the workpiece. They found that the chip-formation mechanism along the cutting edges (lips) of a twist drill appears to be basically the same as for any other single-point metal-cutting operation as shown in Figures 2.1(d,e,f) [20,51,76]. However, that under the chisel edges was quite complex, as can be seen in Figures 2.1(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.
Figure 2.1 Series of photomicrographs of sections through chisel point drill and partly formed chips at successive points along cutting edge from axis to periphery.
2.2.1. Parameters that influence cutting forces.

Cutting forces that are generally of interest in most cases are the thrust and torque. In order to evaluate them, three actions at the cutting and chisel edges have to be considered. There are, as mentioned before, cutting actions at the lip and chisel edges, and the extrusion action at the chisel edges. The extrusion process has a negligible effect on the drill torque but is significant in influencing the drill thrust [61].

In general, quantities that influence the cutting forces are: work material and structure, drill diameter, helix angle, web thickness, point angle, number of cutting edges, speed, feed rate, and drill sharpness [12]; however, the effect of each can be different. For instance, the web thickness of the drill is found to influence the thrust and torque significantly, but the effect of the helix angle is found to be less important. On the other hand, the helix angle does play an important role in influencing the forces when chips start to jam in the flute.

In general, a harder workpiece material, a decrease in the drill sharpness, larger drill diameter, and higher feed rates will tend to increase the cutting forces. Depth of cut and cutting speed have a negligible effect, particularly when the cutting speed is within the commercial range, i.e. greater than 60 feet per minute (fpm) [9].
For standard drills, where the ratio C/D is about 0.8, the expression for the torque and thrust are:

\[
M = \frac{0.8}{1.8} \times Hb \times s \times D
\]

\[
T = \frac{0.8}{0.8} \times Hb \times s \times D + 0.0022 \times Hb \times D^{2}
\]

where, 
- \( M \) = thrust (lb)
- \( T \) = torque (in-lb)
- \( C \) = chisel edge length (in)
- \( D \) = drill diameter (in)
- \( s \) = feed rate (in/rev)
- \( Hb \) = material hardness (BHN)

The two above empirical equations generally agree with those presented by other investigators [9,12,61].

With wear occurring at the drill-point, different characteristics of the cutting forces are observed. Subramanian and Cook [65] 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 on Figure 2.2. Those relations were observed in drilling cast iron using high speed steel (HSS) drills of 10.32 mm diameter at 690 rpm.

Generally, in a drilling process, two directional movements are observed, one in the cutting direction (contributes to torque), and the other in the feed direction (contributes to the thrust). Figures 2.3(a), 2.3(b), show the two categories of drill cutting defect. Figure 2.3(a), shows the wear type which
FLANK WEAR = \( \frac{A \cdot B \cdot C \cdot D}{4} \)

Figure 2.2 Average flank wear.

Figure 2.3 Two categories of the drill cutting edge defects.
has more effect on thrust force, namely, defects includes chisel edge wear, flank wear, and partly corner wear. Figure 2.3(b), shows the wear type which has more effect on the torque and includes defects such as breakage, crater wear, and outer corner wear.

2.2.2. Effect of built-up edge.

The build-up at cutting edges occurs in all but a few exceptional cases. Because it alters the tool angles, it influences cutting forces, cutting temperatures, tool life, and other elements of the drilling process. Generally, with the presence of the built-up edge (BUE), the values of the cutting force will decrease due to the increase of effective rake angle. It also has significant influence on the surface finish of the product because as the BUE grows forward, it will usually also grow downward, causing the finished surface to be undercut, which degrades the quality of the finish, as can be seen in Figure 2.4. Built-up edge has a more pronounced effect near the chisel edge than at the cutting edges [15, 29]. Figure 2.5 shows how the principal cutting force varies for several feeds and also the type of built-up edge formed with speed [47].

2.3. Factors affecting tool wear.

Tool wear is an important phenomenon in metal cutting since it affects significantly the economics of the cutting process. It is unavoidable due to the interactions between the tool and the workpiece on one hand and the chips and the
Figure 2.4 Effect of built-up edge (BUE) on the surface finish of the product.
tool on the other. Knowledge of the mechanisms and factors involved helps in the optimization of the production process. In order to optimize, it is necessary to determine the optimal time to replace the tool, which is referred to as tool-life. Tool wear and tool-life are closely related and it is the extent of wear that determines whether a tool has reached the limits of its economical life or not.

The main cause of wear is the increased temperature in the tool due to the transformation of mechanical work into heat during the cutting operation. It has been found that over 98 percent of the power used in machining goes into heat [11,13]. The two main sources of heat at the cutting edge are the shear zone, where the metal of the workpiece is being formed into a chip, and the tool-chip interface, where the chip rubs against the cutting tool as shown in Figure 2.6.

There are several forms of wear in twist drills, such as flank wear, crater wear, chisel edge wear, outer corner wear, tip wear, margin wear, and chipping at the cutting edges as mentioned before. The severity of the wear depends on the operating conditions. It has been determined that wear starts at the outer corners of the cutting lips and thus it can be used as a performance index because of the relative ease of measurement and its close relationship with the drill life [34]. In fact, twist drills most commonly fail because of wear at the cutting lips. The mode of failure is inherently temperature dependent, if abusive cutting conditions leading to drill breakage of the chisel edge failure are excluded [60].
Figure 2.5 Variations of the principal cutting force with cutting speed for several feeds.

Figure 2.6 The energy regions in metal cutting.
2.3.1. Influence of cutting speed on temperature.

Heat is predominantly generated at the shear zone. As the tool moves through the workpiece, the shear zone appears to the tool as a stationary heat source moving ahead of the tool at the same rate as the tool travels through the workpiece. Heat from this stationary source is conducted in both directions either out with the chips or it remains in the workpiece thus raising its temperature. At high cutting speeds, the tool moves so rapidly that far less heat is conducted into the workpiece, and therefore most of it is taken off with the chips. This will increase, through the tool-chip interface, the temperature of the tool, in addition to the increased frictional interaction between the chip and the tool, as can be seen in Figure 2.7. The maximum chip-tool interface temperature is observed to occur at about two-thirds of the way back from the cutting edge to the point where the chip curls away from the tool [34]. Figure 2.8 indicates this phenomenon. This high chip-tool temperature will promote crater wear on the tool face. Despite the high chip-tool interface temperature, only small amounts of heat were found to be transferred to the tool or the workpiece. Conversely, large amounts of heat were found to flow into the cutting tool when it was operated at low cutting speeds and high feed rates.

2.3.2. Influence of feed, depth of cut, and work material on temperature.

Increasing the feed rate will cause an increase in
Figure 2.7 Temperature distribution on the tool-chip interface.

Figure 2.8 Values of the tool-chip interface temperature at different cutting speeds and feeds.
the interface temperature and heat generation. The depth of cut will generally not increase the interface temperature except through redistribution of the heat flow into the cutting edges. If a workpiece of higher hardness is used, increased work is needed to form and remove the chip, which brings about a higher interface temperature and hence increases the tool wear.

Other added factors, which most likely will influence tool wear other than the few mentioned above, are the grain and structure of the work material, built-up edge (BUE), surface layer of cutting tool and workpiece, relative hardness of the tool and work material, cutting edge sharpness, lubrication or coolant.

2.4. Mechanisms involved in tool wear.

Noticeably, there are four basic mechanisms which can operate singly or in various combinations to produce tool wear. These four mechanisms are adhesive wear, abrasive wear, electrochemical wear, and diffusion wear [70,77]. The predominance of a particular mechanism or some combinations will depend predominantly on the cutting temperature and the properties of the tool and workpiece materials [37]. At low temperatures, mechanical wear processes, such as abrasion and adhesion, are rate-controlling and the wear of the tool material is determined primarily by its hardness. At higher temperatures, the wear rate is predominantly determined by the chemical properties of the tool-workpiece material, hence diffusion wear will be the major type [1].
2.5. **Tool wear sensing techniques.**

The monitoring of tool wear requires the development of very sensitive, accurate, and reliable techniques. It was not until recent years that much attention has been focused on the development of so call "in-process" tool wear monitoring systems. The recently increased interest in this area can be largely related to the advent of stand-alone microprocessors and powerful microprocessor-based analyzers, which rapidly and cost effectively perform the data analysis and evaluation, which otherwise would be impossible.

Numerous sensing technologies are used in industry today. They can be broadly categorized into direct and indirect methods. Direct sensing methods are those that utilize effects caused directly by tool wear. They 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. 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, machine tool vibration, and temperature. Generally, they are much easier to implement.

In order for the sensing technique to be effective, it should provide the following characteristics:

1). Direct correlation with the signal describing the trend of the parameter with tool wear.

2). Minimal delay in the sensing process and a practically
instantaneous reaction to tool failure.

3). It must be capable of providing reliable tool wear trend data as well as being sensitive to sudden changes in the cutting operation.

4). It must be adaptable to the production floor without posing any difficulties to the machining operation and maintenance.

5). Technique has to be reliable.

6). The system has to be capable of withstanding without damage the hostile working environment.

7). Has to be cost effective.

The techniques reviewed are not all truly "in-process" because they involve measurements between cuts, as opposed to measurements during machining process.

2.5.1. Direct methods.

These method are generally, difficult and sometime impossible for "in-process" monitoring, especially where there is a continuous contact between the tool and workpiece.

2.5.1.1. Radioactivity.

This method involves measurement of the volumetric overall loss of the tool material. The entire tool or only the drill-point are made radioactive by irradiating it in a nuclear reactor. Since amount of wear from the drilling process is small, the total activity of the tool has to be high, which calls for extreme precautions in the handling and analysing of the chips or
the wear particles. This technique is very inconvenient and is therefore confined to a few research applications [3]. It is also unlikely to be accepted by workers' unions.

2.5.1.2. Direct wear measurement.

This method involves the interruption of the drilling process at intervals, taking the tool out, and measuring the wear under an optical microscope. It has the disadvantage that the cutting process is interrupted in a way that it would not be acceptable during normal production. The measuring process is lengthy and tedious, and the judgement of the position of the worn edge is difficult and subjective. Strictly speaking, it is an off-line method. Generally, it is used for research purposes where detail deterioration of the tool at stage is needed for evaluating tool performance.

2.5.1.3. Optical sensing.

This method involves the use of the principle of light reflection, and equipment such as fibre optics and TV cameras. It usefulness in application as an in-process method is limited to intermittent cutting operations. It analyses the image of the wear zone either by sending the image into a image analysing computer or displaying it on TV monitor for manual inspection. Reliability of this system is very much in question, it is too slow for "in-process" applications and also technical expertise is required which makes it very expensive to implement. Another approach in this same context is utilizing the different light
reflection behaviour between the worn and unworn area of the cutting edges [48].

Its application is limited because of its relative slow speed, inaccessibility of the cutting edges, presence of coolant mist and hostility of the cutting environment.

2.5.1.4. Electrical resistance.

This method utilizes the reduction in the electrical resistance across the tool-workpiece junction which occurs due to tool wear and the resulting increase of the contact area with the workpiece. The dependence of this contact resistance on changes in cutting parameters such as speed, feed, cutting forces, and temperature makes this approach unsuitable in many applications. However, it has been used successfully to measure tool wear in-process for a range of cutting conditions typical of finishing and turning on a lathe [48].

2.5.1.5. Chemical analysis.

It involves the collection of chips from both the tool and workpiece, separation of tool material and workpiece material by some chemical process, and correlation of wear with the volumetric loss from the tool. It is not a very suitable method for "in-process" monitoring.

2.5.2. Indirect methods.

Because of the difficulties encountered in implementing the direct methods, for "in-process" tool wear monitoring, the
need exists for developing indirect methods of monitoring the tool wear.

2.5.2.1. **Sensors based on measuring forces or torques.**

It is one of the easier methods to implement. This method often utilizes the changes in some component of forces, such as feed force, thrust force, and drilling torque, and correlate it to tool wear. Problems arise when these force components are not constant but vary randomly, in which case mean values have to be used.

It was found that variations in the cutting forces that result from gradual tool wear, are often too small for sufficiently accurate and reliable measurements of wear [48, 49].

2.5.2.2. **Temperature.**

As a cutting tool becomes dull, the frictional effect at the cutting edges increases, which then brings about the increase in the temperature. Using this fact, correlation of temperature with tool wear can be developed.

The cutting temperatures measured with a thermocouple are very sensitive to the chemical composition of the tool-workpiece junction. This requires that the thermocouple be calibrated for every tool workpiece pair which is rather time consuming and uneconomical in a high production environment. Infrared temperature measuring systems, on the other hand, are expensive, complex, and difficult to focus. The main problems are focusing onto the area of interest and an inability to use these
systems in the presence of cutting fluids.

2.5.2.3. Roughness of machined surfaces.

As the tool becomes dull, the resulting machined surface will be rougher. Hence, the degree of roughness of the machined surface can thus be used to correlate with the tool wear. This approach has not been very popular because changes in the surface finish could be due to chatter vibration, the machine tool structure, and also extraneous vibrations from other sources [48].

2.5.2.4. Measurement of workpiece dimensional changes and distance between tool post and workpiece.

During the cutting operation, as the tool wears, the distance between the tool post and the workpiece decreases, and also brings about some changes in the workpiece dimension. Generally, those measurements are prone to errors resulting from [48]:

1). Expansion of the workpiece and cutting tool as temperature rises.

2). Vibration or deflection of the tool or the workpiece due to the increase in cutting force as the tool wears.

3). Inaccuracies in the machine tool structure.
2.5.2.5. **Acoustic Emission.**

Acoustic emission is defined as a high elastic stress wave release from the material, when undergoing plastic deformation or fracture [16]. It is a type of high frequency vibration. Typically, the frequency of the signal is in the range from 100 kHz to 2 MHz. Its application to tool wear monitoring has a few advantages over other methods, namely, it is quite easily adapted to computer control, the frequency of the signal is well beyond the frequency range of the noise from the machine tool dynamics and extraneous sources, the signals are generated by processes in the cutting zone and can therefore be directly related to tool wear [18].

The study of acoustic emission in metal cutting has been a topic of extensive research by numerous researchers [16,17,18,49] and there have been noted success in sensing tool wear via acoustic emission analysis [49]. It is a relatively new nondestructive testing technique and has been also applied to monitor the structural integrity of aerospace and petrochemical structures, bridges and power plant components; to locate leaks and loose parts; and to verify quality of welds on line [28].

It does appear to be of great promise, however there are several problems that need to be overcome first before it can be used as part of a "in-process" tool wear monitoring system. Firstly, the understanding of the source characteristics is still very much incomplete, even though many theoretical explorations have been made. Those theories are either qualitative descriptions or simplifications difficult to prove or disprove
experimentally. Secondly, the signal analysing process involves uses of additional and expensive equipment.

2.5.2.6. Vibration.

Vibration analysis is fast becoming a very prominent preventive and predictive maintenance tool for a wide variety of industrial equipment. It has been successful in reducing catastrophic failures, maintenance cost and downtime, it provides advance warning of impending breakdown of machinery and increases the production rate [26,46,58].

Vibration is also used as a sensing medium in monitoring tool wear in metal cutting operations. Several authors [54,66,75], have investigated the correlation of machine tool vibration with tool wear. They all agree that as the tool becomes dull, the rubbing action between the tool and workpiece increases, which brings about an increase in the vibration level. The vibration signals can be easily monitored, and information can be analysed in a number of ways, either in the time domain or in the frequency domain.

According to [2], the machine tool vibration in a drilling process, analysed either in the time domain or the frequency domain, shows a definite sensitivity to tool wear. With the proper selection of the mode of vibration, the deterioration of the drilling process can be easily monitored [55,64].

Publications are sparse in the field of vibration as a basis of "in-process" monitoring. A possible explanation could be due to the lack of ability to identify frequency domain
spectral peaks with drilling mechanics.

Time domain analysis of the vibration signal has indicated, at least in one study, that it can be utilized to detect improper drilling sequence, tool wear and to predict drill breakage [35].

This method has advantages which include: the ease of installation, durability and reliability of the vibration pick-up by transducer. In addition, it can also pick up faults in the machine other than those due to the drilling process alone.

As can be seen from the above discussion, numerous tool-wear sensing techniques have been developed throughout the years, either applied on-line or off-line, however, none of these methods is universally accepted for all industrial applications.

The foregoing problems have prompted this attempt to develop a tool-wear monitoring system by assessing statistically the vibration data generated during the drilling process. The analysis is done purely in the time-amplitude domain, i.e., the vibration signal is manipulated as a function of time only.
Chapter III

EXPERIMENTAL DETAILS

The main objective of this chapter is to provide a description of the experimental procedure and equipment used in this project. It involves: equipment, tools, workpiece selection and preparation, accelerometer selection and location, operating procedures, tape recording of data and wear measurements.

3.1. Equipment selection.

Drilling machines are available in many different types, sizes, and capacities. In this research, three lathes were selected for study, mainly due to their ability and capacity to deliver the recommended speed and feed rates for the drilling operations. A lathe was chosen over a drill press because it can deliver a constant feed rate. Rather than having the drill rotate, it was held stationary in a chuck and the workpiece was rotated. This arrangement is different from the usual practice of having the workpiece held stationary while drill is being rotated and fed, but the difference in the mechanics involved is believed to be minimal [57]. The three types of lathes used were Harrison M400, Colchester Master 2500, and Okuma type LS.

Accelerometers were used as vibration pick-ups. Their location was selected as close to the drilling action as possible to ensure the predominance of vibration from the drilling operation. Two different types of accelerometers were used to suite the type of tape-recorder. Table 3.1 gives specifications
<table>
<thead>
<tr>
<th>TAPE RECORDER:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>B&amp;K 7005</td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
</tr>
<tr>
<td>- Range</td>
<td>0 to 60 kHz</td>
</tr>
<tr>
<td>Weight</td>
<td>8.8 kg (19.4 lbs)</td>
</tr>
<tr>
<td>Recording Speed</td>
<td>38.1 cm/s</td>
</tr>
<tr>
<td>Attenuation/</td>
<td></td>
</tr>
<tr>
<td>Gain setting</td>
<td>depends on drill size.</td>
</tr>
<tr>
<td>3.18 mm</td>
<td>gain 10 dB</td>
</tr>
<tr>
<td>6.35 mm</td>
<td>gain 1 db</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ACCELEROMETER:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>H&amp;K 4348</td>
</tr>
<tr>
<td>Sensitivity (mv/g)</td>
<td>8.39</td>
</tr>
<tr>
<td>Resonant Frequency</td>
<td></td>
</tr>
<tr>
<td>- Resonant frequency (Hz)</td>
<td>62,000</td>
</tr>
<tr>
<td>Frequency Range</td>
<td></td>
</tr>
<tr>
<td>Frequency Range (Hz)</td>
<td>0 to 20,000</td>
</tr>
<tr>
<td>Weight (gm)</td>
<td>11</td>
</tr>
<tr>
<td>Amplifier/power unit used</td>
<td>Vibration unit</td>
</tr>
<tr>
<td>ZM 0060</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1. Tape-recorders and Accelerometers used.
of the two accelerometers and tape-recorders used in this project.

3.2. Drill and Workpiece selection and preparation.

Selection of the drill and workpiece combination not only gives a rough idea of the operating speed and feed rate required for proper cutting but also some insight into the mechanism involved, such as heat generation, type of chip formed, 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. Figure 3.1 and Figure 3.2 show, respectively, the hot hardness and recovery hardness for several types of cutting tool materials. 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. The mean size range for all twist drills produced would probably be around 4 mm [12,19]. Two drill sizes were used, namely 3.18 mm (1/8 in) and 6.35 mm (1/4 in). Table 3.2 gives the drill specifications and those dimensional tolerance are also included in Table 3.3.

The workpiece materials were selected on the basis of trial and error. After investigating a number of materials, AISI 4340 alloy steel was found to be most desirable due to its ease of machinability. Under the recommended operating speed, the
Figure 3.1 Hot hardness for several types of cutting materials.

Figure 3.2 Recovery hardness for several types of cutting tool materials.
<table>
<thead>
<tr>
<th>Drill Diameter (mm)</th>
<th>Flute Length (mm)</th>
<th>Overall Length (mm)</th>
<th>Lip Relief (°)</th>
<th>Web Thickness (% of drill's diameter)</th>
<th>Include angle at point (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18 (.125 in)</td>
<td>41</td>
<td>70</td>
<td>15</td>
<td>20</td>
<td>118</td>
</tr>
<tr>
<td>6.35 (0.25 in)</td>
<td>73</td>
<td>105</td>
<td>13</td>
<td>17</td>
<td>118</td>
</tr>
</tbody>
</table>

Table 3.2. Drill specifications for 3.18 mm and 6.35 mm drill-size.

<table>
<thead>
<tr>
<th>Drill diameter at point. (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18</td>
<td>+0</td>
</tr>
<tr>
<td>6.35</td>
<td>+0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shank diameter. (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18</td>
<td>+0</td>
</tr>
<tr>
<td>6.35</td>
<td>+0.013</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flute length. (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18</td>
<td>+3.2</td>
</tr>
<tr>
<td>6.35</td>
<td>+3.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Overall length. (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18</td>
<td>+3.2</td>
</tr>
<tr>
<td>6.35</td>
<td>+3.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Include angle at point. (°)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18 &lt; γ &lt; 6.35</td>
<td>118 ± 5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lip height. (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18</td>
<td>0.08</td>
</tr>
<tr>
<td>6.35</td>
<td>0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Centrality of Web. (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18</td>
<td>0.08</td>
</tr>
<tr>
<td>6.35</td>
<td>0.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flute spacing. (mm)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18</td>
<td>0.003</td>
</tr>
<tr>
<td>6.35</td>
<td>0.076</td>
</tr>
</tbody>
</table>

Table 3.3. Dimensional Tolerances for HSS General Purpose Twist Drill of 3.18 mm (1/8 in) and 6.35 mm (1/4 in) in diameter.
tool life obtained was considered to be appropriate for this study. Table 3.4 shows the different percentages of constituents of the alloy steel used.

<table>
<thead>
<tr>
<th>Carbon</th>
<th>C</th>
<th>0.38 - 0.43</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manganese</td>
<td>Mn</td>
<td>0.6 - 0.8</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>P</td>
<td>0.035</td>
</tr>
<tr>
<td>Sulphur</td>
<td>S</td>
<td>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>207</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4. AISI 4340 Alloy Steel

The recommended operating speeds for the sizes of drills and workpiece material can be obtained from Table 3.5.

<table>
<thead>
<tr>
<th>Material Drilled</th>
<th>Hardness Brinell</th>
<th>Cutting tool material (m/min)</th>
<th>Peripheral speed (mm/rev)</th>
<th>Feed rate (°)</th>
<th>Helix angle (°)</th>
<th>Point angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.3-.6C</td>
<td>175-225</td>
<td>HSS</td>
<td>15-18</td>
<td>z</td>
<td>25-35</td>
<td>118</td>
</tr>
</tbody>
</table>

(50-60 SPM)

<table>
<thead>
<tr>
<th>Drill diameter (mm)</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18</td>
<td>0.05 (0.002 in/rev.)</td>
</tr>
<tr>
<td>6.35</td>
<td>0.069 (0.0035 in/rev.)</td>
</tr>
</tbody>
</table>

Table 3.5. Recommended operating conditions for 3.18 mm and 6.35 mm drill-size.

The relationship between drill speed and spindle speed is given by the following equations,
\[ V = 0.00314 \times D \times \text{RPM} \]

or

\[ \text{RPM} = \frac{318.31 \times V}{D} \]

Where,

\( V \) = drill speed. (m/min)

\( D \) = drill diameter. (mm)

\( \text{RPM} \) = spindle speed. (rev/min)

3.4. 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 done so as not to introduce any extraneous vibration into the process. Figure 3.3 shows the experimental setup before any drilling operation. The workpieces were cut from a bar stock into lengths of 50.8 and 25.4 mm depending on the drill's size used. They were also centered-drilled in order to eliminate the wander action at the drill-point when the drill first make contact with the workpiece.

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

1). The lathe was turned on.

2). The tape-recorder was turned on and the necessary comments regarding the drill conditions were recorded on
Figure 3.3 Experimental set-up.
3). Feed was engaged to start drilling only when the constant or steady-state tape speed condition was attained.
4). The drilling operation was stopped after the depth of three times the drill diameter was reached.
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 3.4.
7). Drill was placed back into the chuck at the same location and orientation as before in order to establish consistency in the experiment.
8). Proceed to step (2) until failure occurs, 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 down 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 3.5 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 standard drill data sheets for ease of future analysis and reference. A sample of these data sheets are shown in Figures 3.6(a), 3.6(b).
Figure 3.4 Schematic diagram for tip wear measurement.

Tip wear = D - d

Figure 3.5 Tip wear measurement.
DRILLING DATA

DATARecorded: 20/8/87
DRILL #: D1
DRILL MANUF'TR: OSBORNE-MUSHET
MACHINE TOOL: OKUMA LS
SPINDLE SPEED: 1100 RPM
ACCELEROMETER: B&K 4384
TAPE RECORDER: B&K 7005
CHANNEL 1: Signals
CHANNEL 2: Comments
SPECIMEN MATL: AISI 4340
TOTAL # OF HOLES: 23
HOLE #'S EXCEEDING RANGE:

COMMENTS:
-Good drilling.

Table 3.6(a) Drilling data.

TIP WEAR MEASUREMENT

<table>
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<tr>
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<th>WEAR(mm)</th>
<th>HOLE #</th>
<th>WEAR(mm)</th>
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</thead>
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<td></td>
<td>0.99</td>
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</tr>
<tr>
<td></td>
<td>1.09</td>
<td>22</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.6(b) Tip wear data.
Chapter IV

ANALYSIS OF DATA

In this chapter, the analysis procedures which were developed to extract the required information from the analog vibration signal stored on the magnetic tape are described. The following subjects are included in the discussion:

1). Classification of the vibration signals from the drilling process.

2). Description of equipment required in the data processing.

3). Data preparation.

4). The detail data processing procedures.

5). The use of computer programs in this data analysis process.

4.1. Classification of the vibration signals.

Generally, in the first step of the analysis, it must be established if the signal is deterministic or nondeterministic in nature. Deterministic data are those that can be described by some explicit mathematical function, hence they are usually easier to comprehend and analyze. As shown in Figure 4.1 and Figure 4.2, the particular sets of data can be easily correlated by mathematical functions of straight line and periodic sine wave respectively. On the other hand, non-deterministic data or random data represent a random physical phenomenon which cannot be described by an explicit mathematical relationship because each observation is unique. It is to this latter category that
Figure 4.1 Deterministic data - straight line correlation.

Figure 4.2 Deterministic data - sine function correlation.
vibration signals from the drilling process belong. Certainly, the vibration signal obtained from the drilling process, as shown in Figure 4.3, would be very difficult to be described by any mathematical function. Furthermore, the signal is unique and is strongly related to the type and degree of wear occurring at the cutting edges.

Knowing the fact that vibration signals are non deterministic, it was decided to describe the characteristic of the signals by some sort of statistical functions, such as central tendency, spread/dispersion, asymmetry, etc. This statistical analysis was performed in the time domain.

The following were the statistical parameters chosen for study:
1). Mean value.
2). Standard deviation.
3). Skew.
4). Kurtosis.
5). RMS of the distribution.

4.2. Equipment selection.

Essentially, five pieces of equipment were selected in this data analysing process, as shown in Figure 4.4. There were the tape recorder, B&K 7005 or Nagra IV-JS, for the signal playback, B&K wideband filter (0-10 kHz), AI13 A/D converter (analog to digital signal conversion), Apple II plus computer for performing the data analysis, and the Prowler Digital Oscilloscope for providing visual aid to the signal being analysed.
Figure 4.4 Schematic diagram for the data analysis.
The very first step in the data processing involved the playback of the stored vibration signals, using the same recorder on which the tape was recorded. This helps to minimize any time base errors in signal reproduction which could be due to variation in recording speed between recorders, and/or skew (variation in angle at which the tape passes over the head). Other errors introduced by the tape itself such as dimensional changes of the tape due to temperature, humidity, and tension should also be noted.

The signals were filtered by passing them through a B&K 2638 wideband filter. The passband of the filter used was from 0.1 to 10 kHz. The passband frequencies were chosen mainly because of the fact that the predominant drill vibration in this range was shown to be sensitive to drill wear [53, 64]. According to Xistris, Boast and Sankar [78], an analysis system capable of processing signals with the frequency content up to 10 kHz is sufficient for this type of machinery vibration monitoring.

The filtered analog signals were digitized using AI13 A/D converter which has a sampling rate of 20 kHz. The AI13 A/D converter is a high performance 12-bit data acquisition system for the Apple II computer. It plugs directly into any one of the Apple expansion slots and gives the Apple the ability to make precision voltage measurements. It can select one of the 16 input channels, scale the input according to any one of the 8 full-scale range, and return the result in less than 20 microseconds, represented by a number between 0 and 4095. The conversion process is done by some successive approximation
steps, a binary search for the value of the unknown input signal. A more detailed description of this piece of equipment is given in Appendix B. The digitized data were stored in the memory of the Apple II plus computer and were then analysed by programs written in Applesoft Basic.

The sole function of the prowler digital oscilloscope was to provide visual presentation of signals being analysed. This piece of equipment is manufactured by Norland corporation and has three functional characteristics, namely as an oscilloscope capable of acquiring signals from dc to 20 MHz, powerful analysis instrument with a variety of pre-programmed operations, and it is programmable.

4.3. Data Preparation.

In most cases, signal/raw data has to be "prepared" before any detailed analysis can be performed. In this study, as the analysis was performed digitally, the preparation steps can be grouped as follow:

1). Data editing.
2). Digitization.
4.3.1. Data Editing.

Data editing is the process involving the playing-back of vibration signals on the tape recorder and displaying them on the Prowler digital oscilloscope. By visually inspecting the signals, it was easy to determine if they were recorded properly in terms of signal to noise ratio, and whether enough gain or attenuation had been introduced prior to recording. Hence, it is designed mainly to detect and eliminate spurious and/or degraded data signals which might have resulted from acquisition and recording problems such as those mentioned above i.e. excessive noise, signal dropout, etc. Another valuable piece of information can also be extracted through this process, namely the highest amplitude range of the signal, which is very useful in the digitization process.

4.3.2. Digitization.

It consists of two distinct operations: sampling, and quantization. In this study, these operations were performed by the A113 A/D converter. The process consists of 6 microseconds of sampling and hold, and 13 microseconds of conversion time (quantization). This operation is very important in all analysis which involves the data conversion from analog to digital, hence special attention should be paid to the theory, processing, and potential sources of error encountered.

4.3.2.1. Sampling.

Sampling is the process of defining the instantaneous points of some continuous time record. Figure 4.5
Figure 4.5 Sampling process of a continuous time record.
shows the process of sampling of a continuous record. As can be seen, sampling is usually performed at equally spaced intervals "h". Determination of this sampling interval, "h" does involve some theoretical justification. Too small a sample interval will result in highly redundant data, and thus an unnecessary increase in the labour and cost of calculations. On the other hand, sampling at points which are too far apart will lead to confusion between the low and high frequency components in the original data. The latter problem is called aliasing. From theory, in order to eliminate the problem of aliasing, the sampling rate required for A/D should be at least 2.56 time the highest cutoff frequency of the original data.

Unfortunately, due to the limited memory space in the Apple II plus computer (64 k), one additional quantity has to be introduced in this sampling process, namely sampling interval delay (Ds). As the name implies, sampling interval delay will decrease the sampling range of points of the original data. It can be incorporated into this sampling operation by using Figure 4.6, after knowing the number of digitized data desired and the time required in drilling a hole.

4.3.2.2: Quantization.

It is a process of representing the magnitude of each data sample by some number. Since only a fixed number of levels are available for approximating the infinite number of levels in the continuous data, a choice between two consecutive values will be required. The error occurring in this data representation is called quantization error and in most cases it
Figure 4.6 Plot of interval delay versus time at different number of digitized data.
is unimportant relative to other sources of error in the data acquisition and processing procedures. Using the AI13 A/D converter, the range of numbers representing the data sampled is between 0 to 4095. To minimize this quantization error, care should be exercised to assure that the amplitude range of the continuous data is set to occupy as much of the available quantizing range as possible. As can be seen, the determination of the highest amplitude range of the analog signal during the process of data editing is important.

Conversion of the digitized data back to physical units is needed in most cases of data analysis. Knowing that, most digitizing procedures produce information in units that are related linearly to the true physical units, a common technique is to digitize a reference or calibration signal at the same time the data are digitized. It is then possible to determine the relationship between digitized units and physical units directly. In this study, a calibration signal of 158 Hz with magnitude of 1 g (gravitational unit), has been recorded on the start of every new tape, solely to serve the above purpose in data processing.

4.4. Data analysing procedures.

With the digitized data residing in the computer memory, two operations can be performed on the data, namely store the raw data onto the diskette, and/or go through a 'grouping' operation. Generally speaking, those two operations are equally time consuming. Figure 4.7 shows just how it would take to store or group different number of digitized data.
Figure 4.7 Time required to store and group different number of digitized data.
If the data are in the order in which they occur, they are said to be in the form of ungrouped data/raw data. Grouping of data in classes of equal interval/width can be proven to be more advantageous if the total number of samples is greater than 40 [50]. Arrangement of samples in class interval, with the class frequencies tallied, produces a grouped frequency distribution of amplitude or statistical frequency distribution. The noted advantages of grouping over ungrouped data are: faster statistical computation and the frequency of occurrence or clustering at different class intervals can be easily determined from the distribution. The choice of the number of classes in this grouping operation has been simulated and obtained by a computer program.

Figure 4.8 shows the computation time needed in calculating the five statistical parameters, previously mentioned, on a grouped as compared to ungrouped raw data. Clearly, the grouped case has a significant reduction in the computation time, more so as the sample taken increase in size. In this project, all statistical analyses were started with grouping of the raw data. Figure 4.9 shows diagrammatically the process of digitizing the analog signal and expressing the digitized data in the form of a statistical frequency distribution (grouping).

Information about the characteristics of the statistical frequency distribution can be described through the measure of its central tendency, dispersion, asymmetry, and peakedness.
Figure 4.8 Computation time required to calculate those statistical parameters of grouped data as compared to ungrouped case.
Figure 4.9 The schematic diagram of digitization, and grouping process.
In order to present information about the distribution in a clear and concise form, some sort of numerical measure of those characteristics have to be developed.

Suppose in a statistical frequency distribution, there are $N$ different values $X_1, X_2, X_3, \ldots, X_N$ which occur respectively $F_1, F_2, F_3, \ldots, F_N$ times; as shown in Figure 4.10. The $r^{th}$ moment of the distribution about the weighted mean $\bar{X}$ can be defined by

$$M_r = \frac{\sum_{i=1}^{N} F_i (X_i - \bar{X})^r}{\sum_{i=1}^{N} F_i} \quad 4.1$$

$$\bar{X} = \frac{\sum_{i=1}^{N} F_i X_i}{\sum_{i=1}^{N} F_i} \quad 4.2$$

4.4.1. **Measure of central tendency.**

Observations generally have the tendency to center or group themselves around a central value. The measure that can be used to describe this characteristic is the mean $\bar{X}$ defined by equation 4.2. The mean is also known as the first moment about the origin.
Figure 4.10 Typical statistical frequency distribution.

Figure 4.11 Distributions with different degree of dispersion.
4.4.2. Measure of dispersion.

Dispersion can be defined as the degree of clusterness of observations about the mean. As shown in Figure 4.11 clearly, both distributions exhibit essentially the same central tendency, but distribution A does show less variation about the mean than distribution B.

The measure that can be used to show this characteristic of the distribution is the second moment about the mean, defined by equation 4.1, with \( r=2 \), called the variance. As the dimension of variance is in square units, which is sometimes awkward to interpret, another measure, called standard deviation, i.e. the positive square root of the variance, is used. It is defined by

\[
\sigma = (M_2)^{0.5}
\]

4.4.3. Measure of asymmetry.

Consider the three distributions as shown in Figure 4.12. Distribution A is symmetrical, whereas distribution B and C show lack of symmetry. So skew, 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.

\[
\mu_3 = M_3 / (M_2)^{3/2}
\]
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 4.12, distribution A has the value of $\mu_3$ equal 0 where as distribution B and C have the sign of $\mu_3$ to be positive and negative respectively.

4.4.4. Measure of peakedness.

As shown in Figure 4.13, all three distributions exhibit more or less the same central tendency, dispersion, and the same symmetry, but different degree of peakedness. Kurtosis, the fourth order normalized central moment is the measure that is needed to describe this characteristic of the distribution and is defined as follow.

$$
\mu_4 = \frac{M_4}{(M_2)^2}
$$

4.5

This measure, however, is very sensitive to the tails of the distribution. In other word, it is dominated by the deviations from the mean to the fourth order.

From Figure 4.13, distribution A has more or less a normal distribution, hence the corresponding kurtosis value will be close to 3. Distribution B has a larger deviation than A, hence its kurtosis will have a value greater than 3. Distribution C has the largest deviation among the three, therefore its kurtosis will be the largest.
Figure 4.12 Distributions with different degree of asymmetry.

Figure 4.13 Distributions with different degree of peakedness.
Another measure of the peakedness of the distribution, which is not sensitive to the spread of the tails of the distribution, is the RMS of the distribution defined by the following formula.

\[ \text{RMS} = \sqrt{\frac{\sum_{i=1}^{N} f_i^2}{N}} \]

4.5. **Computer program.**

Under the situation where the analysing procedure is definable, repetitive and involving large quantity of data, it is justifiable to use a computer for processing. In this study, three major Applesoft basic programs were written for data processing. Figure 4.14 shows the schematic diagram of the computer-network used.

4.5.1. **Data acquisition program.**

The data is acquired from the tape recorder through the use of the AI13 A/D converter. As storing the digitized data onto the diskette and 'grouping' take more or less the same amount of time, but with a significant increase in storage space needed on the diskette, the following options were included in this program.

1). Acquiring data by specifying the number of digitized data desired (N), the amount of sample interval delay needed (D),
Figure 4.14 Schematic diagram of the computer-network employed.
and the selection of the input signal level (GC).

2). Option of storing the digitized data onto the diskette and/or proceeding to the grouping operation.

3). Acquire another signal.

Figure 4.15 shows the top-level flow-chart of this data acquisition program. The program listing is included in Appendix C.

4.5.2. **Statistical analysis program.**

This is the program that calculates the five chosen statistical parameters. The analysis can be performed either on the grouped or ungrouped data. In addition, routines such as grouping, storing the statistical data (grouped) and statistical results onto the diskette, printing of raw data, statistical data and results either on the screen or the printer, are also included. The top-level flow-chart of this program is shown in Figure 4.16 and the program listing is also included in Appendix C.

4.5.3. **Plotting and curve-fitting program.**

This program plays a very important role in the data-analysis network as it is used not only at the early stages of the analysis for visual inspection of relationship between variables, but also for the presentation of final results at the final stage of the analysis. Presentation of data/results in graphic form has noted advantages over other form of presentation because it can be developed quickly and easily, outliers can be
N = Number of digitized data desired.
D = Sample interval delay.
GC = Gain-code (Range of the input signal).
DIV = Number of divisions/classes.

Figure 4.15 Top-level flow chart for the data acquisition program.
Figure 4.16 Top-level flow chart for the statistical analysis program.
identified easily and eliminated, and often a large amount of data can be presented in a compact form. The options included in this plotting and curve-fit program were:

1). Location of data/results.

2). Device used for plotting namely: screen, printer, or plotter.

3). Elimination of outliers through the data-manipulation routine.

4). Curve-fitting the data/results.

The top-level flow-chart of the program can be seen in Figure 4.17 and the program listing is available in Appendix C.
Figure 4.17 Top-level flow chart for the plotting and curve-fitting program.
Chapter V

DISCUSSION OF RESULTS

The results that are presented in this chapter correspond to the fifteen 3.18 mm diameter drill bits which were used for this investigation with additional results obtained from 6.35 mm drills. The analysing procedures which were described in Chapter IV were used.

Table 5.1 and Table 5.2, give basic data of all these drills, with additional information on operating conditions; drilling machine, workpiece material, vibration transducers, tape recorders and the tool-life observed in terms of the total number of holes drilled. All listing of the statistical results are included in Appendix A.

5.1 Drill-life distribution

As can be seen from Table 5.1, there is quite a scatter in the drill-life distribution for drills operated near the recommended conditions for the 3.18 mm diameter, namely, an operating speed of 1700 RPM and a feed rate of 0.002 in/Rev. Assuming that all drills in Table 5.1 are operated under similar conditions, then the observed mean drill-life is 26 holes with a standard deviation of 16 holes.

A similar analogy can also be drawn from Table 5.2, for the 6.35 mm drill-size, namely the observed mean drill-life is 25 holes with a standard deviation of 6 holes.

The coefficient of variation for this type of machining
Drill Diameter: 3.18 mm (1/8 in)
Manufacturer: Cleveland

<table>
<thead>
<tr>
<th>Drill #</th>
<th>Speed (RPM)</th>
<th>Feed Rate (in/rev)</th>
<th>Machine Tool</th>
<th>Acc. Type</th>
<th>Tape Recorder</th>
<th>Workpiece Material</th>
<th>Total #</th>
<th>Vib. signal</th>
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<td>BK 7005</td>
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</tr>
<tr>
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<td></td>
<td>Colchester</td>
<td>PC8 307A</td>
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<td>59 db</td>
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</tbody>
</table>

Table 5.1. Drilling data for 3.18 mm drill-size.

Drill Diameter: 6.35 mm (1/4 in)
Manufacturer: OSBORNE-MUSHET

<table>
<thead>
<tr>
<th>Drill #</th>
<th>Speed (RPM)</th>
<th>Feed Rate (in/rev)</th>
<th>Machine Tool</th>
<th>Acc. Type</th>
<th>Tape Recorder</th>
<th>Workpiece Material</th>
<th>Total #</th>
<th>Vib. signal</th>
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</tr>
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<td></td>
<td>44</td>
<td>59 db</td>
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</tbody>
</table>

Table 5.2. Drilling data for 6.35 mm drill-size.
operation can be as high as 0.6[42].

5.2. Time-amplitude signal.

There is a definite difference between the amplitude vs time signal for the 3.18 mm and 6.35 mm drill-sizes, as can be seen in Figures 5.1 and 5.2, respectively. Generally, for the 3.18 mm drill-size, the signal can be classified to be more uniformly distributed (denser) throughout each drilling sequence of about 3 seconds and there is an increase in the level of spikiness or amplitude level with wear, as can be seen in Figure 5.3. For the 6.35 mm drill-size, signals are less uniformly distributed as in the case for 3.18 mm drill-size, but significant increases in the level of spikiness or amplitude level are observed with wear, as shown in Figure 5.4. Vibration signals obtained with the 6.35 mm drill-size, generally speaking, exhibit a larger amplitude level than those for the 3.18 mm drills, roughly in the ratio of 5 to 1.

5.3. Tip wear curve.

As shown in Figure 5.5, there are four groups of tip wear curves observed in this research. That is, with chipping occurring at the cutting lips during the early part of the drilling process as shown by curve A, with a very rapid rate of tip wear and fails when levelling off as in curve B, an initial and final rapid wear phase separated by a normal section as shown by curve C, and lastly, curve D with a roughly opposite characteristics to that of C. Curve C corresponds reasonably
Figure 5.1 Vibration signal for 3.18 mm drill-size.

Figure 5.2 Vibration signal for 6.35 mm drill-size.
Figure 5.3 Vibration signals at various degree of tip wear for 3.18 mm drill-size.
Figure 5.4 Vibration signals at various degrees of tip wear for 6.35 mm drill-size.
Figure 5.5 Typical set of tip wear curves observed.
close to normal drill wear and offers the best trend for wear monitoring.

An explanation of the behaviour of curve C is given in [6, 37, 60]. Initially when the drill is sharp, the real area of contact between the tool and workpiece A, is essentially zero, hence P/A, the uniaxial flow stress of the material, is much greater than Hb/3, a quantity related to the hardness of tool material, which results in a high wear rate. The rate of wear decreases as the value of A increases and eventually at a point where thermal softening occurs, the hardness of the material, Hb decreases, which again brings about a high wear rate until failure occurs. Of course, there are other factors that can influence the rate of wear, such as the tool and workpiece material history, its homogeneity, operating speed and feed rate, drilling machine, etc.

The machine tool also has some influence on drill-life, the type of dominant wear mechanism, and most of all, the vibration signal being picked up by the transducer. It is difficult to conclude at this point how the machine will influence the drill performance, but some indication of the effect by three machine tools is presented in Table 5.3. From the table, Harrison M400 seems to be the best among the three drilling machines, in term of the average drill-life obtained, assuming negligible effects due to the differential in the operating conditions.

Monitoring drill health for different drilling machines using vibration signals emitted during operation, is currently
investigated in another project. There, more emphasis will be placed on establishing and identifying the different frequency components from the drilling machines or other related source during operations.

<table>
<thead>
<tr>
<th>Drilling machine</th>
<th>Operating conditions</th>
<th>Average drill life</th>
<th>Type of Tip wear curve</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Speed (RPM)</td>
<td>Feed rate (in/Rev)</td>
<td>holes</td>
</tr>
<tr>
<td>3.18 mm Drill diameter.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harrison M 400</td>
<td>2000</td>
<td>0.0004</td>
<td>35</td>
</tr>
<tr>
<td>Colchester Master 2500</td>
<td>1860</td>
<td>0.0004</td>
<td>29</td>
</tr>
<tr>
<td>Okuma Type LS</td>
<td>2000</td>
<td>0.0028</td>
<td>24</td>
</tr>
<tr>
<td>Okuma Type LS</td>
<td>2000</td>
<td>0.0036</td>
<td>12</td>
</tr>
<tr>
<td>Okuma Type LS</td>
<td>2000</td>
<td>0.0031</td>
<td>15</td>
</tr>
<tr>
<td>6.35 mm Drill diameter.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Okuma Type LS</td>
<td>1100</td>
<td>0.0052</td>
<td>25</td>
</tr>
<tr>
<td>Harrison M 400</td>
<td>1000</td>
<td>0.005</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 5.3. Drill performance on different drilling machines.
5.4. Statistical parameters.

5.4.1. Statistical frequency distribution of the signals.

As mentioned before, time-amplitude signals were grouped before any statistical analysis was performed, mainly in order to reduce the analysis time involved. The grouped data known as the statistical frequency distribution for 3.18 mm drill-size can be seen in Figure 5.6. Generally, as the wear increases, the height of the distribution decreases with a corresponding increase in the spread/base of the distribution. Figure 5.7 shows the statistical frequency distribution of the vibration signals for 6.35 mm drill-size. In this case, the changes with wear are not as clearly defined as previously and significant changes can be observed only when tool failure is imminent, that is, when the tip wear is greater than 42%.

5.4.2. Standard deviation and RMS of the distribution.

Plot of standard deviation versus percentage tip wear for the 3.18 mm drill size is shown in Figure 5.8. At approximately 60 percentage tip wear and standard deviation of 2 EU, the curve started to rise rapidly until failure. In other words, this stage of rapid increase in standard deviation signifies that drill failure is imminent and tool replacement is needed.

Figure 5.9 shows an inverse relationship of RMS of the distribution with percentage tip wear.

A definite trend exists between the standard deviation...
Figure 5.6 Statistical frequency distribution of 3.18-mm drill-size at various degree of tip wear.
Figure 5.7 Statistical frequency distribution of 6.35 mm drill-size at various degree of tip wear.
Figure 5.8: Plot of standard deviation versus percentage tip wear for 3.18 mm drill-size.
Figure 5.9 Plot of RMS of the distribution versus percentage tip wear for 3.18 mm drill-size.
and the RMS of the distribution against different groups of tip wear curves as mentioned before for different drilling machines. Table 5.4 gives an account of the values of those statistical descriptors and the related parameters at that instant when rapid changes occur.

<table>
<thead>
<tr>
<th>Drilling machine</th>
<th>Drill number</th>
<th>St. Dev. (EU)</th>
<th>RMS</th>
<th>% Tip wear</th>
<th>% Life Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harrison M 400</td>
<td>A1 2</td>
<td>1.2</td>
<td>57</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A2 6.25</td>
<td>1.1</td>
<td>69</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A3 6</td>
<td>1.1</td>
<td>68</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A4 6.1</td>
<td>1</td>
<td>63</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>Colchester Master 2500</td>
<td>B1 2</td>
<td>1.5</td>
<td>40</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Colchester Master 2500</td>
<td>B2 2</td>
<td>1.8</td>
<td>27</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3 2</td>
<td>1.7</td>
<td>29</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>Okuma Type LS</td>
<td>C1 1</td>
<td>1.2</td>
<td>45</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td>Okuma Type LS</td>
<td>C2 1</td>
<td>1.3</td>
<td>54</td>
<td>74</td>
<td></td>
</tr>
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<td>Okuma Type LS</td>
<td>C3 0.9</td>
<td>1.5</td>
<td>38</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>Okuma Type LS</td>
<td>C4 0.9</td>
<td>1.3</td>
<td>60</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>Okuma Type LS</td>
<td>C5 1.05</td>
<td>1.4</td>
<td>42</td>
<td>75</td>
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</tr>
<tr>
<td>Okuma Type LS</td>
<td>C6 1.1</td>
<td>1.3</td>
<td>46</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>Okuma Type LS</td>
<td>C7 1.04</td>
<td>1.4</td>
<td>36</td>
<td>80</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.4. Standard deviation and RMS of the distribution for 3.18 mm drill-size.

As can be seen in Table 5.4, for different drilling machines, different standard deviation and RMS values are observed. It was found that standard deviation does vary to some degree with type of drill wear occurring at the cutting lips and this variation is dependent on the type of drilling machine. For instance, Harrison M-400 lathe induces a significant drill
wear at the cutting lips. Drill# A1 exhibits a normal type of wear and the observed standard deviation is 2 whereas the rest with some chipping on the lips have a value of about 6. The RMS was found to be around 1.1 for all cases. As for the other two lathes, the standard deviation was found to be around 2 and 1 and the corresponding RMS values of 1.7 and 1.3, regardless of the type of drill wear involved during the operation.

The above observations can be reproduced reasonably consistently for the 3.18 mm drill-size. However, for the drill-size of 6.35 mm, only a very weak relationships exists mainly due to the nature of vibration signals generated during the drilling process, namely, the uniformity and the denseness of the vibration signal together with its level of spikiness. The plot of standard deviation and RMS of the distribution with percentage tip wear are shown in Figures 5.10 and 5.11, respectively.

5.4.3. Mean values.

Mean values of the signal for both 3.18 mm and 6.35 mm drill-size remained fairly constant at 0 volts at all time as shown in Figure 5.12.

5.4.4. Skew and kurtosis values.

A typical plot of skew and kurtosis values versus percentage tip wear for 3.18 mm drill-size can be seen in Figures 5.13 and 5.14, respectively. In both plots, large and cyclic fluctuations in the values occur for a major portion of the
Figure 5.10 Plot of standard deviation versus percentage tip wear for 6.35mm drill-size.
Figure 5.11 Plot of RMS of the distribution versus percentage tip wear for 6.35mm drill-size.
Figure 5.12 Plot of mean versus percentage tip wear.
Figure 5.13 Plot of skew versus percentage tip wear for 3.18 mm drill-size.
Figure 5.14 Plot of kurtosis versus percentage tip wear for 3.18 mm drill-size.
tool-life, except at the initial portion and the portion just prior to tool failure. As mentioned before, in the section on "Analysis of data", those two descriptors are somewhat sensitive to the spread of the distribution, especially in cases with few peaks that are clearly distinct from the rest.

In a tool wear model, presented by Braun, Lenz and Wu [10], it was stated that due to production tolerances a drill is slightly asymmetric, hence it only wears at one lip until the heights of both lips are equal. The second lip, which is now sharper, starts cutting more. Depending on the dullness of the cutting lips, different vibration levels are observed. This alternating process continues until both lips have no more clearance at the margin. At this time, the drill sticks to the workpiece and breaks if the drilling process is not stopped in time. This model of an alternate wearing process at the cutting lips is suggested by the cyclic-fluctuating values of skew and kurtosis, as shown in Figures 5.13 and 5.14, respectively. The magnitude of the fluctuation is dependent upon the differences in sharpness between the two lips and also the stage of the tool's condition. Just prior to tool failure, both lips are having the same degree of dullness and bring about a high level of vibration, hence give rise to small values of skew and kurtosis. The state of convergency of this two descriptors, in general, corresponds to the situation when the drill is about to fail and to a significant change in the standard deviation and RMS of the distribution. Table 5.5 shows the skew and kurtosis values at the above mentioned state. As can be seen from the
values at the above mentioned state. As can be seen from the Table, skew does not show any consistency in values at the state just prior to drill failure, however it is a small number. On the other hand, depending on the type of drilling machine, different kurtosis values are obtained. For Harrison M-400, the kurtosis value is about 8 whereas the other two lathes have the value of about 19.

<table>
<thead>
<tr>
<th>Drilling machine</th>
<th>Drill number</th>
<th>skew</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harrison M 400</td>
<td>A1</td>
<td>0.04</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>0.19</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>0.02</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>A4</td>
<td>0.01</td>
<td>5.2</td>
</tr>
<tr>
<td>Colchester</td>
<td>B1</td>
<td>0.59</td>
<td>19</td>
</tr>
<tr>
<td>Master 2500</td>
<td>B2</td>
<td>-0.4</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>-1.2</td>
<td>19</td>
</tr>
<tr>
<td>Okuma Type LS</td>
<td>C1</td>
<td>0.5</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>0.08</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>-1.3</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>C4</td>
<td>0.33</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>C5</td>
<td>-1.1</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>C6</td>
<td>-1.3</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>C7</td>
<td>0.9</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 5.5. Skew and kurtosis values when breakage is imminent.

However, due to the lower density and high level of spikiness of the vibration signal for the 6.35 mm drill-size, which give rise to a large spread in the frequency distribution, no promising relationships of skew and kurtosis with wear were found, as can be seen in Figures 5.15 and 5.16, respectively.
Figure 5.15 Plot of skew versus percentage tip wear for 6.35 mm drill-size.
Figure 5.16 Plot of kurtosis versus percentage tip wear for 6.35 mm drill-size.
Due to the distinct characteristic behaviour of standard deviation and RMS of the distribution with tip wear, another descriptor, namely, variance/RMS was developed. This descriptor, improves the sensitivity to tip wear and exhibits a significant rise in the curve when failure is imminent as shown in Figure 5.17; however, it is not good for 6.35mm diameter drill bits.

5.5. Influence of the number of sampled points on the statistical results.

The number of digitized points chosen in this project illustrates a compromise between the computer memory available and the time involved in drilling a hole. It was accomplished by introducing some sample interval delay when required, as described before. Two drills, drill# C2 of 3.18 mm diameter and drill# E1 of 6.35 mm diameter were chosen in the study because they both exhibited a closely normal type of tip wear curve. Due to the limited capacity of the computer memory, the maximum number of sampled points allowed is 6000. Hence, six groups of sampled points were chosen, namely 1000, 1200, 1500, 2000, 3000 and 6000. A selective number of vibration signals were picked for the evaluation, as shown in Table 5.6.

In general, standard deviation and RMS of the distribution are not that sensitive to the number of sampled points taken as can be seen in Figures 5.18, 5.19, 5.20 and 5.21. Each cross on the plot denotes a descriptor's value at a specific number of sampled point. The spread of those crosses illustrates the sensitivity of the descriptor to the number of sampled
Figure 5.17 Plot of variance/RMS versus percentage tip wear for 3.18 mm drill-size.
Figure 5.18 Effects of sample sizes on standard deviation for 3.18 mm drill-size.
Figure 5.19 Effects of sample sizes on standard deviation for 6.35 mm drill-size.
Figure 5.20 Effects of sample sizes on RMS of the distribution for 3.18 mm drill-size.
Figure 5.21 Effects of sample sizes on RMS of the distribution for 6.35 mm drill-size.
points.

Skew and kurtosis, on the other hand, are very sensitive to the number of sampled points taken if the vibration signal is spiky, as is illustrated for the 6.35 mm drill-size shown in Figures 5.22 and 5.23.

Vibration signals for 3.18 mm diameter drill bits, generally change from a low amplitude and dense form, signifying sharp drilling, to transitional stage where the level of spikiness increases, and finally to a very dense and high amplitude form denoting that failure is imminent. During these transitional stages of the signals, skew and kurtosis are very sensitive to the number of sampled points taken as shown in Figures 5.24 and 5.25.

<table>
<thead>
<tr>
<th>DRILL# C2 (3.18 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole #</td>
</tr>
<tr>
<td>% tip wear: sharp</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DRILL# E1 (6.35 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole #</td>
</tr>
<tr>
<td>% tip wear: sharp</td>
</tr>
</tbody>
</table>

Table 5.6. Vibration signals used to study the influence of the number of sampled points on the statistical results.
Figure 5.22 Effects of sample sizes on skew for 6.35 mm drill-size.
Figure 5.23 Effects of sample sizes on kurtosis for 6.35 mm drill-size.
Figure 5.24 Effects of sample sizes on skew for 3.18 mm drill-size.
Figure 5.25 Effects of sample sizes on kurtosis for 3.18 mm drill-size.
5.6. **Consistency of the statistical results.**

5.6.1. **3.18 mm diameter drill bits.**

Four drills, namely drill# C1, C2, C3 and C4 from a same drilling machine, Okuma type LS, were picked in the study. Under the same operating conditions, a very consistent trend of standard deviation and RMS of the distribution Vs normalized tip wear were obtained as shown in Figures 5.26 and 5.27, respectively. Figure 5.28, plot of variance/RMS Vs normalized tip wear, shows a very significant upward trend when normalized tip wear is greater than 0.8. Skew and kurtosis, on the other hand, do not show consistency in the results except when failure is imminent as shown in Figure 5.29 and Figure 5.30, respectively.

5.6.2. **6.35 mm diameter drill bits.**

Three drills drilled on Okuma type LS lathe were picked, namely drill# D1, D2 and D3. There exists a weak correlation between standard deviation, RMS of the distribution and variance/RMS with the normalized tip wear as shown in Figures 5.31, 5.32 and 5.33, respectively. No consistency in the skew and kurtosis with normalized tip wear as shown in figures 5.34 and 5.35.
Figure 5.26 Standard deviation versus normalized tip wear for four 3.18 mm drills.
Figure 5.27 RMS of the distribution versus normalized tip wear for four 3.18 mm drills.
Figure 5.28 Variance/RMS versus normalized tip wear for four 3.18 mm drills.
Figure 5.29 Skew versus normalized tip wear for four 3.18 mm drills.
Figure 5.30 Kurtosis versus normalized tip wear for four 3.18 mm drills.
Figure 5.31 Standard deviation versus normalized tip wear for three 6.25 mm drills.
Figure 5.32 RMS of the distribution versus normalized tip wear for three 6.35 mm drills.
Figure 5.33 Variance/RMS versus normalized tip wear for three 6.35 mm drills.
Figure 5.34 Skew versus normalized tip wear for three 6.35 mm drills.
Figure 5.35 Kurtosis versus normalized tip wear for three 6.35 mm drills.
Chapter VI

CONCLUSIONS

The following conclusions have been reached, after studying the results of the data analysis:

1). Statistical results for the 3.18 mm drill-size were better in comparison to those obtained from the 6.35 mm drill. This was predominantly due to the nature of the vibration signal obtained during the operation, i.e., more dense and spikes are more uniformly distributed for the smaller size.

2). The sampling rate which was used for digitizing has a significant influence only when the analog signals are spiky and with descriptors that exhibit a higher central moment about the mean, such as skew and kurtosis.

3). Mean values of the time-amplitude signal were found to be fairly constant at zero volts for both drill-sizes.

4). Plots of standard deviation versus percentage tip-wear for the 3.18 mm drill-size exhibited a very consistent trend with a very suitable shape for monitoring purposes. Only a weak increase in standard deviation was found with tip wear for 6.35 mm diameter drill bits.

5). The RMS of the frequency distribution is a more effective measure of the peakedness of the distribution than kurtosis. Again, for the 3.18 mm drill-size it did shown a good and consistent trend when plotted against the percentage tip-wear. The corresponding results for the 6.35 mm drills were
far less useful.

6). Skew and kurtosis, generally, do not appear to be good descriptors for drill-wear monitoring, due to their random behaviour during a major portion of the drill-life. But they can be used as secondary descriptors for checking if tool failure is imminent because of their characteristic behaviour of convergence with wear. However, the author strongly feels that with a higher rate of sampling, ability to capturing more points, the effectiveness of these two descriptors will be improved. No correlation is evident between skew and kurtosis with tip wear for the 6.35 mm diameter drill bits.

7). The descriptor, variance/RMS significantly improves the sensitivity to tip wear, especially when failure is imminent, for 3.18 mm but not for 6.35 mm diameter drill bits.
Chapter VII

RECOMMENDATIONS

The use of vibration, with statistically evaluated descriptors, for tool-wear monitoring has great promise. However, there are still quite a number of areas that can be improved.

(1). The dynamic frequency range of the accelerometer-tape-recorder combination could have been higher instead of the 20 KHz.

(2). The A/D convertor used has a highest sampling rate of 20 KHz. A higher value is likely to improve results, particularly for larger diameter drills.

(3). A procedure using a larger number of points would improve the results.

(4). At present, only two drill-sizes were studied, namely 3.18 mm and 6.35 mm. In order to provide better basic information for monitoring system, the scope of the investigation should be extended to include:

(a). Different drill-size;

(b). Different drill and workpiece materials;

(c). Different drilling-machines;
REFERENCES


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APPENDIX A.

Statistical Results
<table>
<thead>
<tr>
<th>HOLE#</th>
<th>% WEAR</th>
<th>MEAN</th>
<th>ST. DEV</th>
<th>SKEW</th>
<th>KURTOSIS</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
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<td>4.094</td>
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<td>6.359</td>
<td>2.848</td>
</tr>
<tr>
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<td>15.11</td>
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<td>2.830</td>
</tr>
<tr>
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<td>15.74</td>
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</tr>
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<td>19.21</td>
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<td>3.474</td>
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</tr>
<tr>
<td>5</td>
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<td>0</td>
<td>.3190</td>
<td>1.823</td>
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</tr>
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<td>2.555</td>
</tr>
<tr>
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</tr>
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<td>8</td>
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</tr>
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<td>18</td>
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<td>41.02</td>
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131
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**COLCHESTER MASTER 2500, SPEED=1860 RPM, FEED=0.004 IN/REV**

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132
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**OKUMA TYPE LS, SPEED=2000 RPM, FEED=0.0031 IN/REV**

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**DRILL SIZE:** 3.18 mm

OKUMA TYPE LS, SPEED=2000 RPM, FEED=0.0036 IN/REV

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### DRILL #:C6
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Appendix B.

AI13 A/D Converter
A113 A/D Converter

The A113 Analog Input System is a high-performance 12-bit data acquisition system for the Apple II computer. It plugs directly into one of the expansion slots and gives the Apple the ability to make precision voltage measurements.

With the A113, any instrument or sensor producing an electrical signal becomes an Apple II input device. Software selects the input range, so sensor output ranges from 0.5 volts down to 0-100 millivolts can be accommodated. The operation process is fast, allowing acquisition of DC through audio frequencies.

It is designed to make voltage readings and return a number proportional to the result for analysis by a program. It can select one of the 16 input channels, scale the input according to any of the 8 full-scale ranges, and return the result in less than 20 microseconds. Table B.1 gives all the A113 performance specifications.

When a conversion is requested by the program, the desired analog signal is selected by a 16 channel multiplexer. The signal is sampled for a 6 microseconds interval, then held constant by a sample and hold amplifier. The conversion process consists of twelve 1-microsecond successive approximation steps, a binary search for the value of the unknown input signal. The converter first tests the signal to determine if it is in the upper or the lower half of the range. This determines the most significant bit. Next a test is made to determine which quarter
within the half contains the signal value, then which eighth
within that quarter, etc. The most significant four bits are
completed after a total of 11 microseconds including hole and
conversion time. In high speed applications, the program may
actually read these four bits before the entire conversion is
completed and thus "overlap" the read and convert functions. The
complete 12-bit result is ready after 19 microseconds. Figure B.1
shows schematically how this conversion process is done by AI13
A/D converter.

Modification of one of the five programs, namely GETAI13
available on the demonstration diskette is needed in order to suit
the needs of this project. GETAI13 is a utility subroutine which
rapidly makes a list of analog readings and returns the results
to an Aplesoft program. The sampling rate during a call to
GETAI13 is approximately 20,000 samples per second.

Figure B.1 The schematic diagram of the A/D process in AI13.
Input Full-scale Ranges (volts)

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<tr>
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</tr>
<tr>
<td>2</td>
<td>0 TO 0.5</td>
</tr>
<tr>
<td>3</td>
<td>0 TO 0.1</td>
</tr>
<tr>
<td>4</td>
<td>-5.0 TO +5.0</td>
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<td>5</td>
<td>-1.0 TO +1.0</td>
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<td>-0.5 TO +0.5</td>
</tr>
<tr>
<td>7</td>
<td>-0.1 TO +0.1</td>
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</table>

Input Impedance: 10 MegaOhms.

Input Protection: 'Input can withstand 22 volts.

Resolution: 12 Bits, 4096 steps.

Coding: Binary, 0 to 4095 full-scale. 0 is min. 4095 is max. value.

Overrange Processing: Values greater Max. will appear as 4095. Values less than Min. appear as 0.

Deviation from ideal step size: 0.024 % maximum.

Selection and Sampling: 6 microseconds.

Hold and Conversion: 13 microseconds.

Total Conversion time: 20 microseconds.

Sampling Aperture: 125 nanoseconds.

Table B.1. A113 Performance Specifications
APPENDIX C.

Computer programs
COMPUTER PROGRAMS

Computer programs are a very essential part of this research project as a large quantity of data have to be captured, processed, and presented. As mentioned previously, three user-friendly computer programs, written in Applesoft basic were developed, each serves its unique purpose of data capturing (Data acquisition program), data processing (Statistical analysis program), and data presentation (Plotting and curve-fitting program). The related accessories used are:

1. DUMPLING-GX parallel printer interface-card.
2. EPSON SPECTRUM LX-80 Printer.
3. IEEE-488 INTERFACE CARD.
4. HP 7475A GRAPHICS PLOTTER.
5. AI13 A/D CONVERTER.

The listing for the three programs are included in the next few pages.
C.1. DATA ACQUISITION PROGRAM.

10 HOME: VTAB 10; PRINT TAB(12):"WAIT......"
20 REM
30 REM
40 REM
50 REM
60 REM
70 REM
80 REM
90 PRINT CHR$(4):"LOAD GETAIL3.DELAY,AS9000"
92 TEXT : HOME : VTAB 2; HTAB 10; PRINT "DATA ACQUISITION"
93 HTAB 10; FOR I = 1 TO 16; PRINT ":"; NEXT
100 DIM A$(1,4000),S$(260),X$(260),Y$(260)
110 REM
120 REM
130 REM
140 REM
150 REM
160 REM
170 REM
180 PRINT : PRINT
182 HTAB 8: INPUT "NUMBER OF DIGITIZED DATA :";PTS
189 HTAB 8: INPUT "ENTER DELAY VALUE:";D
200 .POKE 25,D
210 A$(0,0) = 5:A$(1,0) = PTS
220 HTAB 8: INPUT "GAIN CODE:";GC;DD = 1 + GC * 16
230 PRINT : PRINT TAB(16);"WAIT, SET UP CHANNEL"
240 FOR I = 1 TO PTS;A$(I,1) = DD; NEXT I
250 VTAB 23: HTAB 8: PRINT "PRESS ANY KEY TO "; INVERSE : PRINT "CAPTURE SIGNAL"; NORMAI : GET Z$,
260 REM **** CAPTURE DATA ****
270 POKE 8,1: CALL 36864
280 VTAB 23: HTAB 1: CALL - 868
290 VTAB 12; PRINT TAB(10);"1. STORE DATA ?": PRINT TAB(10);"2. DISP...
298 PRINT TAB(10);"3. GROUPING ?"
292 PRINT TAB(10);"4. ANOTHER SIGNAL ?": PRINT TAB(10);"5. EXIT ?"
300 VTAB 19: HTAB 10: INPUT "SELECTION (1-5):";ANS
302 IF VAL(ANS) < 1 OR VAL(ANS) > 5 THEN CALL - 868: GOTO 300
310 IF ANS = "2" THEN FOR I = 1 TO PTS; PRINT TAB(10);I; TAB(20);A$(I,1); NEXT I: GET Z$: HOME : GOTO 290
320 IF ANS = "3" THEN 490
321 IF ANS = "1" THEN 340
322 IF ANS = "4" THEN HOME : GOTO 1070
324 IF ANS = "5" THEN END
340 REM **** STORE RAW DATA ****
350 PRINT : INPUT "FILE # ? "; F
360 INPUT "FILENAME:":NAME$
370 INPUT "DRIVE(D1/D2) ? "";
380 INPUT "SATISFY (Y/N) ? ";OF
390 IF ANS = "N" THEN 350
400 PRINT CHR$(4):"OPEN":NAME$:", + DR$
420  PRINT HOLE: PRINT PTS
430  FOR KK = 1 TO PTS
440  PRINT A%(1,KK): NEXT KK
450  PRINT CHR$(4);"CLOSE"
452  GOTO 290
460  REM
490  HOME : VTAB 3: HTABLE: PRINT "GROUPING RAW DATA": PRINT
500  VTAB 5: HTABLE: PRINT "$ OF DIVISION/CLASS ":DIV
510  VTAB 7: HTABLE: INPUT "SATISFY (Y/N) ?":ANS: PRINT
520  IF ANS = "Y" THEN 700.
530  IF ANS < > "N" THEN 510
540  HTABLE: INPUT "NUMBER OF DIVISION ":DIV
570  REM
580  REM  "*********** GROUPING ROUTINE ***********"
590  REM  * SDR%(I) = CLASS BOUNDARY  * 
600  REM  * X%(I) = CLASS MID-POINT  * 
610  REM  * Y%(I) = CLASS FREQUENCY  * 
620  REM  "*********** GROUPING ROUTINE ***********"
630  RANGE = 4096
640  INC = RANGE / DIV.
650  SDR%(0) = 0
660  FOR I = 1 TO DIV
670  SDR%(I) = I * INC
680  X%(I) = (SDR%(I) + SDR%(I - 1)) / 2.
690  NEXT I.
700  HOME : HTABLE: PRINT "WAIT... GROUPING ":PTS
710  FOR I = 1 TO PTS
720  RRNT = INT (A%(1,I) / INC)
730  Y%(RRNT + 1) = Y%(RRNT + 1) + 1
740  NEXT I.
750  HOME : VTAB 10: HTABLE: PRINT "END...GROUPING":
760  PRINT : VTAB 15: HTABLE: PRINT "1). STORE STATS DATA ?": PRINT TAB( 
770  "40):"2.). PRINT STATS DATA ?": PRINT TAB( 10):"3). CONTINUE ?": PRINT 
780  HTABLE: INPUT "SELECTION (1/2/3) ":;ANS
790  IF ANS = "1" OR ANS > 3 THEN 760
790  IF ANS = "2" THEN 980
790  IF ANS = "3" THEN 1030
800  IF ANS = "1" THEN 810
802  REM  "**** STORE GROUPED DATA ****
810  REM  "HOLE #:"; HOLE
820  PRINT "FILENAME STORE(SD) ?":;NAMES
830  PRINT "DRIVE (D1YD2) ?":;DRS
840  VTAB 12: INPUT "SATISFY (Y/N) ?":;ANS
850  IF ANS = "N" THEN 810
860  VTAB 15: HTABLE: PRINT "SAVING...WAIT"
890  PRINT CHR$(4);"OPEN":NAMES + "," + DRS
900  PRINT CHR$(4);"WRITE":NAMES
910  PRINT HOLE: PRINT DIV
920  FOR I = 1 TO DIV: PRINT X%(I): PRINT Y%(I): NEXT I
930  PRINT TAB(16):"STATS DATA"
940  PRINT TAB(10):"AMPLITUDE";TAB(25):"OCCURANCE": FOR I = 1 TO 38: PRINT 
950  "-"; NEXT I: PRINT " "
970  HOME : PRINT TAB(16):""; NEXT I: PRINT " 
990  PRINT TAB(10):"AMPLITUDE"; TAB(25);"OCCURANCE": FOR I = 1 TO 38; PRINT 
990  "-"; NEXT I: PRINT " "
990  PRINT TAB(10):"AMPLITUDE"; TAB(25);"OCCURANCE": FOR I = 1 TO 38; PRINT 
990  "-"; NEXT I: PRINT " 
990
1000 FOR I = 1 TO DIV
1010 PRINT TAB(14);X$(I); TAB(28);Y$(I)
1020 NEXT I
1022 GET Z$; HOME; GOTO 760
1030 HOME; VTAB 3; INPUT "ANOTHER SET OF READING (Y/N)"; ANS
1040 IF ANS = "N" THEN 1120
1050 IF ANS < > "Y" THEN 1030
1060 FOR I = 1 TO DIV; Y$(I) = 0; NEXT I
1070 PRINT; PRINT "SATISFY WITH "; PTS; " POINTS & "; D; " DELAY"
1080 VTab 7; INPUT "(Y/N)"; ANS
1090 IF ANS = "Y" THEN 250
1100 IF ANS = "N" THEN 180
1110 GOTO 1080
1120 END
C.2. STATISTICAL ANALYSIS PROGRAM.

10 REM ****************************
20 REM * STATISTICAL ANALYSIS PROGRAM *
30 REM * OPTIONS AVAILABLE: *
40 REM * 1. DATA PREPARATION *
50 REM * 2. GROUPING RAW DATA *
60 REM * 3. READ/PRINT RAW DATA *
70 REM * 4. PRINT STATISTICAL DATA *
80 REM * 5. PRINT STATISTICAL RESULTS *
90 REM * 6. STATISTICAL ANALYSIS *
100 REM * NOTE: PRINTING DONE ON *
110 REM * SCREEN OR PRINTER *
120 REM ****************************
130 DATA "HOLE#", "MEAN", "STD", "SKEW", "KURT", "RMS"
140 DIM X(150), Y(150), HDS(9), DDM(150,10), YY(500)
150 DIM A0(5000)
160 FOR I = 1 TO 6: READ HDS(I): NEXT I
170 REM
180 REM
190 HOME: VTAB 3: PRINT "P2 V1.0"
200 POKE 34, 1: VTAB 3: PRINT TAB( 4)": ... STATISTICAL SIGNAL ANALYSIS :
... PRINT TAB( 4): FOR I = 1 TO 37: PRINT "=": NEXT I: PRINT
210 PRINT TAB(10);"1. DATA PREPARATION?"
220 PRINT TAB(10);"2. GROUP RAW DATA?"
230 PRINT TAB(10);"3. READ/PRINT RAW DATA?"
240 PRINT TAB(10);"4. PRINT STATS. DATA?"
250 PRINT TAB(10);"5. PRINT STATS. RESULTS?"
260 PRINT TAB(10);"6. STATS. ANALYSIS?"
270 PRINT TAB(10);"7. EXIT?": POKE 34, 11
280 PRINT : HTAB 6: INPUT "PRESS NUMBER TO RESPONSE (1-7)"; RES$ 
290 REM
300 REM
310 IF RES$ < "1" OR RES$ > "7" THEN VTAB 14: GOTO 280
320. POKE 34, 0
330 REM
340 IF RES$ = "2" THEN HOME: VTAB 2: PRINT TAB( 5)": GROUPING RAW DATA :
... POKE 34, 3: GOSUB 2410: POKE 34, 0 
350 REM
360 IF RES$ = "7" THEN 480 
370 REM
380 IF RES$ = "1" THEN HOME: VTAB 2: PRINT TAB( 8): "DATA PREPARATION :
... POKE 34, 3: GOSUB 2750: POKE 34, 0 
390 REM
400 IF RES$ = "3" THEN HOME: VTAB 2: PRINT TAB( 8): "READ/PRINT RAW DATA :
... POKE 34, 3: GOSUB 500: POKE 34, 0 
410 REM
420 IF RES$ = "4" THEN HOME: VTAB 2: PRINT TAB( 6): "PRINT STATISTICAL DATA :
... POKE 34, 3: GOSUB 1860: POKE 34, 0 
430 REM
440 IF RES$ = "5" THEN HOME: VTAB 2: PRINT TAB( 6): "STATISTICAL ANALYSIS :
... POKE 34, 3: GOSUB 900: POKE 34, 0 
450 REM
460 IF RES$ = "5" THEN HOME: VTAB 2: HTAB 6: PRINT "": PRINT STATISTICAL RESULTS :
... POKE 34, 3: GOSUB 2290: PRINT : HTAB 10: INPUT "# OF READINGS "; IC: GOSUB 1500: POKE 34, 0 
470 GOTO 190
510  REM *  READ/PRINT RAW DATA  *
520  REM ***************************
530  GOSUB 2290
540  PRINT CHR$(4);"OPEN";NAME$ + ":" + DRS
550  HOME: VTAB 5; PRINT TAB( 5);"WAIT....READING DATA FROM...";NAME$
560  PRINT CHR$(4);"READ";NAME$
570  INPUT HOLE: INPUT PTS
580  FOR I = 1 TO PTS
590  INPUT A$(I): NEXT I
600  PRINT CHR$(4);"CLOSE"
610  HOME: VTAB 5: HTAB 8: PRINT ":=";NAME$" HAS ";PTS;" POINTS <=="
620  VTAB 7: HTAB 10: PRINT ":1). PRINT ALL POINTS ?"; PRINT TAB( 10);"2)
630  . SOME INTERVAL ?"; PRINT TAB( 10);"3). CONTINUE ?"
640  VTAB 12: HTAB 10: INPUT "SELECTION (1/2/3)";AN
640  IF AN < 1 OR AN > 3 THEN 630
650  IF AN = 3 THEN 720
660  IF AN = 1 THEN PP = 1;LL = PTS: GOTO 690
670  PRINT : HTAB 10: INPUT "STARTING POINTS ";PP
680  HTAB 10: INPUT "ENDING POINT ";LL
690  GOSUB 1790
700  GOSUB 750
710  GET 2$: HOME: GOTO 610
720  RETURN
730  REM ***************************
740  REM *  PRINT RAW DATA-PRINTER  *
750  REM ***************************
760  IF AN = 2 THEN 840
770  PR# 1: PRINT CHR$(9);"80N": POKE 36,20: PRINT "POINT #";: POKE 36,
780  40: PRINT "AMPLITUDE"
790  FOR I = PP TO LL
800  PRINT I;: PRINT ":": PRINT LEFT$( STR$(A$(I)),5);: PRINT ":";
810  NEXT I
820  PR# 0: GOTO' 890
830  REM ***************************
840  REM *  PRINT RAW DATA-SCREEN  *
850  HOME: VTAB 4: PRINT TAB( 10);"POINT #"; TAB( 25);"AMPLITUDE": FOR
860  I = 1 TO 38: PRINT ":": NEXT I: PRINT ":": POKE 34,5
870  FOR I = FF TO LL
880  PRINT TAB( 13);I; TAB( 27);A$(I)
890  NEXT I
900  POKE 34,3: RETURN
910  REM ***************************
920  REM *  STATISTICAL ANALYSIS  *
930  HOME: VTAB 3: PRINT TAB( 13);"FOR 'SD' :-": GOSUB 2290
940  HTAB 13: PRINT "DATA SELECTION --" (1). UNGROUPED DATA ?": PRINT TAB( 13);"2). GROUPED
950  DATA ?": PRINT TAB( 13);"3). PROB. DENSITY ?"
960  HTAB 13: INPUT "SELECTION (1-3)";AN
970  NBM$ = NAME$;DDS = DRS
980  HTAB 5: INPUT "WANT TO STORE STATS RESULTS (Y/N) ?";AAS
990 IF AAS = "Y" THEN HOME: VTAB 3: CALL - 868: PRINT "TAB( 13):"FOR
'SR' := "": COSUB 2290: GOTO 1010
1000 IF AAS < > "N" THEN 980
1010 HOME
1020 PRINT CHR$ (4); "OPEN"; NMS + ";" + DD$ 
1030 PRINT CHR$ (4); "READ"; NMS
1040 FOR I = 0 TO 5; SUM(I) = 0: NEXT I
1050 INPUT HOLE: INPUT PTS
1060 FOR I = 1 TO PTS
1070 INPUT X(I): INPUT Y(I)
1080 NEXT I
1090 PRINT CHR$ (4); "CLOSE"
1100 VTAB 10: PRINT TAB(10); NMS$; " NMS$
1110 VTAB 23: CALL - 868: H1TAB 5: PRINT ";" WAIT! PROCESSING...."
1120 FOR I = 1 TO PTS
1130 SUM(0) = SUM(0) + Y(I) ^ 2
1140 ON AN GOTO 1150, 1160, 1170
1150 SUM(1) = SUM(1) + Y(I): GOTO 1180
1160 SUM(1) = SUM(1) + Y(I): SUM(2) = SUM(2) + X(I) * Y(I): GOTO 1180
1170 SUM(I) = SUM(I) + X(I) * Y(I)
1180 NEXT I
1190 RMS = (SUM(0) / PTS) ^ 0.5
1200 ON AN GOTO 1210, 1220, 1230
1210 YMEAN = SUM(1) / PTS: SUM(1) = 0: GOTO 1240
1220 YMEAN = SUM(2) / SUM(1): SUM(2) = 0: GOTO 1240
1230 YMEAN = SUM(1): SUM(1) = 0
1240 DY = MX
1250 FOR I = 1 TO PTS
1260 IF AN = 1 THEN YDEV = Y(I) - DY: GOTO 1280
1270 YDEV = X(I) - DY
1280 FOR J = 2 TO 4
1290 IF AN = 1 THEN SUM(J) = SUM(J) + YDEV ^ J: GOTO 1310
1300 SUM(J) = SUM(J) + YDEV ^ J * Y(I)
1310 NEXT J
1320 NEXT I
1330 IF AN = 3 THEN 1380
1340 FOR I = 2 TO 5
1350 IF AN = 1 THEN SUM(I) = SUM(I) / PTS: GOTO 1370
1360 SUM(I) = SUM(I) / SUM(I)
1370 NEXT I
1380 YSTD = SUM(2) ^ 0.5
1390 SK = SUM(3) / YSTD ^ 3
1400 KUR = SUM(4) / YSTD ^ 4
1410 PRINT "HOLE# = "; HOLE; " MEAN = "; YMEAN; " STA.D = "; YSTD
1420 PRINT "SKEW = "; SK; " KURT, = "; KUR; " RMS = "; RMS
1430 IF AAS = "N" THEN 1490
1440 PRINT CHR$ (4); "OPEN"; NMS$ + ";" + DR$.
1450 PRINT CHR$ (4); "APPEND"; NMS$ 
1460 PRINT CHR$ (4); "WRITE"; NMS$
1470 PRINT HOLE: PRINT YMEAN; PRINT YSTD; PRINT SK; PRINT KUR; PRINT RMS
1480 PRINT CHR$ (4); "CLOSE"; NMS$
1490 RETURN
1500 REM ***************
1510 REM * PRINT STATISTICS=RESULTS *
1520 REM ***************
1530 HOME: VTAB 10: HTAB 8: PRINT "WAIT! READING RESULTS....."
1540 PRINT CHR$ (4):"OPEN"; NAMES + ";" + DR$ 
1550 PRINT CHR$ (4):"READ"; NAMES 
1560 FOR I = 1 TO IC: FOR J = 1 TO 6: INPUT DDM(I,J): NEXT J: NEXT I 
1570 PRINT CHR$ (4):"CLOSE"
1580 IF AN = 3 THEN 1780 
1590 IF AN = 2 THEN 1700 
1600 REM *****************************************
1610 REM * PRINT (SR) - PRINTER * 
1620 REM *****************************************
1630 PRINT 1: PRINT CHR$ (9); "80N" 
1640 POKE 36,3;J = 1; FOR I = 4 TO 57 STEP 9; POKE 36,I: PRINT HEDS(J);; 
J = J + 1: NEXT I: PRINT ""
1650 FOR I = 1 TO IC 
1660 POKE 36,3;J = 1; FOR K = 4 TO 57 STEP 9; POKE 36,K: PRINT LEFT$( STR$( 
1670 DDM(I,J)),5);J = J + 1: NEXT K: PRINT "" 
1680 NEXT I 
1690 GO TO 1750 
1700 REM *****************************************
1710 REM *. PRINT (SR) - SCREEN * 
1720 REM *****************************************
1730 HOME: VTAB 2;J = 1; FOR I = 3 TO 33 STEP 6: PRINT TAB( I);HEDS(J);; 
J = J + 1: NEXT I; PRINT "; FOR I = 1 TO 38: PRINT "-";: NEXT I 
1740 FOR I = 1 TO IC 
1750 FOR J = 1 TO 6: PRINT TAB( J - 1 * 6): LEFT$( STR$( DDM(I,J)),5);: 
NEXT J 
1760 NEXT I 
1770 GET 2$ 
1780 RETURN 
1790 REM *****************************************
1800 REM * OUTPUT DEVICE SELECTION * 
1810 REM *****************************************
1820 HOME: VTAB 5; HTAB 13: PRINT ";1). PRINTER ?": PRINT TAB( 13);"2). 
SCREEN ?": PRINT TAB( 13);"3). CONTINUE ?" 
1830 VTAB 9; HTAB 13: INPUT "SELECTION (1/2/3) ":;AN 
1840 IF AN < 1 OR AN > 3 THEN 1830 
1850 RETURN 
1860 REM *****************************************
1870 REM * PRINT STATISTICAL DATA * 
1880 REM *****************************************
1890 COSUB 2290 
1900 COSUB 1790 
1910 HOME 
1920 PRINT CHR$ (4);"OPEN"; NAMES + ";" + DR$ 
1930 PRINT CHR$ (4);"READ"; NAMES 
1940 INPUT HOLE: INPUT PTS 
1950 FOR I = 1 TO PTS: INPUT X(I); INPUT Y(I): NEXT I 
1960 PRINT CHR$ (4);"CLOSE"
1970 IF AN = 1 THEN 2070 
1980 IF AN = 3 THEN 2160
1990 REM ***************************
2000 REM * PRINT (SD) - SCREEN *
2010 REM ***************************
2020 PRINT CHR$(4);"CLOSE"
2030 VTAB 4; CALL - 868: PRINT TAB(6);"POINT ";TAB(16);"AMPLITUDE"
2040 FOR K = 1 TO PTS
2050 CALL - 868: PRINT TAB(8);K;TAB(19);X(K);TAB(30);Y(K): NEXT K
2060 GET Z$: POKE 34,3; GOTO 2160
2070 REM ***************************
2080 REM * PRINT (SD) - PRINTER *
2090 REM ***************************
2092 INPUT "COL#":U
2100 PR# 1; PRINT CHR$(9);"80N"
2120 FOR I = 1 TO PTS
2130 POKE 36,U; PRINT LEFT$(STR$(X(I)),5): POKE 36,U + 6; PRINT LEFT$(
2140 NEXT I
2150 PR# 0
2160 RETURN
2170 REM ***************************
2180 REM * SEE CATALOG (D1/D2) *
2190 REM ***************************
2200 HOME
2210 VTAB 5; HTAB 9: PRINT ": WANT TO SEE CATALOG IN :"; PRINT
2220 PRINT TAB(10);"1"). DRIVE 1 ?"; PRINT TAB(10);"2). DRIVE 2 ?"; PRINT
2230 VTAB 12; HTAB 10: INPUT "SELECTION (1/2/3) ";SEL
2240 IF SEL = 1 THEN PRINT CHR$(4);"CATALOG,D1"
2250 IF SEL = 2 THEN PRINT CHR$(4);"CATALOG,D2"
2260 IF SEL = 3 THEN 2280
2270 GET Z$: GOTO 2200
2280 GET Z$: HOME : RETURN
2290 REM ***************************
2300 REM * FILE MANAGEMENT *
2310 REM ***************************
2320 VTAB 5
2330 HTAB 13: INPUT "FILENAME ":;NAMES
2340 HTAB 13: INPUT "STORE DRIVE(D1/D2) ";DRS
2350 VTAB 9; HTAB 8: INPUT "SATISFY ? Y/N,(C)AT,(R)ESTART ";ANS
2360 IF ANS = "Y" THEN GOSUB 2170: GOTO 2320
2370 IF ANS = "N" THEN 2320
2380 IF ANS = "R" THEN POKE 34,0: HOME : GOTO 200
2390 IF ANS < > "Y" THEN 2350
2400 RETURN
2410 REM ***************************
2420 REM * GROUPING (RD) *
2430 REM ***************************
2440 VTAB 5; HTAB 3: INPUT "DATA AVAILABLE IN MEMORY (Y/N) ";ANS
2450 IF ANS = "N" THEN GOSUB 500: GOTO 2480
2460 IF ANS < > "Y" THEN 2440
2480 HTAB 8: INPUT "NUMBER OF DIVISION ";DIV
2490 INC = 4096 / DIV
2492 X(0) = 0
2500 FOR K = 1 TO DIV
2510 X(K) = K * INC; Y(K) = 0: NEXT K
2520 FOR J = 1 TO Pts
2530 RRNT = INT (A(J) / INC)
2540 Y(RRNT + 1) = Y(RRNT + 1) + 1
2550 NEXT J
2560 HOME: VTAB 10: PRINT TAB(10); "WAIT......SAVING"; TX
2570 DL = X(CF - 1)
2580 FOR I = CF TO CL
2590 DU = X(I)
2610 \( \frac{X(I)}{DU} \) = \( \frac{DL + DU}{2} \)
2620 NEXT I
2630 PRINT CHR$(4); "OPEN"; NAMES + ";" + DR$...
2640 PRINT CHR$(4); "APPEND"; NAMES...
2650 PRINT CHR$(4); "WRITE"; NAMES...
2660 PRINT HOLE: PRINT DIV
2670 FOR I = 1 TO DIV
2680 PRINT X(I): PRINT Y(I)
2690 NEXT I
2700 PRINT CHR$(4); "CLOSE"
2710 FOR I = 1 TO DIV: Y(I) = 0: NEXT I
2720 NEXT TX
2730 HOME: VTAB 10: PRINT TAB(10); "GROUPING...", NAMES", "...DONE"
2740 GET Z$: RETURN
2750 REM ********************************************
2760 REM * DATA PERPARATION *
2770 REM * EXPRESS *:
2780 REM * AMPLITUDE IN 'EU'-X(I) *
2790 REM * FREQUENCY IN 'EU'-Y(I) *
2800 REM ********************************************
2810 HOME
2820 VTAB 3: HTAB 8: INPUT "SD IN MEMORY (Y/N, Q) ?"; ANS
2830 IF ANS = "Y" THEN 2850
2840 PRINT TAB(8); "GO AND GET (SD)...": GET Z$
2850 GOTO 3130
2860 VTAB 4: HTAB 8: INPUT "AMPL. CAL. SIGNAL ": CS.
2870 HTAB 8: INPUT "MEAN (CAL. SIGNAL) ": ME
2880 SS = 0
2890 FOR I = 1 TO Pts
2900 SS = SS + Y(I)
2910 DD = (X(I) - MX) / CS
2920 X(I) = DD
2930 NEXT I
2940 FOR I = 1 TO Pts
2950 IF SS = 0 THEN Y(I) = Y(I): GOTO 2970
2960 Y(I) = Y(I) / SS * 100
2970 NEXT I
2980 HTAB 8: INPUT "DISPLAY 'SD' (Y/N) ?"; ANS
2990 IF ANS = "N" THEN 3100
3000 FOR I = 1 TO Pts; PRINT X(I), Y(I): NEXT I
3010 PRINT: HTAB 8: INPUT "STORE DATA (Y/N) ?"; ANS
3020 IF AN$ = "N" THEN 3130
3030 IF AN$ < > "Y" THEN 3010
3040 GOSUB 2290
3050 PRINT : HTAB 8: PRINT "STORING DATA....."
3060 PRINT CHR$(4);"OPEN"; NAMES + ";" + DR$
3070 PRINT CHR$(4);"WRITE"; NAMES
3080 PRINT HOLE: PRINT PTS
3090 FOR I = 1 TO PTS
3100 PRINT X(I): PRINT Y(I)
3110 NEXT I
3120 PRINT CHR$(4);"CLOSE"
3130 RETURN
C.3. PLOTTING AND CURVE-FITTING PROGRAM.

10 CALL PEEK (175) + 256 * PEEK (176) - 46
20 & "RELOCATE"
40 L$ = "X-AXIS"
50 L$ = "Y-AXIS"
60 L$: = "X VS Y"
80 DIM A(10,10),R(10),V(10),P(20)
90 DIM X(200),Y(200),B(10)
130 OCS$ = "N"
140 HOME : VTAB 2; HTAB 10: INVERSE : PRINT "PLOTTING & CURVE-FIT": NORMAL : POKE 34,2
150 VTAB 5; HTAB 5: INPUT "DATA AVAILABLE ON FILE (Y/N) ?";ANS
160 IF NOT (ANS$ = "Y" OR ANS$ = "N") THEN VTAB 5; CALL - 958: GOTO 150
170 IF ANS$ = "Y" THEN 272
180 GOSUB 1150
220 GOSUB 1000
272 Y$ = L$38; Y$ = - L$38; X$ = - L$38; X$ = L$38
280 HOME : VTAB 4; HTAB 10: PRINT "1. DATA?": PRINT TAB(10); "2. RESULTS": PRINT TAB(10); "3. RESTART?": PRINT TAB(10); "4. QUIT?"
285 VTAB 8; HTAB 10: INPUT "SECTION (1-4) ?"; SEL$ OR VAL(S$) < 1 OR VAL(S$) > 4 THEN 285
290 IF SEL$ = "3" THEN 130
300 IF SEL$ = "4" THEN 890
305 IF SEL$ = "1" THEN NC = 2; XX = 1; YY = 2; GOTO 50D
310 PRINT : HTAB 10: INPUT "NUMBER OF ROW": NR
315 HTAB 10: INPUT "NUMBER OF COLUMN": PC
320 HTAB 10: INPUT "X-AXIS (XX) ?"; XX
325 HTAB 10: INPUT "Y-AXIS (YY) ?"; YY
500 GOSUB 7000
510 HOME : VTAB 14; HTAB 1: FLASH : PRINT "WAIT...READING...": NAM$; NORMAL
802 PRINT CHR$(4); "OPEN": NAM$ + "," + DR$
804 PRINT CHR$(4); "READ": NAM$ + 
806 IF SEL$ = "1" THEN INPUT HOLE: INPUT NR
808 FOR I = 1 TO NR
810 FOR J = 1 TO PC: INPUT DMY(J); NEXT J
811 X(I) = DMY(XX); Y(I) = DMY(YY)
812 GOSUB 940
816 NEXT I
820 PRINT CHR$(4); "CLOSE"
830 GOSUB 1000
850 GOTO 140
890 HOME : VTAB 12; HTAB 12: FLASH : PRINT "HAVE A NICE DAY": NORMAL
895 END
940 REM : DETERMINE MAX X&YY AND MIN X&YY
950 IF Y(I) > YS THEN YS = Y(I)
960 IF Y(I) < Y7 THEN Y7 = Y(I)
970 IF X(I) > X8 THEN X8 = X(I)
980 IF X(I) < X7 THEN X7 = X(I)
990 RETURN
1000 REM : DECIDE TO PLOT,CURVE-PIT,PRINT,RESTART OR QUIT
1005 HOME ; VTAB 2; CALL - 868; HTAB 10: PRINT "; MAIN MENU ...": PRINT TAB(10); "=="
1010 VTAB 5: HTAB 10: PRINT "1). PLOTTING?"
1020 HTAB 10: PRINT "2). CURVE-FIT?"
1030 HTAB 10: PRINT "3). DATA MANIPULATION?"
1035 HTAB 10: PRINT "4). VIEW PLOT?"
1037 HTAB 10: PRINT "5). CONTINUE (GRAPH OVERLAY)?"
1040 HTAB 10: PRINT "6). RESTART?"
1050 HTAB 10: PRINT "7). QUIT?" : POKE 34,14; POKE 35,15
1060 VTAB 15: HTAB 5: INPUT "TYPE NUMBER TO RESPONSE (1-7):" ; Z2S
1070 IF VAL (Z2S) < 1 OR VAL (Z2S) > 7 THEN 1060
1075 POKE 34,1: POKE 35,24
1080 ON VAL (Z2S) GOSUB 2410,3330,5000,4000
1110 IF VAL (Z2S) = 5 THEN 140
1120 IF VAL (Z2S) = 6 THEN 130
1121 IF VAL (Z2S) = 7 THEN 890
1130 GOTO 1000
1140 RETURN
1150 REM: ENTER SOME DATAS TO PLAY WITH
1160 HOME : VTAB 5: HTAB 7: INPUT "WANT TO INPUT DATA (Y/N) ?" ; ANS
1170 IF .NOT. (ANS = "Y" OR ANS = "N") THEN GOTO 1160
1180 IF ANS = "Y" THEN 1230
1190 PRINT : HTAB 10 : INPUT "(Q)UIT,(R)ESTART?" ; ANS
1200 IF NOT (ANS = "Q" OR ANS = "R") THEN GOTO 1190
1210 IF ANS = "R" THEN 130
1220 IF ANS = "Q" THEN 890
1230 MX = 100
1240 X7 = 1E38; Y8 = -1E38; X7 = 1E38; X8 = -1E38
1260 Q = MD * 2: EP = 999: J = 0
1270 HOME : VTAB 1 : PRINT TAB (8) ; "DATA PAIRS ALLOWED :" ; MX : PRINT TAB(9) ; "TO END INPUT: TYPE 999,999" : POKE 34,3: VTAB 4
1280 J = J + 1: HTAB 8: PRINT "X(" ; J ; ")",Y(" ; J ; ")" = "" ; INPUT X(J),Y(J)
1290 IF X(J) = EP AND Y(J) = EP THEN J = J - 1: POKE 34,0: GOTO 1330
1300 IF J = MX THEN PRINT ; PRINT TAB(10) ; "NO MORE DATA ALLOWED" ; GOTO 1330
1310 I = J: GOSUB 940: GOTO 1280
1330 NP = J
1340 IF NP = 0 THEN GOSUB 1800: PRINT TAB(10) ; "NO DATA ENTERED" ; GOTO 1160
1380 RETURN
1390 REM: "POLYNOMIAL CURVE-FIT BY LEAST SQUARE"
1400 HOME
1410 PRINT NP; "DATA PAIRS ENTERED" ; PRINT
1420 MD = 7: REM 7D ONLY
1430 PRINT : INPUT "DEGREE OF POLYNOMIAL TO BE FITTED?" ; D: PRINT
1440 IF D < 0 THEN GOSUB 1780: PRINT "DEGREE MUST BE >= 0" ; GOTO 1430
1450 D = INT (D): IF D < NP THEN 1470
1460 GOSUB 1780: PRINT "NOT ENOUGH DATA" ; GOTO 1430
1470 D2 = 2 * D: IF D > MD THEN GOSUB 1780: PRINT "DEGREE TOO HIGH" ; GOTO 1430
1480 N = D + 1
1490 FOR J = 1 TO D2:P(J) = 0: FOR K = 1 TO NP
1500 P(J) = P(J) + X(K) ^ J : NEXT: NEXT : P(0) = NP
1510 R(1) = 0: FOR J = 1 TO NP: R(1) = R(1) + Y(J)
1520 NEXT : IF N = 1 THEN 1550
1530 FOR J = 2 TO N: R(J) = 0: FOR K = J TO NP
1540 \( R(J) = R(J) + Y(K) \times X(K) \times (J - 1) \); NEXT : NEXT
1550 FOR J = 1 TO N: FOR K = 1 TO N:A(J,K) = P(J + K - 2): NEXT : NEXT
1560 GOSUB 1820
1570 PRINT : PRINT TAB(1); "X POWER COEFFICIENT".
1580 PRINT TAB(N); FOR J = 1 TO 7: PRINT ";-";: NEXT : PRINT TAB( 7)
1590 FOR J = 1 TO N; PRINT "--": NEXT : PRINT
1600 FOR J = 1 TO N: PRINT "-;J-1,V(J):"; NEXT : PRINT : PRINT
1610 Q = 0; FOR J = 1 TO N:Q = Q + Y(J); NEXT : M = Q / N; T = 0; G = 0; FOR
1620 S = 0; FOR K = 1 TO N;S = S + V(K) \times X(J) \times (K - 1); NEXT : T = T + (Y(J) - M) \times (K - 1); NEXT : G = 2 \times (G + Y(J) - M) \times 2; NEXT : IF G = 0 THEN T = 100: GOTO 1650
1640 T = 100 * SQR(1 - T / G)
1650 PRINT "PERCENT GOODNESS OF FIT= "; T
1660 PRINT : PRINT"
1670 PRINT "1 - DETERMINE SPECIFIC POINTS";
1680 PRINT "2 - FIT ANOTHER DEGREE TO SAME DATA"
1690 PRINT "3 - END CURVE-FIT";
1700 INPUT "WHAT NEXT? ";Q:Q = INT(Q); IF Q = 3 THEN 2000
1710 IF Q = 2 THEN 1430
1720 IF Q < > 1 THEN 1660
1730 PRINT : PRINT "ENTER ";IF; " TO LEAVE THIS MODE"
1740 PRINT : INPUT "X= ";XV: IF XV = EF THEN 1660
1750 YV = 0; FOR K = 1 TO N
1760 YV = YV + V(K) \times XV \times (K - 1); NEXT : PRINT "Y= ";YV
1770 GOTO 1740
1780 PRINT "** ";: FLASH : PRINT "ERROR! ";: NORMAL
1790 PRINT "** -- ";: RETURN
1800 PRINT "** ";: FLASH : PRINT "FATAL ERROR! ";: NORMAL
1810 PRINT "** -- ";: RETURN
1820 IF N = 1 THEN V(1) = R(1) / A(1,1); RETURN
1830 FOR K = 1 TO N - 1
1840 I = K + 1
1850 L = K
1860 IF ABS(A(I,K)) > ABS(A(L,K)) THEN L = I
1870 IF I < N THEN I = I + 1: GOTO 1860
1880 IF L = K THEN 1920
1890 FOR J = K TO N:Q = A(K,J) : A(K,J) = A(L,J)
1900 A(L,J) = Q: NEXT
1910 Q = R(K); R(K) = R(L); R(L) = Q
1920 I = K + 1
1930 Q = A(I,K) / A(K,K) : A(I,K) = 0
1940 FOR J = K + 1 TO N: A(I,J) = A(I,J) - Q \times A(K,J) : NEXT
1950 R(I) = R(I) - Q \times R(K) : IF I < N THEN I = I + 1: GOTO 1930
1960 NEXT
1970 V(J) = R(N) / A(N,N); FOR I = N - 1 TO 1 STEP - 1
1980 Q = 0; FOR J = I + 1 TO N; Q = Q + A(I,J) \times V(J)
1990 V(I) = (R(I) - Q) / A(I,I); NEXT : NEXT
2000 RETURN
2100 REM : LET'S DO SOME PLOTTING
2110 IF OSC = "Y" THEN & "CHART.GMD": GOTO 2762
2120 HOME : PRINT "VALUES DETERMINE FROM DATA "; PRINT " "
2130 PRINT "Xmin, Xmax = "; PRINT TAB(15);X7;: PRINT TAB( 30);X8
2440 PRINT "Ymin,Ymax = " ; PRINT TAB(15); "Y7" ; PRINT TAB(30); "Y8
2450 VTAB 8; PRINT" ; INPUT "XMIN,XMAX = " ;XF, XL
2460 INPUT "YMIN,YMAX = " ;MIY,MAY
2470 INPUT "XSEP,YSEP = " ;XS,YS
2472 INPUT "SATISFY (Y/N) ?" ;AN$  
2474 IF AN$ = "N" THEN 2450  
2480 HOME ; VTAB 2; PRINT "LABEL FOR = " ; HTAB 2; PRINT "1" ; X-AXIS: " ;LB  
"S" ; PRINT TAB(2); "2" ; Y-AXIS: " ;LLS; HTAB 2; PRINT "3" ; TITLE: " ;LTS
2490 INPUT "SATISFY WITH THE LABELLING ? (Y/N) "; AN$  
2500 IF NOT (AN$ = "Y") OR AN$ = "N") THEN 2480
2510 IF AN$ = "Y" THEN 2530
2520 INPUT "X-AXIS LABEL ";LBS; INPUT "Y-AXIS LABEL ";LLS; INPUT "TITLE OF GRAPH ";LTS
2530 & "CHART",GCO(1)
2550 & "CHART",CLP(40,265,40,180);& "CHART",FRM
2560 & "CHART",SCL(XF,XL,MIY,MAY).
2570 GOSUB 3030
2580 FOR I = XF TO XL STEP XS
2590 X = I + XS
2600 & "CHART",HLB(STR$(I),II,U2, - 5)
2610 NEXT I
2620 FOR I = MIY TO MAY STEP YS
2630 & "CHART",HLB(STR$(I),U1,L1, - 8)
2640 NEXT I
2650 GOTO 2700
2700 MN = (40 + 265) / 2 - (LEN(LBS)/2) * 6.2
2710 & "CHART",STU(MN,22,U1,U2)
2720 & "CHART",HLB(LBS,U1,U2, - 2)
2730 MN = (180 + 40) / 2 - (LEN(LLS)/2) * 7
2740 & "CHART",STU(MN,U1,U2)
2750 & "CHART",VLB(LLS,U1,U2, - 6)
2752 MN = (40 + 265) / 2 - (LEN(LTS)/2) * 6.2
2754 & "CHART",STU(MN,187,U1,U2)
2755 & "CHART",HLB(LTS,U1,U2, - 2)
2762 FOR I = 1 TO MP
2764 & "CHART",HLB("+",X(I),Y(I),5)
2766 NEXT I
2780 & "CHART",MIX; HOME
2790 VTAB 23; INPUT "WANT TO CURVE-FIT THE DATAS ? ";CN$  
2800 IF NOT (CN$ = "Y") OR CN$ = "N") THEN 2790  
2810 IF CN$ = "N" THEN 2890
2820 & "CHART",TMX; GOSUB 3330
2830 & "CHART",GMD; & "CHART",NMX
2840 GOSUB 3150
2850 & "CHART",MIX  
2860 HOME ; VTAB 23; HTAB 2; INPUT "WANT TO OVERLAY CORR. CURVE (Y/N) ?" ;AN$  
2870 IF NOT (AN$ = "Y") OR AN$ = "N") THEN 2860
2880 IF AN$ = "Y" THEN 2820
2890 HOME ; VTAB 23; INPUT "WANT TO SAVE THE PLOT (Y OR N) ?" ;AN$  
2900 IF NOT (AN$ = "Y") OR AN$ = "N") THEN 2890
2910 IF AN$ = "N" THEN 2960
2920 HOME ; VTAB 22; INPUT "FILENAME TO STORE THE PLOT ";NAME$  
2930 INPUT "WHERE TO STORE (D1 OR D2 ? ";DR$
2940 IF NOT (DRS = "D1" OR DRS = "D2") THEN 2930
2950 PRINT "CHR$(4);""BSAVE";";"NAME$"; + ""; + DRS + ",";A$2000,L$2000"
2960 HOME -> VTAB 23: INPUT "WANT TO GET A DUMP OF THE PLOT ?";ANS
2970 IF NOT (ANS = "Y" OR ANS = "N") THEN 2960
2980 IF ANS = "N" THEN 3012
3000 PR$ 1: PRINT CHR$(9);"G"; PR$ 0
3012 HOME : VTAB 23: H TAB 5: INPUT "WANT TO OVERLAY PLOTS (Y/N)?";OC$;
3013 IF NOT (OC$ = "Y" OR OC$ = "N") THEN 3012
3015 GET Z$: & "CHART",THD.
3029 RETURN
3030 REM : W HERE TO PUT THE CROSSING OF AXES
3040 XO = 0; YO = 0
3050 IF XL < 0 AND XF < 0 THEN XO = XL
3060 IF MAY < 0 AND MYY < 0 THEN YO = MAY
3070 IF XL > 0 AND XF > 0 THEN XO = XF
3080 IF MAY > 0 AND MYY > 0 THEN YO = MYY
3090 HCOLOR = 3
3100 & "CHART",AXS(XS,YS,XO,YO)
3110 & "CHART",STU(36,32,U1,U2): & "CHART",STJ(32,32,U3,U4)
3120 IF XO = 0 THEN 3140
3130 & "CHART",HLB(STRS(XO),U3,U2,6)
3140 RETURN
3150 REM : PLOT THE CORRELATION CURVE
3160 & "CHART",SEL(XF,XL,MAY,MYY)
3170 SEP = ABS ((XL - XF) / 100)
3180 I = XF
3190 IF IC = 2 AND XF = 0 THEN I = I + SEP
3200 IF I > XL THEN 3320
3210 ON IC GOTO 3220,3230,3240,3250,3260
3220 SUM = A + B * I: GOTO 3300
3230 SUM = A + B * LOG(I): GOTO 3300
3240 SUM = A + I * B: GOTO 3300
3250 SUM = A * EXP (B * I): GOTO 3300
3260 SUM = 0
3270 FOR J = 1 TO N
3280 SUM = SUM + V(J) * I ^ (J - 1)
3290 NEXT J
3300 & "CHART",PLT(I,SUM)
3310 I = I + SEP: GOTO 3190
3320 RETURN
3340 REM : S T A R T THE CURVE-FIT PROCESS
3350 VTAB 4: HTAB 5: PRINT "1). LINEAR CURVE-FIT :": HTAB 10: PRINT "Y=a+b*X": PRINT
3360 HTAB 5: PRINT "2). LOGARITHMIC CURVE-FIT :": HTAB 10: PRINT "Y=a+b*LOG(X)"; PRINT
3370 HTAB 5: PRINT "3). POWER CURVE-FIT :": HTAB 10: PRINT "Y=a*x*b": PRINT
3380 HTAB 5: PRINT "4). EXPONENTIAL CURVE-FIT :": HTAB 10: PRINT "Y=a*EXP(b*x)": PRINT
3390 HTAB 5: PRINT "5). POLYNOMIAL CURVE-FIT "
3400 VTAB 20: HTAB 5: INPUT "PRESS NUMBER TO RESPONSE (1-6) ";IC
3410 IF IC < 1 OR IC > 6 THEN 3350
3412 POKE 34,0: POKE 35,24
3420 IF IC = 5 THEN GOSUB 1390: GOTO 3990
3425 IF IC = 6 THEN 3990  
3430 REM : COMPUTATION OF REGRESSION AND DETERMINATION COEFFICIENTS
3440 X0 = 0: Y0 = 0: X2 = 0: Y2 = 0: X3 = 0
3450 FOR I = 1 TO NP
3460 ON IC GOTO 3470,3490,3510,3530
3470 C = X(I): D = Y(I)
3480 GOTO 3540
3490 C = LOG (X(I)): D = Y(I)
3500 GOTO 3540  
3510 C = LOG (X(I)): D = LOG (Y(I))
3520 GOTO 3540
3530 C = X(I): D = LOG (Y(I))
3540 X0 = X0 + C: Y0 = Y0 + D
3550 X2 = X2 + C * C: X3 = X3 + C * D: Y2 = Y2 + D * D
3560 NEXT I
3570 X0 = X0 / NP: Y0 = Y0 / NP
3580 B = (X3 - NP * X0 * X0) / (X2 - NP * X0 * X0)
3590 A = Y0 - B * X0
3600 IF IC < 3 THEN 3620
3610 A = EXP (A)
3620 R2 = B * B * (X2 - NP * X0 * X0) / (Y2 - NP * Y0 * Y0)
3630 REM : COMPUTE SUM OF SQUARE OF RESIDUALS
3640 S = 0  
3650 FOR I = 1 TO NP
3660 ON IC GOTO 3670,3690,3710,3730
3670 S0 = A + B * X(I) - Y(I)
3680 GOTO 3740
3690 S0 = A + B * LOG (X(I)) - Y(I)
3700 GOTO 3740
3710 S0 = A * (X(I) ^ B) - Y(I)
3720 GOTO 3740
3730 S0 = A * EXP (B * X(I)) - Y(I)
3740 S = S + S0 * S0
3750 NEXT I
3770 HTAB 5: PRINT "COEFFICIENT OF DETERMINATION: R": PRINT TAB(10): LEFT$ ( STR$ (R2),5): PRINT
3780 HTAB 5: PRINT "SUM OF SQUARE OF RESIDUALS: S": PRINT TAB(10): LEFT$ ( STR$ (S),5): PRINT
3790 VTAB 18: HTAB 12: PRINT "1). FIT A POINT?"
3800 HTAB 10: PRINT "2). ANOTHER CURVE-FIT?"
3810 HTAB 10: PRINT "3). END CURVE-FIT?"
3820 VTAB 22: HTAB 8: INPUT "PRESS NUMBER TO RESPONSE (1-3) "; ZZ
3840 IF ZZ < 1 OR ZZ > 3 THEN 3830
3850 ON ZZ GOTO 3880,3330,3990
3860 IF ANS = "2" THEN 3360
3870 IF ANS = "4" THEN 5020
3880 PRINT : HTAB 10: INPUT "X = ";X1
3890 ON IC GOTO 3900,3920,3940,3960
3900 Y1 = A + B * X1
3910 GOTO 3970
3920 Y1 = A + B * LOG(X1)
3930 GOTO 3970
3940 Y1 = A * X1 - B
3950 GOTO 3970
3960 Y1 = A * EXP(B * X1)
3970 HTAB 7; PRINT "** X =";X1; TAB(20);"Y =";Y1
3980 GET ZS: HOME: GOTO 3970
3990 RETURN
4000 REM: VIEW PLOT
4010 &"CHART",GMD
4015 &"CHART",NXM
4020 GET ZS: &"CHART",TMD
4030 RETURN
5000 REM:: DATA MANIPULATION::
5100 POKE 34,0: HOME: VTAB 3; HTAB 10: PRINT "DATA MANIPULATION": HTAB 10: FOR I = 1 TO 17: PRINT "-": NEXT
5160 VTAB 5; HTAB 10: PRINT "1). ADDING DATA ?"
5170 HTAB 10: PRINT "2). CHANGING DATA ?"
5180 HTAB 10: PRINT "3). DELETING DATA ?"
5190 HTAB 10: PRINT "4). VIEW DATA ?"
5200 HTAB 10: PRINT "5). SAVE DATA ?"
5205 HTAB 10: PRINT "6). CONTINUE ?"
5210 VTAB 12; HTAB 5; INPUT "PRESS NUMBER TO RESPONSE (1-6) ":ZZ
5220 IF ZZ < 1 OR ZZ > 6 THEN 5210
5230 IF ZZ = 6 THEN 5330
5250 ON ZZ GOSUB 6000,5340,6090,6210,5580
5252 IF NP = DMY THEN 5325
5255 Y7 = 1E38; Y8 = -1E38; X7 = 1E38; X8 = -1E38
5290 FOR I = 1 TO NP
5300 GOSUB 940
5320 NEXT I
5325 GOTO 5100
5330 RETURN
5340 REM:: CHANGE DATA
5350 HOME
5352 VTAB 2; HTAB 10: PRINT "** CHANGE DATA **"
5355 VTAB 5; HTAB 8: INPUT "WHICH POINT ?";II
5357 PRINT'
5360 PRINT TAB(5);"X(";II;");";X(II)
5362 PRINT TAB(5);"Y(";II;");";Y(II)
5365 VTAB 10; HTAB 5; INPUT "THIS PAIR ...(Y/N) ?":ANS
5370 IF NOT(ANS = "Y" OR ANS = "N") THEN VTAB 10: CALL - 958: GOTO 5
5375 IF ANS = "N" THEN 5570
5380 VTAB 12; HTAB 5; PRINT "ENTER NEW DATA FOR POINT ":II
5382 PRINT TAB(5);"X(";II;");"; INPUT X(II)
5385 PRINT TAB(5);"Y(";II;");"; INPUT Y(II)
5570 RETURN
5580 REM:: SAVING THE DATA'S FILE
5582 HOME: VTAB 2; HTAB 10: PRINT "** SAVE DATA **
5590 VTAB 5; HTAB 10: PRINT "WANT TO SAVE DATA"
5595 VTAB 7; HTAB 10: INPUT "(Y/N) ?":ANS
5600 IF NOT(ANS = "Y" OR ANS = "N") THEN 5595
5610 IF ANS = "N" THEN 5710
5615 GOSUB 7000
5620 HOME : VTAB 15: HTAB 13: FLASH : PRINT "WAIT ... SAVING": NORMAL.
5640 PRINT CHR$(4);"OPEN"; NAMES + "," + DRS
5650 PRINT CHR$(4);"WRITE"; NAMES
5660 PRINT HOLE: PRINT NP
5670 FOR I = 1 TO NP
5680 PRINT X(I): PRINT Y(I)
5690 NEXT I
5700 PRINT CHR$(4);"CLOSE"
5710 RETURN
6000 REM : ADDING
6002 HOME : VTAB 2: HTAB 10: PRINT "** ADDING DATA **": POKE 34,3
6005 VTAB 5: HTAB 10: INPUT "WHICH POINT ?";ST
6020 FOR I = NP TO ST STEP - 1
6030 Y(I + 1) = Y(I); X(I + 1) = X(I)
6040 NEXT I
6050 HOME : VTAB 10: HTAB 7: PRINT "ENTER NEW DATA PAIR FOR :";ST
6060 VTAB 12: HTAB 10: INPUT "X ; Y = ?";X(ST),Y(ST)
6070 NP = NP + 1
6080 RETURN
6090 REM : DELETING
6100 HOME : VTAB 2: HTAB 10: PRINT "** DELETE DATA **": POKE 34,3
6110 VTAB 5: HTAB 10: INPUT "WHICH POINT ";ST
6120 IF ST < 1 OR ST > NP THEN HOME : VTAB 5: HTAB 10: PRINT "OUT OF RANGE ": PRINT : HTAB 10: INPUT "TRY AGAIN WHICH POINT ?";ST: GOTO 6120
6122 HOME : VTAB 5: HTAB 10: PRINT "DATA PAIR ..":ST
6124 HTAB 10: PRINT "X(";ST;") ;;X(ST)
6126 HTAB 10: PRINT "Y(";ST;") ;;Y(ST)
6130 VTAB 10: HTAB 5: PRINT "ARE YOU SURE TO DELETE ": HTAB 5: PRINT "DATA PAIR ":ST; VTAB 12: HTAB 10: INPUT "(Y/N) ?";ANS
6140 IF NOT (ANS = "Y" OR ANS = "N") THEN 6120
6150 IF ANS = "N" THEN 6200
6160 FOR I = ST TO NP
6170 X(I) = X(I + 1); Y(I) = Y(I + 1)
6180 NEXT I
6190 NP = NP - 1
6200 RETURN
6210 REM : VIEW DATA
6220 HOME : VTAB 2: HTAB 5: PRINT "POINT ": HTAB 15: PRINT LBS; HTAB
6225: PRINT LLS: POKE 34,2
6230 P1 = 15 + LEN (LBS) / 2 + 0.5; P2 = 23 + LEN (LLS) / 2 + 0.5
6240 FOR I = 1 TO NP
6250 CALL 868: HTAB 7: PRINT I;; VTAB P1: PRINT LEFTS (STXS (X(I)),
6254);; HTAB P2: PRINT LEFTS (STRS (Y(I)),5): NEXT I
6320 GET ZS: POKE 34,0
6330 RETURN
7000 REM ***** FILE
7010 VTAB 15
7015 HTAB 10: INPUT "FILENAME:";NAME$ 
7020 HTAB 10: INPUT "STORE DRIVE(D1/D2):";DR$ 
7025 VTAB 18: HTAB 5: INPUT "SATISFY.(Y/N), (C)AT., (R)ESTART ?";ANS 
7030 IF ANS = "C" THEN GOSUB 7200: GOTO 7010 
7035 IF AN$ = "N" THEN 7010 
7040 IF AN$ = "R" THEN 130 
7045 IF AN$ < > "Y" THEN 7025 
7050 RETURN 
7200 REM :***** CATALOG 
7210 HOME 
7215 VTAB 5: HTAB 10: PRINT "WANT TO SEE CATALOG IN:" 
7220 PRINT TAB(10);"1. DRIVE 1 ?": PRINT TAB(10);"2. DRIVE 2 ?": PRINT 
    TAB(10);"3. CONTINUE ?" 
7225 VTAB 9: HTAB 10: INPUT "SELECTION (1/2/3):";SEL 
7230 IF SEL = 1 THEN PRINT CHR$(4);"CATALOG,D1" 
7235 IF SEL = 2 THEN PRINT CHR$(4);"CATALOG,D2" 
7240 IF SEL = 3 THEN 7250 
7245 GET Z$: GOTO 7210 
7250 GET Z$: RETURN
VITA AUCTORIS

1961 Born in Sibu, Malaysia.

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