Piston slap detection in combustion engines using unique signal analysis techniques.

Hugh W. Miller
University of Windsor

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PISTON SLAP DETECTION IN COMBUSTION ENGINES
USING UNIQUE SIGNAL ANALYSIS TECHNIQUES

by

HUGH W. MILLER

A Thesis
Submitted to the
Faculty of Graduate Studies and Research
through the Department of Mechanical Engineering in
Partial Fulfillment of the Requirements for the
Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada
1989
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ABSTRACT

Research was conducted on the use of mechanical signature analysis techniques for the detection of piston slap in internal combustion engines.

An extensive literature survey revealed a lack of any established technique for the detection of piston slap. In fact, with three exceptions, little information about any engine fault diagnostic methods were found.

The non-destructive diagnosis of faults, such as piston slap, is worth a great deal both in reputable and monetary terms to engine manufacturers. This encouraged an engine manufacturer to begin field studies into techniques which could diagnose these faults, prompting this research.

The underlying goal during the field studies was to develop a non-destructive technique for the detection of piston slap in combustion engines. These studies were conducted with engines containing piston slap in at least one cylinder and with engines containing altered piston parameters that are traditionally thought to affect piston slap. Data was collected from each engine, cylinder by cylinder, using an accelerometer positioned directly over
each cylinder wall on the block of the engine. This data was processed by mechanical signature analysis techniques and the results were analyzed.

Analysis of the data revealed that the energy envelope of the time domain average signal and the variance analysis of the signal are very effective techniques for the detection of piston slap. The characteristic pattern of piston slap in these techniques are sharp peaks located at the crank angles associated with ignition. In some cases these peaks can be found at the bottom dead center of the piston stroke. A correlation between the mechanical signature analysis results and the severity of piston slap is not addressed in the studies but suggested as future research.
DEDICATION

This work is dedicated to the memory of my grandfather, Hugh Llewellyn Miller. A man I never met but yet admire.
ACKNOWLEDGMENTS

The author would like to express his appreciation to Dr. R.G. Gaspar for his guidance and tolerance. Thanks are also due to Dr. Z. Reif and Dr. G. Abdou for their assistance.

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$\bar{X}$
average of quantity X

BDC
bottom dead center of a piston stroke

BTDC
before top dead center

D.C.
direct current or steady value

DFT
discrete fourier transform

E.E.
energy envelope

$f$
frequency

$f(t)$
continuous time series

$f(t)$
hilbert transform of a continuous time series

$f(t)$
analytic signal of a continuous time series

FFT
fast fourier transform

$F(f(t))$
fourier transform of a continuous time series

freqspan
the size in hertz of a range of frequencies

$g$
unit of acceleration (9.8 meter/ second$^2$)

Hz
hertz

$i$
the index variable for data points in a time trace

I.C.
internal combustion

IEEE
Institute of Electrical and Electronic Engineers

IFFT
inverse fast fourier transform

$j$
the complex number $\sqrt{-1}$
m  total number of time traces
MSA  mechanical signature analysis
n  nth point of some array
N  number of data points in a time trace
r  index variable for time traces
rpm  revolutions per minute
T  sampling time in seconds
TDA  time domain average or time domain averaging
TDC  top dead center of a piston stroke
VAR(X)  the variance of vector X
x  time trace vector
Y  average time trace vector
z  the variance vector
Δf  change in frequency
Δt  change in time measured in seconds
Δθ  change in crank angle measured in degrees for a particular engine speed
Δθ₁  change in crank angle for a faster engine speed
Δθ₂  change in crank angle for a slower engine speed
Δθ₃  range of angle of sampling for a varying speed engine
θ  crank angle in degrees.
I. INTRODUCTION

North American engine manufacturing facilities on average produce 2000 engines, at a cost of 30 million dollars, every production day. This represents a large contribution to a local and in a general sense the national economy. If the quality with which these engines are manufactured becomes questionable, a threat to a very basic cornerstone of the economy exists. This is exactly the position that many engine manufacturers find themselves today.

This concern over quality results from the complaints of customers, who are experiencing engine problems often caused by a mistake in manufacturing. Typically, the culprit engines contain no major manufacturing mistakes which would lead to immediate or catastrophic failure of the engine. This is prevented by power and fuel tests at the manufacturing plant. Not prevented by these tests are non major defects of the type that would lead to shortened engine life, excessive vibration or unusual noises. Several of these non major defects are listed in the following in no particular order.
1) missing camshaft or crankshaft inserts
2) spun bearings
3) rough bearing surfaces
4) blocked lubrication passages
5) missed or improperly inserted valve seats and guides
6) squeaky valve rocker arm assemblies
7) rough camshaft lobes
8) poor gear matching
9) piston slap

Currently, the quality control methods used to detect these faults are aimed at the reduction of percentage defects. These methods require the testing of sample engines which act as representatives of the entire engine population. These engines are disassembled and any defects are recorded and assumed to represent the percentage defects of the entire population. This type of method still allows defective engines to enter the marketplace and only identifies trouble areas in the manufacturing process. The manufacturer, for whom this work was completed, currently experiences a 0.2 percentage "defect to market rate" compared to a 2 percentage "defect to market rate", at the launch of the engine.
Many engine manufacturers, aware of the cost of these defective engines entering the marketplace, have decided to develop non-destructive techniques for the detection of these defects. It is conceivable, if such methods could exist, that all engines manufactured could be tested for non major defects. This type of analysis could bring "defect to market rates" down close to zero.

The major constraint for any technique that detects engine faults is the time involved. This follows from a long held manufacturing credo that states, the most efficient condition at which a manufacturing facility operates is at maximum output. If these fault diagnostics cause any loss of production, they will appear to have decreased the efficiency of the manufacturing facility, despite any future benefits which may be gained from such a program.

A logical approach for the development of such diagnostic techniques for internal combustion engines is to begin by tackling the defect which is either the most severe or the most common. The engine in this study has a decent quality record but it is plagued by some recurring problems. The manufacturing problem which most often ends up in a customer complaint is piston slap and this particular
problem will become the subject of this thesis. Due to the suitability of MSA techniques as viable non-destructive diagnostic methods, they are applied to the detection of piston slap in this thesis.

For all the previously mentioned reasons the following goals have been established for this thesis:

1. TO DEVELOP A METHOD TO DETECT PISTON SLAP BY NON DESTRUCTIVE MEANS

2. TO STUDY THE APPLICATION OF MECHANICAL SIGNATURE ANALYSIS TECHNIQUES FOR DETECTION OF PISTON SLAP

3. TO FIND APPROPRIATE TRANSDUCERS FOR THE DETECTION OF PISTON SLAP BY NON DESTRUCTIVE MEANS

To accomplish these goals other objectives must be met beforehand and these objectives are listed below:

1. TO SURVEY EXISTING LITERATURE ON INTERNAL COMBUSTION ENGINES AND ROTATING MACHINERY WITH EMPHASIS ON PISTON SLAP DETECTION
2. TO EXTRACT THE MOST USEFUL MSA TECHNIQUES FROM THE LITERATURE SURVEY FOR APPLICATION TO PISTON SLAP DETECTION

3. TO DEVELOP A DATA ACQUISITION SYSTEM TO COLLECT THE APPROPRIATE DATA

4. TO CONTRAST AND ANALYZE THE DATA FROM FAULTY AND NON FAULTY ENGINES

There are other goals which will follow from this thesis which are mainly of concern to the manufacturing facility. Some initial work is presented on these goals but further work is beyond the scope of these studies. These goals are:

1. TO CONDUCT QUANTIFICATION OF PISTON SLAP SEVERITY AGAINST ANALYSIS RESULTS

2. TO AID IN THE IDENTIFICATION OF PARAMETERS WHICH CONTRIBUTE TO THE PROBLEM OF PISTON SLAP

3. TO DEVELOP AN ON-LINE SYSTEM WHICH CAN DETECT PISTON SLAP IN EVERY FAULTY ENGINE MANUFACTURED AT THE PRODUCTION FACILITY
II. PISTON SLAP DEFINITION AND CAUSES

Piston slap is a problem which manifests itself as a "knocking noise" in the cylinders of an engine. This "knocking" can often be confused with a related phenomenon known as detonation knock. The difference in these types of phenomena are their root causes and these will be described below.

2.1 Piston Slap and Detonation Knock

The word "knock" was coined to describe the resulting noise from two types of physical phenomena that can occur between a piston and a cylinder. One cause of knock and the most widely studied form is "detonation knock". This type of knock is caused by irregular combustion which generates pressure oscillations in the cylinder. These pressure oscillations produce an uneven pressure profile across the piston dome causing it to rotate about its piston pin [1].

Detonation knock is controlled at the design stage and by proper fuel selection. The placement and design of valves, spark plugs, fuel injection ports and the additive contents in engine fuel all affect the formation of
detonation knock. Detonation Knock is annoying, certainly it is a problem in automotive engines but it is out of the control of a manufacturing facility.

The second cause of knock, is a manufacturing defect known as piston slap. It is a result of unusually bad clearances or poor shape matching between a piston and a cylinder. The "Slap" or "Knock" is produced as a result of the changing orientation of a piston inside the cylinder. These changes in orientation occur whenever there is a change in direction of horizontal force in the piston's connecting rod [1]. Figures 2.1 will help explain the process. The positions, in most engines, associated with the changes in the horizontal force of the connecting rod are the bottom dead center, top dead center and midpoint of the piston stroke.

A problem for any detection method of piston slap is to differentiate between these two causes of knock since both result in the production of the knock noise. Fortunately, piston slap appears to occur at specific locations in an engine cycle and detonation knock appears to be a random event.
2.2 Factors that Affect Piston Slap

Excessive clearance between piston and cylinder, as alluded to in the above sections, is the primary cause of piston slap. This clearance could simply be the result of boring too much metal from the cylinder or an under size piston. This last type of problem is easy to check by direct measurements of the size of piston and cylinder diameters, but this is not the only cause of large piston cylinder clearance. The other causes, unfortunately, occur while the engine is running or in the last stages of assembly. These factors will be discussed below.

2.2.1 Piston Clearance and Operating Temperature

The combustion process, which occurs in the cylinder of an engine, takes place at very high temperatures in the neighborhood of 300 degrees Celsius. The piston dome, which is exposed directly to this temperature, undergoes thermal expansion. Heat transfers through the piston from the dome down to the skirt, resulting in a temperature gradient along the piston. At the skirt of the piston, the temperature is significantly lower and the skirt undergoes much less thermal expansion. This causes, under operating
temperatures, larger clearances at the skirt. The usual correction applied to this problem is a tapered piston (see figure 2.2a) with a larger diameter at the skirt. This taper is designed for average operating temperatures only. In unusually cold weather and initially after starting an engine, clearances still result at the skirt. This can promote piston slap[2].

2.2.2 Cylinder Distortion

Nominally, the shape of a cylinder bore, is of course circular. In the assembly process, forces from the installation of heads and manifolds, can often distort this circular shape. The resulting shape can often lead to piston slap. In particular, if an oval shape results, clearance on the major axis of this oval will often allow the piston to move laterally, causing piston slap. If the cylinder bore distortion is clover shaped, which is the most acceptable type of distortion, (see figure 2.2b) then piston movement is still restricted [2].

2.2.3 Skirt Flexibility

Lately engines parts have been manufactured with weaker but lighter materials, in an attempt to increase fuel efficiency. Pistons have also been designed so as not to
waste these new and expensive materials, resulting in much weaker designs coupled with much weaker materials. This can be a particular problem at the piston skirt. The piston skirt, under the force of the connecting rod, is pressed against one side of the cylinder wall (see figure 2.2c). The skirt can deform, creating clearance and causing elastic rebound, which sometimes results in piston slap[2].

2.3 Results of Piston Slap on an Engine

The major effect of piston slap is subjective and deals with the customer's impression of the quality of the engine. The other effects are mechanical in nature including erosion of piston rings, holes in the edge of the piston dome and scored cylinder walls. These mechanical problems may lead to oil burning, combustion pressure loss and piston destruction.[3]
III. LITERATURE SURVEY

One of the questions to answer in this thesis is to determine if the detection of piston slap by MSA techniques is possible. The following literature survey was conducted to determine if any such work or similar work had already taken place. An extensive survey of existing literature did not reveal any objective method for the detection of piston slap. Despite this lack of information on piston slap diagnostics there still exists some good research into other I.C. engine defects. This literature concerns the following types of problems:

a. engine "knock" detection
b. spun and missing bearings
c. injector and fuel pump noise

A knowledge of these defects, coupled with knowledge of analysis techniques may suggest some way of detecting faults in an internal combustion engine. A description of the analysis techniques will be presented in the theory section of this thesis. A description of these engine faults and if applicable, any accompanying analysis techniques will be presented in the following sections. If questions arise as to which components of an engine are involved in these
problems consult Appendix A which contains a brief list of books that give an excellent description of an engine and its parts.

3.1 Detonation Knock Detection

The detection of detonation knock is by no means a new field. Recently most work has been conducted in Italy by Arrigoni et al. [3], leading to the development of a knock sensor which is directly placed on an engine. The technique is basically a threshold measurement system. At ignition, accelerometer data is acquired for a specified period of time and passed through a threshold device. If the signal exceeds the threshold it suggests knocking, according to the developers of the technique [3]. The technique can also be applied to pressure data during combustion. A set of diagrams will help in understanding the technique (refer to figures 3.1a, 3.1b, and 3.1c.).

3.1.1 Evaluation of the Technique

This technique is employed to indicate "knock" in the general sense, detecting both detonation and mechanical knock. The result of the technique is a single number,
FIGURE 3.1: THRESHOLD KNOCK DETECTION SYSTEM
a) SENSOR DATA
b) THRESHOLD GATE
c) RESULTANT SIGNAL
which is proportional to the amount over a threshold value of a signal. Manufacturing facilities, interested in piston slap only, could not use this technique as a means of evaluating this type of fault.

3.2 Detection of Spun and Missing Camshaft Bearings

Seth and Field worked on the problem of missing and spun camshaft bearings [4]. The data acquired in their study was processed using time domain averaging (TDA), variance analysis and the FFT. These techniques proved to be very effective in the detection of these spun and missing camshaft bearing inserts. The work also exposed the need to contrast the results of normal and faulty engines in order to develop a detection method.

TDA and variance analysis methods used in this study were referenced to the various angular positions of the crankshaft. These position oriented analysis methods may be quite appropriate for piston slap detection, which, according to authors [1,2,3,5], is a position locked problem.
3.3 **Electrical Fuel Pump Signature**

Kemmner et al. recently studied electrical fuel pump noise [6]. Although criteria for fault detection is not provided in the literature, a method for evaluating vibration and pressure signatures is proposed. This method of measuring the noise relied heavily on the FFT. This measurement technique could be used to measure the fuel pump noise of adequate and faulty fuel pumps. The difference in these noise signatures might be used as a diagnostic technique to detect faulty fuel pumps. This procedure could be extended to piston slap detection if significant differences exist between the FFT patterns and magnitudes of slapping and non slapping engines.

3.4 **Miscellaneous but Useful Information**

The most useful information gained from the literature, was the type and placement of transducers that proved suitable for studying detonation knock. Authors [1,2,3,5] suggested the use of accelerometers and pressure transducers over microphones, citing that although "knock" is an audible phenomenon, microphone data would not be very sensitive in the detection of knock. This is understandable, considering
the possible background noise in the environments in which these measurements are taken. The time information from the microphone tests was never provided, as such, it is hard to completely accept their conclusion.

As mentioned previously, authors suggest the use of accelerometers for the collection of knock data. The locations for the accelerometers, which the authors suggest would lead to clearer signals, are the crankcase and the oil pan [3,5]. They also suggest that stronger signals could be obtained on the head bolts, but the signal strength becomes a function of the bolt torque. Another drawback to placing the accelerometer on the head bolts is signal contamination by manifold and exhaust noise.

Another suggested method, which is fairly unique, is interferometer holography. By use of interferometer holography centers of surface vibration are highlighted. This method is very new, and as a result, currently only provides qualitative information. It does highlight, in a dramatic fashion, centers of high surface vibration and in the case of knock this vibration is visible in the piston wall area. Figure 3.2 is an illustration of a knocking
FIGURE 3.2: INTERFEROMETER HOLOGRAPHY APPLIED TO A KNOCKING ENGINE
engine with this technique employed. The method is interesting but the lack of quantification of vibration makes it useless at present.
IV. SIGNAL PROCESSING MATHEMATICS

This chapter contains the mathematical concepts that were not discussed in the literature survey, these concepts are outlined here as they are used in the studies. When appropriate the concluding equations are provided and if too voluminous references are indicated for the reader to consult.

4.1 Fast Fourier Transform

The fast fourier transform has become an ubiquitous tool in mechanical signature analysis used in most forms of problem diagnosis. Significant use of the FFT technique has been made in subject areas such as preventive maintenance, misalignment detection, out of balance detection and noise quantification. The uses are numerous and the technique applies quite well to rotating machinery. In application to reciprocating machinery the technique begins to fail. This is a result of impact information from reciprocating machines, such as an engine, clouding the FFT results.
The FFT is useful as an intermediary step in many mathematical calculations. It can also be used in fault studies of engine components which are in constant speed operation, such as, alternators or fuel pumps.

4.1.1 Mathematical Description

The fast fourier transform (FFT) is a quick and efficient method for the calculation of the discrete fourier transform (DFT) and provides an identical final answer. The DFT, is an approximation of the continuous fourier transform and a development can be found in references [7,8,9,10].

4.1.2 Properties of the FFT

After a time signal has gone through a fast fourier transform, the result is a vector of frequency information. Each value in this vector represents the total magnitude of the signal's frequency components over the range of frequency values represented by that data value. The first value in the array represents the D.C. or zero frequency component of the time signal. The second point spans between 0 and Δf. Where Δf can be calculated from:
\[ \Delta f = \frac{1}{T} \]  

(4.1)

where

\( T \) = the sampling rate

The third frequency value represents the frequency range from \( \Delta f \) to \( 2\Delta f \). The \( n \)th data value spans the range \((n-2)\Delta f\) to \((n-1)\Delta f\). The number of valid data points is \( N/2+1 \) for a \( N \) point sampled array.

4.1.3 Problems with the Fast Fourier Transform

The use of the FFT to determine the frequency characteristics of a time signal, although fast and efficient, poses several problems that may mar the results. The two major problems are known as leakage and aliasing.

Leakage is a periodicity problem in the FFT algorithm but can be solved by using a technique known as windowing. A description of leakage and windowing can be found in the following references [7,10].

Aliasing is a problem associated with the sampling rate of the device collecting the discrete information. It follows the Nyquist theory which states that frequency
content in the data over half the sampling frequency will not be represented properly. The solution to the problem is the use of a low pass filter set to eliminate frequencies over half the sampling frequency. A more detailed description of Aliasing can be found in references [7, 10].

4.2 Time Domain Averaging

Time domain averaging is a technique used to reduce "noise", which are the non repetitive components of a signal. It is accomplished by simply averaging several time traces, data point by data point, producing an average time trace. If a TDA average is to work properly, certain conditions on the sampling of these time traces must be met.

4.2.1 Event Initiated Averaging

To perform a TDA, the data collection of each time trace must be initiated by a particular event and ended by another particular event. The data must also be sampled at the same sampling rate in each time trace. In rotating machinery the initiating event could be the passing of a keyway on each revolution, and the termination event could be this same keyway passing again or the time it takes for one
revolution. If time traces for several of these cycles are collected and stored the true periodic signals from the machine can be acquired by averaging.

For example, an engine running at a speed of 1500 rpm has acceleration data taken from its block. A single trace yields the results in figure 4.1. This signal is a combination of the periodic vibration from the engine, vibration transmitted through the floor by other machines, other background noise and semi-periodic vibration from the engine itself. By taking 50 of such traces and performing a point by point averaging, the end result is a TDA trace that is depicted in figure 4.2. This signal is quite different from that in the last figure. The vibration data is essentially a function of the engine's periodic vibration properties and no longer a function of both the engine periodic vibration and the "noise".

Time domain averaging is extremely valuable in the detection of problems such as out of balance or misalignment. It can also be useful for any fault which would occur consistently at certain locations in a cycle. It is not necessarily useful in the detection of semi-periodic faults but it is an essential step in the
FIGURE 4.1: SINGLE TIME TRACE FROM AN ENGINE

FIGURE 4.2: AVERAGED TRACE FROM AN ENGINE
process. A mathematical description of the TDA technique, including its properties as a filter in eliminating non cycle linked signals, is provided in reference [11].

4.3 Variance Analysis

In the last section time domain averaging was described, this technique extracts signals which are always present in a cycle. Other signals, which are not always present in every cycle but have amplitude changes at specific positions in these cycles, are termed semi-periodic. These types of signals can be valuable in determining faults such as ball bearing defects, bad meshing gears and a periodically misfiring spark plug. The technique most often used to extract these signals is the variance analysis method. To aid in understanding this method the three basic components of a time signal must be described.

4.3.1 The Three Components of a Time Signal

In the field of Mechanical Signature Analysis there exists three principle types of components of which a time trace is composed of, these are: the periodic, the semi-periodic and noise. The breakdown of such signal components is illustrated in figure 4.3.
FIGURE 4.3: THREE TYPES OF SIGNAL COMPONENTS
a) COMPLETE SIGNAL
b) AVERAGE (PERIODIC COMPONENT)
c) SEMI-PERIODIC COMPONENT
d) NOISE COMPONENT
Figure 4.3a represents the time trace as acquired by the sampling unit. Figure 4.3b represents the average or periodic component of the trace as extracted by use of TDA. The fourth graph of that series represents the noise of the signal. Noise, in this case, is now defined as signals which have absolutely no association with the periodic signal. These signals come primarily from background vibration sources. Figure 4.3c depicts the semi-periodic waveform.

4.3.2 Mathematical Description of Variance Analysis

The mathematical development of the variance method can be found in reference [12] and examples of its use can be found in references [12,4]. The basic equations needed to perform this analysis are brief and are given below.

\[ AV(X(i)) = Y(i) = \frac{1}{m} \sum_{i=0}^{n-1} X(i) \]  \hspace{1cm} (4.2)

\[ Z(i) = \text{VAR}(X(i)) = AV\left( (X(i) - Y(i))^2 \right) \] \hspace{1cm} (4.3)

where

\( m = \) the number of traces collected

\( i = \) the index for vector data points
\( r \) = the index of a particular trace

\( X(i) \) = the \( i \)th component of a vector \( X \)

\( Y(i) \) = the average vector for all traces \( X \)

\( Z(i) \) = the \( i \)th component of the variance vector

In these computations the removal of the periodic function is accomplished, and by squaring the result, the semi-periodic function information is exaggerated. This exaggeration protects the semi-periodic information from filtering out, while at the same time noise signals converge to a specific constant value over the whole variance vector.

4.4 Hilbert Transform and Envelope Detection

The hilbert transform is a principal step in taking a time signal and calculating what is called an energy envelope. This envelope contains information about abrupt changes in signal energy content. It is therefore well suited to the detection of signals that involve impacts or bursts.
4.4.1 Mathematical Description of The Hilbert Transform

Mathematically, the hilbert transform is formed from a transform of a real valued time series. If the hilbert transform is added appropriately to the original time signal, it forms a complex value time series known as an analytic signal.

\[ f_\times(t) = f(t) + j\gamma(t) \]  

(4.4)

where

\[ f_\times(t) \] is the analytic signal

\[ f(t) \] is the original time signal

\[ \gamma(t) \] is the actual hilbert transform

The analytic signal has the following fourier transform properties

\[ F(f_\times(t)) = \begin{cases} 
2F(f(t)) & \text{for } f > 0 \\
F(f(t)) & \text{for } f = 0 \\
0 & \text{for } f < 0 
\end{cases} \]  

(4.5)

The rigorous mathematics which lead to these equations are described in reference [13].

These last equations suggest a method for the quick calculation of the hilbert transform by use of the FFT. The
time signal is first acquired and a FFT is performed on the signal. The part of the FFT representing positive frequency values is increased by a factor of 2, except that which corresponds to a frequency of 0 which remains at its initial value. The parts of the FFT representing the negative frequency values are set to 0. Then an IFFT is performed, providing the analytic signal of which the hilbert transform is the imaginary portion.

4.4.2 Energy Envelope

The energy envelope or the amplitude modulation curve, as it is sometimes called, is nothing more than the magnitude of the analytic signal. This envelope is useful in the analysis of systems where high frequency transients (bursts) repeating at a lower frequency exist[14]. Figure 4.4 illustrates the type of signal referred to in the last statement.

In this signal, the frequency content of the bursts could result from resonances excited in a system such as a punch press. These excited resonant frequencies are the principle frequencies at which the system vibrates, but this vibration is excited by a punching process which occurs at a different but lower frequency. In a normal analysis, using
Fig. 4.4: Time trace of a burst signal.
the FFT, the resonant frequencies would dominate the spectrum. The frequency at which the impacts take place would almost be undetectable. In an energy envelope of this time signal, the impact events would dominate the envelope trace. Therefore an FFT of the envelope trace would reveal the frequency of the impacts.

The next two figures, figures 4.5a and 4.5b, show how buried information can be uncovered using the energy envelope technique. The spectrums in figure 4.5a are the FFTs of time traces taken from a machine with good and then bad bearings respectively. These machines also have a lubricator which shoots lubricant into the bearings periodically. The FFT spectrums of the energy envelope from these machines are illustrated in figure 4.5b. In this figure, the lubrication frequency is revealed in both spectra, as well as, a ball pass frequency in the machine with a bearing defect.
FIGURE 4.5a: FFT FROM A MACHINE WITH GOOD AND FAULTY BEARINGS [15]

FIGURE 4.5b: FFT OF AN ENERGY ENVELOPE FROM A MACHINE WITH GOOD AND FAULTY BEARINGS [15]
V. MEASUREMENT SYSTEM

The most important and difficult step in preparing a method to predict engine faults was collecting the appropriate data. The data, which was analyzed using various techniques described in the theory section had to conform to the restrictions of these techniques. Fortunately, all the techniques required the same type of raw data (time data from a transducer), reducing the amount necessary to acquire. The following sections will describe the measurement theory, the measuring system and a description of tests on this system.

5.1 Measurement Theory

Three of the MSA techniques require that the initiation of sampling, termination of sampling and the sampling of each individual data point be referenced to a particular event in a cycle. This assures that significant changes in raw or processed time signals can be linked to specific events in the machine. In combustion engine studies, events are usually referenced either by crankshaft or camshaft angle.
After a method of referencing collection is decided upon another factor which must be considered is the amount of time data that should be collected from each measured point. It is reasonable to assume that once data collection is initiated, time data should be collected for at least one complete engine cycle. This helps guarantee that no engine fault can take place and be missed by the data collection system. The variance technique and TDA technique require that several separate samples of an engine cycle be taken, typically 25 cycles are acquired. Therefore, it is not necessary to collect more than one engine cycle per sample.

The trigger event which initiates data collection must occur only once in a complete engine cycle, it must also occur at the same crankshaft or camshaft angle in all engine cycles. There must be a consistent method of detecting this event. Fortunately, two separate events can be related to satisfy these requirements. These events are the Top Dead Center of a piston stroke before the power stroke and the firing of the spark plug of that cylinder. Alone these events cannot be used as references, TDC occurs twice in a cycle and firing of the spark plug does not occur at the same position in every engine cycle. Fortunately, the spark plug always fires a few degrees before TDC of a piston's
power stroke. This angle before TDC (BTDC) is easy to acquire from a device attached to the crankshaft. Therefore, it is quite simple to determine at what time after the firing of a spark plug TDC occurs, provided that the engine is moving at a constant rpm.

The next restriction on the system to be addressed is the time involved in collecting the measured data, which must be short to comply with manufacturing requirements. Assuming data transfer between computers to be very efficient, the main restriction becomes the types of transducers that can be used. The transducers that were determined to be applicable under these conditions are microphones, high temperature accelerometers and pressure transducers. Microphones and accelerometers are quick and easy to apply to an engine, while a pressure transducer is difficult to apply. A pressure transducer must be inserted either into the engine's lubrication system, cooling system, intake and exhaust system or directly into the engine cylinder. The problem with measuring pressure in most of these systems is the lack of mounting positions. This requires drilling and tapping mounting holes, significantly increasing time and cost of the analysis. The solution to the mounting position problem is the use of a spark plug
pressure transducer. This device is both a spark plug and a pressure transducer and is inserted directly into the cylinder, via the normal spark plug threads. Piston slap is most likely to exhibit itself inside the cylinder, in terms of engine pressure changes, and therefore this transducer solves the problem most effectively.

The next question to answer is where on the engine to measure the data. The positioning of the transducers (excluding the pressure transducer whose position cannot be varied) is of particular concern to the success at which piston slap can be detected. This concern over transducer position is prompted by the fact that engine surface vibration and sound emission has many sources, of which piston slap is included but not exclusively. Logically, there should exist positions on the engine where piston slap signals are the strongest signal present. According to literature, these positions should be the cylinder head bolts, the oil pan and the crankcase. This location problem is further compounded when trying to establish a method of determining which particular cylinder(s) are experiencing piston slap. This implies that the engine block is the best location for the evaluation of piston slap, since transducers could be placed directly over a cylinder where
the signals from that cylinder should dominate.

5.2 Time Locked Sampling Concerns

The trigger in this measurement system only initiates sampling. The result is a engine measurement system which is unique in the fact that is does not use external sampling. External sampling is a process where triggering does not only initiate sampling it also triggers each individual sampling data point. Usually, the technique employs an encoder which outputs 512 or some other power of 2 pulses per engine cycle from a device directly attached to the crankshaft. At each one of these pulses data is sampled, guaranteeing that sampling occurs at the same positions in every time trace taken. This technique is very effective even on systems with moderately unstable speed. The sampling rate, however, becomes a direct function of the engine speed and this drawback is the main reason for not using the technique. In fact, for a system with a 512 pulse per cycle encoder, the sampling time can be easily calculated at \((60/(\text{rpm}*512))\) seconds between samples. This predetermines the Nyquist frequency and low pass filter cut-off frequency, which could cause loss of information at specific speeds of interest. If, for example, piston slap
characteristics at 800 rpm are under study, frequencies over 3500 Hz will be eliminated by a filter needed to prevent aliasing. This could be disastrous if the piston slap characteristic frequencies are over such a frequency value.

External sampling is not necessary in this measurement system because the dynamometer controls the speed of the engine to within 1 rpm. This implies that measurements made on the engine can be directly converted to position since the engine is essentially at constant speed. This provides the freedom to sample at any desired rate, however, this method is not free from error.

5.2.1 Errors in Time Locked Data Collection

TDA and variance analysis in this measurement system rely on a time locked method, in which accuracy is highly dependent upon the dynamometer's ability to hold engine speed steady. The dynamometer used in the data collection did an excellent job keeping speed variations to within 1 rpm. These variations in speed, though slight, can still introduce an error in averaging termed "smear". Smear becomes a significant problem when the speed variations are
large enough to cause data points to overlap, making it possible for all signals late in the cycle to degrade to noise.

These errors can be analyzed by considering a mean sample location and superimposing the range over which the data may be sampled. To accomplish this, we convert the sampling time and speed variations into angles.

for sampling:

\[
\Delta \theta = \frac{1}{\frac{2.56 \text{ freqspan}}{60} \times 360^\circ} \times \frac{\text{RPM}}{60} \times 360^\circ
\] (5.1)

at any particular sample point (n):

\[
\theta = n \Delta \theta
\] (5.2)

typically for a frequency span of 5000 Hz and a RPM of 1500:

\[
\Delta \theta = .70^\circ
\]

angular variations with rpm = 1500 ± 1:

\[
\Delta \theta, i = \frac{1}{\frac{2.56 \text{ freqspan}}{60} \times 360^\circ} \times \frac{\text{RPM} + 1}{60} \times 360^\circ
\] (5.3)
\[ \Delta \theta_{-1} = \frac{1}{2.56 \text{freqspan}} \times \frac{RPM - 1}{60} \times 360^\circ \]  

(5.4)

\[ \Delta \theta_s = n(\Delta \theta_{-1} - \Delta \theta_{-1}) \]  

(5.5)

\[ \Delta \theta_s = \frac{n}{2.56 \text{freqspan}} \times \frac{2}{60} \times 360^\circ \]

Figure 5.1 illustrates over which range the data is possibly acquired. This would imply that the calculated average is an average for this region, rather than at the mean location alone.

At the sample point \( n \), where data can overlap another mean data point, the averaging process begins to degrade rapidly. The calculation to determine this point \( n \) is as follows:

\[ n(\Delta \theta_s) = 2 \Delta \theta \]

In the above example with a freqspan=5000 Hz and an rpm=1500 this overlapping occurs at \( n=1500 \). However, by \( n=1024 \) the data collection would have terminated, implying that the data collection was not subject to smear.

Further, this variation in dynamometer speed does not occur constantly. These variations, therefore, will not
FIGURE 5.1: AVERAGING RANGE FOR SMEARED DATA
show up in every sample trace and should not significantly affect the data. This can be shown by examining averaging and the changes in averaging, as the averaging number increases. The following average data was taken from an engine and consists of 25, 50, 75 and 100 ensemble averages. These are illustrated in figures 5.2a, 5.2b, 5.2c and 5.2d and show very little difference from average to average, whereas, if there had been significant smear the averages should have degraded to noise.

5.3 The Measurement System

The block diagram in figure 5.3 represents the interaction of the components in the measuring system. The basic components are the trigger, transducers, analyzer, computers and the feedback speed control from the dynamometer.

5.3.1 Trigger System

The event on which data collection will commence was predetermined to be the TDC of a piston immediately after ignition of that cylinder. Just as a matter of choice, the
FIGURE 5.2a: 25 ENSEMBLE AVERAGE OF DATA FROM AN ENGINE BLOCK

FIGURE 5.2b: 50 ENSEMBLE AVERAGE OF DATA FROM AN ENGINE BLOCK
FIGURE 5.2c: 75 ENSEMBLE AVERAGE OF DATA FROM AN ENGINE BLOCK

FIGURE 5.2d: 100 ENSEMBLE AVERAGE OF DATA FROM AN ENGINE BLOCK
FIGURE 5.3: BLOCK DIAGRAM OF MEASUREMENT SYSTEM
first cylinder was selected as the location for the particular triggering event. All that was left to determine was how to physically detect this event.

A spark plug fires at a tremendously high voltage in the neighborhood of 30,000 volts. A magnetic field placed around a spark plug cable would also experience a voltage increase by induction but at a much reduced magnitude due to the insulation of the spark plug cable. This change in voltage is detected in this measurement system by a magnetic pickup and a trigger box. This box outputs a trigger signal in the form of a TTL compatible voltage signal to the analyzer. This trigger box also protects the analyzer from the unknown voltage characteristics of the inducted voltage in the magnetic pickup.

5.3.2 Data Acquisition System

The data acquisition system consists of a computer with software, an analyzer, a filter and transducers. The data acquisition begins with transducers mounted on the engine in the desired fashion. The data passes through the filter where alias frequencies are removed. After triggering, the data is then collected by digital sampling in the HP3561A analyzer. This data is then transferred over an IEEE-488
interface to the computer and is then stored on disk for permanent record. The specifications of these pieces of equipment are well documented and are presented in Appendix C.

The program which controls the measuring system sets the sampling rate, the total sampling time, the filter cutoff frequencies, activates the trigger and systematically acquires the following data. The system first averages data by continuously transferring time traces and performing a point by point average. Then it acquires 25 separate time trace samples and stores this information with the TDA in a disk storage device. The flow diagram for this program is illustrated in figure 5.4 and a listing is in Appendix B.

5.4 Testing the Measurement System

The measurement system described in the previous section had to be tested to assure it was functioning properly. This involved developing methods to test the triggering methods used, the data acquisition system and averaging.
FIGURE 5.4: FLOW DIAGRAM OF DATA ACQUISITION PROGRAM
5.4.1 Triggering Tests

The system has a trigger box that sends a trigger signal on the firing of a spark plug. The computer then sends a delay command to the analyzer, causing the analyzer to pause until the TDC of the piston stroke. The analyzer waits for the delay period to expire and then starts collecting data. A question could arise as to how well this actually works and whether it is consistent. It is conceivable that the analyzer may not react as expected to the signals from the trigger box, taking too much time to set data input ranges. This consistency problem was previously encountered in another make of analyzer. It is also conceivable that the trigger box could send out false signals triggering at just about anytime. Two tests were conducted to test for these problems.

5.4.1.1 Triggering Consistency

The following figure, figure 5.5, is a block diagram of the experiment used to test the triggering consistency.

The test uses a trigger signal to initiate triggering and the data acquisition system collects this same trigger signal. If the trigger system is consistent, averaging several of these signals together should not drastically
FIGURE 5.5: BLOCK DIAGRAM OF TRIGGER CONSISTENCY TEST SYSTEM
change the appearance of these signals. The test was conducted using 25, 50 and 100 average ensembles. A direct comparison of a typical trigger pulse to these 3 curves, presented in figures 5.6a, 5.6b, 5.6c and 5.6d, clearly shows the triggering system is quite consistent.

5.4.1.2 False Triggering Test

A reasonable fear exists that false signals, caused by induction, could enter the magnetic pickup from other spark plugs or electric fields. This could initiate data collection at a non referenced location defeating the purpose of the trigger. If false triggering occurs, it probably will not appear in each cycle but if enough data is collected it should eventually appear. The procedure employed to analyze the problem included the use of a digital oscilloscope to analyze the trigger signal. The digital oscilloscope was set to acquire 4 cycles per trace and to collect over 100 traces. Therefore 400 trigger cycles could be analyzed. The 100 traces were then examined to determine if any false triggering had occurred. The trigger signals were similar to those in figure 5.7.

The $\Delta t$ between trigger pulses should equal the time for one complete engine cycle. If all the $\Delta t's$ are not equal to
FIGURE 5.6a: 25 ENSEMBLE AVERAGE OF THE TRIGGER SIGNAL

FIGURE 5.6b: 50 ENSEMBLE AVERAGE OF THE TRIGGER SIGNAL
FIGURE 5.6c: 75 ENSEMBLE AVERAGE OF THE TRIGGER SIGNAL

FIGURE 5.6d: 100 ENSEMBLE AVERAGE OF THE TRIGGER SIGNAL
FIGURE 5.7: TYPICAL TRACE FROM FALSE TRIGGERING TEST
the time for one complete cycle then false triggering is occurring. In the 400 cycles no evidence of false triggering was found.

5.4.2 Data Acquisition System

The primary function of the data acquisition system is to transfer the data from the analyzer to the computer where it is stored for later use. A simple test was devised to verify the correct operation of the system. A known signal was applied to the analyzer and after transferring to the computer the data was stored and plotted. The signal was also displayed on the analyzer and plotted directly from the analyzer to the plotter. These two results were then compared to each other. After applying this procedure several times, it was apparent that the data acquisition system was working well.

5.4.3 Filter Delay Calculation

The filter used in these studies is an analog filter, but it still requires time to process signals, delaying signal output by a definite amount of time. In other words, if the filter is used, a further delay must be incorporated into the trigger setup of the analyzer. This delay time is not a constant and changes with the cutoff frequency set.
The manufacturer did not supply any information on such a delay and after correspondence with the company it was discovered that no such information existed. It became necessary to determine these delays for various cutoff frequencies. The method of determining these delays required the use of a two channel oscilloscope and a signal generator. The description of the experimental setup is given in figure 5.8.

In the experiment a harmonic function at half the cut-off frequency was applied to a digital oscilloscope. This ensured that only two local maximums occurred in each acquired time trace. In one channel the signal was applied directly to the oscilloscope and in the other channel the signal was first passed through the filter. The value of the first local maximum in the non filtered signal was located. Then the first local maximum in the filtered time trace was located starting from the time position where the non filtered local maximum was found. The difference in the time scale between these points is the filter time delay. A series of these were calculated and then averaged. These were repeated for several cut-off frequencies and are tabulated in Appendix D.
FIGURE 5.8: BLOCK DIAGRAM OF FILTER DELAY TEST SYSTEM
VI. DATA AND RESULTS

Currently, the detection of piston slap is conducted on a subjective basis, relying on the hearing capabilities of experienced technicians and engineers. This often results in conflicting and erroneous results and severely complicates the process of correlating a signature analysis technique against piston slap. This prompted the following approach in collecting the data.

The first engine in the study, named the "base engine", was purposely constructed to produce audible piston slap in the sixth cylinder and to not produce slap in any other cylinder. The second and third engines in the study, named FRET1 (first field return engine) and FRET2 (second field return engine) respectively, were engines returned by customers for reasons of excessive knock. The knock in these returned engines was diagnosed as piston slap. The results of these tests were examined against a set of 9 other engines.

Time data acquired from these engines was processed to determine which signature analysis technique and which transducers would lead to an effective method of determining piston slap.
6.1 Base Engine Test

The base engine, which was constructed to simulate piston slap, provided the majority of test results. The results included the selection of an appropriate transducer for the detection of piston slap and an initial analysis of the MSA techniques.

6.1.1 Transducer Selection

Transducer selection was conducted by comparison of MSA technique results. This would imply that first an MSA technique of detecting piston slap would have already been decided upon and then the data acquired from each transducer evaluated as to its merit. Fortunately this was not necessary in these studies, a simple comparison of the MSA results was capable of demonstrating which transducers were the least effective from the stand point of studying piston slap.

6.1.1.1 Pressure Data

The pressure data was collected from the base engine by use of a spark plug transducer. Results were acquired for all six cylinders and are presented in the figures.
6.1, 6.2, 6.3 and 6.4. These figures are a comparison of the results of the 4 MSA techniques between cylinder 6, which contains audible piston slap and cylinder 1. The results of cylinder 1 are typical for all the non piston slap cylinders.

6.1.1.2 Microphone Data

The microphone data was collected from each cylinder of the base engine by placing the microphone close to the cylinder block. The processed results from this time data are depicted in figures 6.5, 6.6, 6.7 and 6.8.

6.1.1.3 Accelerometer Data

The accelerometer data was collected from each cylinder of the base engine by attaching the accelerometers to the cylinder block as in figure 6.9. The results of this time data are depicted in figures 6.10, 6.11, 6.12 and 6.13.

6.1.2 Transducer Test Results

The results from the pressure transducers and the microphone are clearly of no value for the detection of piston slap. There are no significant differences between the results of the data from the cylinder containing the slap and the cylinders which did not. It is important to
FIGURE 6.1a: TDA DATA FROM PRESSURE TRANSDUCER IN CYLINDER 6 OF THE BASE ENGINE

FIGURE 6.1b: TDA DATA FROM PRESSURE TRANSDUCER IN CYLINDER 1 OF THE BASE ENGINE
FIGURE 6.2a: VARIANCE DATA FROM PRESSURE TRANSUDCER IN CYLINDER 6 OF THE BASE ENGINE

FIGURE 6.2b: VARIANCE DATA FROM PRESSURE TRANSUDCER IN CYLINDER 1 OF THE BASE ENGINE
Figure 6.3a: Energy Envelope Data from Pressure Transducer in Cylinder 6 of the Base Engine

Figure 6.3b: Energy Envelope Data from Pressure Transducer in Cylinder 1 of the Base Engine
FIGURE 6.4a: FFT DATA FROM PRESSURE TRANSDUCER IN CYLINDER 6 OF THE BASE ENGINE

FIGURE 6.4b: FFT DATA FROM PRESSURE TRANSDUCER IN CYLINDER 1 OF THE BASE ENGINE
FIGURE 6.5a: TDA DATA FROM THE MICROPHONE NEAR CYLINDER 6 OF THE BASE ENGINE

FIGURE 6.5b: TDA DATA FROM THE MICROPHONE NEAR CYLINDER 5 OF THE BASE ENGINE
FIGURE 6.6a: VARIANCE DATA FROM THE MICROPHONE NEAR CYLINDER 6 OF THE BASE ENGINE

FIGURE 6.6b: VARIANCE DATA FROM THE MICROPHONE NEAR CYLINDER 5 OF THE BASE ENGINE
FIGURE 6.7a: ENERGY ENVELOPE DATA FROM THE MICROPHONE NEAR CYLINDER 6 OF THE BASE ENGINE

FIGURE 6.7b: ENERGY ENVELOPE DATA FROM THE MICROPHONE NEAR CYLINDER 5 OF THE BASE ENGINE
FIGURE 6.8a: FFT DATA FROM THE MICROPHONE NEAR CYLINDER 6 OF THE BASE ENGINE

FIGURE 6.8b: FFT DATA FROM THE MICROPHONE NEAR CYLINDER 5 OF THE BASE ENGINE
FIGURE 6.9: CYLINDER BLOCK ACCELEROMETER PLACEMENT
FIGURE 6.10a: TDA DATA FROM THE ACCELEROMETER ON CYLINDER 6 OF THE BASE ENGINE

FIGURE 6.10b: TDA DATA FROM THE ACCELEROMETER ON CYLINDER 5 OF THE BASE ENGINE
FIGURE 6.11a: VARIANCE DATA FROM THE ACCELEROMETER ON CYLINDER 6 OF THE BASE ENGINE

FIGURE 6.11b: VARIANCE DATA FROM THE ACCELEROMETER ON CYLINDER 5 OF THE BASE ENGINE
**FIGURE 6.12a:** ENERGY ENVELOPE DATA FROM THE ACCELEROMETER ON CYLINDER 6 OF THE BASE ENGINE

**FIGURE 6.12b:** ENERGY ENVELOPE DATA FROM THE ACCELEROMETER ON CYLINDER 5 OF THE BASE ENGINE
FIGURE 6.13a: FFT DATA FROM THE ACCELEROMETER ON CYLINDER 6 OF THE BASE ENGINE

FIGURE 6.13b: FFT DATA FROM THE ACCELEROMETER ON CYLINDER 5 OF THE BASE ENGINE
remember that the piston slap in the base engine can be considered extreme. Any MSA technique and transducer combination which does not clearly show a difference between the sixth cylinder and the rest of the cylinders is simply not going to be sensitive enough to detect piston slap in the industrial environment.

The results of the accelerometer tests are very encouraging. There are clearly significant differences in the MSA results of the 6th cylinder and the other non-slapping cylinders. It was concluded, after visualizing these results, that any further tests need only be conducted with the accelerometer. The accelerometer makes a great deal of sense from a manufacturing point of view as well. It is easier to apply to an engine than the spark plug pressure transducer and is not as affected by background noise as is the microphone.

6.1.3 Procedure for Isolating a Cylinder with "Slap"

The results from this engine also provided another useful piece of information. The severe piston slap in the sixth cylinder of this engine could be identified, while the rest of the cylinders were identified as not containing piston slap. For example, cylinder 5, the nearest neighbor
to cylinder 6 had distinctly different MSA technique results. This implies that the identification of a particular cylinder with piston slap is possible and the results help bear this out. The rest of the results from this engine can be found in Appendix D.

6.2 Field Return Engine No. 1 Data

The second engine in the investigation was a customer returned engine which contained what the customer believed to be an excessive knocking noise. The noise was not audible on the test stand, however, technicians by use of a stethoscope probe identified it as a piston slap in the sixth cylinder. The left bank of cylinders (cylinder 4, 5 and 6) were studied and used to acquire data. The results are presented in figures 6.14, 6.15, 6.16, 6.17 and 6.18.

6.3 Field Return Engine No. 2 Data

The third engine in the study was another field return engine identified as suffering from piston slap. The sound was not audible on the test stand but was identified by stethoscope probe as definitely occurring in the second
**FIGURE 6.14a:**  TDA DATA FROM THE FIRST FIELD RETURN ENGINE ON CYLINDER 6

**FIGURE 6.14b:**  TDA DATA FROM THE FIRST FIELD RETURN ENGINE ON CYLINDER 5
FIGURE 6.15a: VARIANCE DATA FROM THE FIRST FIELD RETURN ENGINE ON CYLINDER 6

FIGURE 6.15b: VARIANCE DATA FROM THE FIRST FIELD RETURN ENGINE ON CYLINDER 5
**Figure 6.16a:** Energy Envelope Data From the First Field Return Engine On Cylinder 6

**Figure 6.16b:** Energy Envelope Data From the First Field Return Engine On Cylinder 5
FIGURE 6.17a: FFT DATA FROM THE FIRST FIELD RETURN ENGINE ON CYLINDER 6

FIGURE 6.17b: FFT DATA FROM THE FIRST FIELD RETURN ENGINE ON CYLINDER 5
FIGURE 6.18a: TDA DATA FROM THE FIRST FIELD RETURN ENGINE ON CYLINDER 4

FIGURE 6.18b: VARIANCE DATA FROM THE FIRST FIELD RETURN ENGINE ON CYLINDER 4
FIGURE 6.18c: ENERGY ENVELOPE DATA FROM THE FIRST FIELD RETURN ENGINE ON CYLINDER 4

FIGURE 6.18d: FFT DATA FROM THE FIRST FIELD RETURN ENGINE ON CYLINDER 4
cylinder and possibly in the 4th cylinder. Some of the data acquired is presented in figures 6.19, 6.20, 6.21 and 6.22, and the rest of the data is presented in appendix D.

6.4 **Time Domain Averaging Results**

If piston slap is periodic then the "slap" should manifest itself in the average signal. This is demonstrated in the first and second field return engines. At ignition angles, large amplitude variations occur in the average signal but in the base engine it is more difficult to notice these sharp amplitude changes. The difficulty experienced in the base engine TDA results can be simply avoided by using the energy envelope method with the average signal.

6.5 **Energy Envelope Technique Results**

The energy envelope technique, described in the theory chapter, represents the change of energy in a time signal. When a piston starts to slap and strikes the cylinder wall it imparts a great deal of energy to the crankcase. This increase in energy is manifested in the energy envelope technique as a sharp rise in amplitude.
FIGURE 6.19a: TDA DATA FROM THE SECOND FIELD RETURN ENGINE ON CYLINDER 2

FIGURE 6.19b: TDA DATA FROM THE SECOND FIELD RETURN ENGINE ON CYLINDER 2
FIGURE 6.20a: VARIANCE DATA FROM THE SECOND FIELD RETURN ENGINE ON CYLINDER 2

FIGURE 6.20b: VARIANCE DATA FROM THE SECOND FIELD RETURN ENGINE ON CYLINDER 5
FIGURE 6.21a: ENERGY ENVELOPE DATA FROM THE SECOND FIELD RETURN ENGINE ON CYLINDER 2

FIGURE 6.21b: ENERGY ENVELOPE DATA FROM THE SECOND FIELD RETURN ENGINE ON CYLINDER 5
FIGURE 6.22a: FFT DATA FROM THE SECOND FIELD RETURN ENGINE ON CYLINDER 2

FIGURE 6.22b: FFT DATA FROM THE SECOND FIELD RETURN ENGINE ON CYLINDER 5
If the "slap" phenomena is periodic then the average signal trace should contain this information. An energy envelope of this curve will show an increase in energy level at each "slap". If the piston slap occurs semi-periodically it is still possible for the method to identify piston slap phenomena, but it is likely the averaging process will filter out this piston slap information.

6.6 Variance Analysis Results

If piston slap occurs semi-periodically either in terms of strength or appearance the average signal will not contain all the slap information. Variance analysis concentrates on the difference in signals from the average signal and then amplifies the difference. This detects any semi-periodic signals such as this type of piston slap. This is illustrated in the variance results from the base engine which shows slapping noises occurring 60 degrees before ignition. These "slap" signals are totally missed by TDA and the energy envelope method.
6.7 **FFT Analysis Results**

The difference in frequency traces between those cylinders and engines in which the piston slap is occurring, and those which aren't experiencing piston slap do not appear significantly different in any respect. This clearly demonstrates the ineffectiveness of this method for this type of diagnostics.

6.8 **Piston Slap Detection Procedure**

The three initial engines in this study all contain a cylinder in which piston slap could be heard. The results from variance analysis, energy envelope analysis and sometimes TDA show distinct peaks in the cylinders which contain piston slap. Most of these peaks are separated by 120 degree intervals and most occur at the crank angles associated with ignition. In the second field return a peak also occurs at BDC which is consistent with literature [1,2,3,5].

These distinctive peaks do not always appear in all of the MSA results even though the data has been collected from a cylinder with piston slap. This can be explained by
examining how the slap phenomena can behave. "Slapping" can occur in the same position with the same strength in every cycle. This type of piston slap is periodic and can be detected easily by the energy envelope or TDA method. "Slapping" can also appear at particular locations in a cycle but not necessarily in every cycle or with the same strength. This type of piston slap is semi-periodic and variance analysis is more sensitive to this problem.

In summary, to detect piston slap the use of both the energy envelope of the TDA signal and the variance of the signal is suggested. A six peak or multi peak trace probably denotes periodic or semi-periodic "slap".

The amplitudes of these peaks versus the severity of the slap at this point cannot be correlated. The following table, table 1, will denote the maximum and average value of peaks by use of energy envelope and variance analysis techniques from those cylinders in which the knock was audible.
<table>
<thead>
<tr>
<th>Engine Name</th>
<th># of peaks</th>
<th>Energy Envelope (g)</th>
<th># of peaks</th>
<th>Variance (g²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Maximum</td>
<td>Avg</td>
<td>Maximum</td>
</tr>
<tr>
<td>Base</td>
<td>6</td>
<td>3.74</td>
<td>3.37</td>
<td>6</td>
</tr>
<tr>
<td>Fret1</td>
<td>6</td>
<td>5.91</td>
<td>5.32</td>
<td>5</td>
</tr>
<tr>
<td>Fret2</td>
<td>6</td>
<td>5.79</td>
<td>3.76</td>
<td>7</td>
</tr>
</tbody>
</table>

6.9 **Further Testing of the Method**

In order to establish if it is possible to determine at what amplitude in the characteristic piston slap pattern that piston slap becomes audible, nine further engines were tested. These nine engines were part of an earlier test at the manufacturing facility, which had failed due to a lack of a measurement technique and diagnostic logic. In the tests, parameters which are traditionally thought to affect piston slap were studied. These parameters were varied on a low high basis and are listed in table 2. Engines were constructed with these varied parameters and coded by colour and are listed in figure 6.23.
<table>
<thead>
<tr>
<th>ENGINE</th>
<th>HEAT TREAT</th>
<th>MAT.</th>
<th>SKIRT DESIGN</th>
<th>PIN BORE OFFSET</th>
<th>CYL. BORE CLEAR</th>
<th>PISTON PIN FIT</th>
<th>RING LAND DIA.</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHITE</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>GREEN</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>RED</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>YELLOW</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>BROWN</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PINK</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>BLUE</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>BLACK</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

**FIGURE 6.23:** PISTON SLAP VARIABLE TEST PARAMETERS
The color coded engines did not exhibit audible slap even when investigated with the stethoscope probe. Signature patterns, similar to those found in the audible piston slap tests, were found but at a much reduced amplitude. The large majority of peak magnitudes were less than 1 g in the energy envelope technique and less than 1 g² in the variance technique. If the slap detection procedure is valid, then these values can be considered piston slap but of a lower severity, below the audible range. The results of tests on these engines are presented in figure 6.24. In the figure, spaces filled with an asterisk indicate cylinders containing signature patterns similar to those acquired from the audible slapping cylinders.

The analysis of these tests lead to conclusions that were contrary to those previously accepted by the test
<table>
<thead>
<tr>
<th>ENGINE NAME</th>
<th>CYLINDER 1</th>
<th>CYLINDER 2</th>
<th>CYLINDER 3</th>
<th>CYLINDER 4</th>
<th>CYLINDER 5</th>
<th>CYLINDER 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHITE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>GREEN</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RED</td>
<td></td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>YELLOW</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BROWN</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PINK</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>BLUE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LACK</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

OTHER RESULTS

| PV901       |            |            |            |            |            | *          |
| FRET1       |            |            |            |            |            | *          |
| FRET2       | *          |            |            |            |            |            |
| BASE        |            |            |            |            |            | *          |
| TOTAL       | 3/12       | 4/12       | 4/12       | 0/12       | 0/12       | 5/12       |

FIGURE 6.24: PISTON SLAP VARIABLE TEST RESULTS
designers. In fact, the tests showed that the variables mentioned in table 2 had very little to do with the formation of slap. This was perplexing but the test designers had forgotten one important variable, cylinder bore distortion. These results were later correlated against bore distortion data providing more acceptable results.

6.9.1 Cylinder Bore Distortion Vs. Piston Slap

Bore distortions are the minute changes in shape from round cylinder dimensions due to the forces and torques exerted on a block in the assembly process. Statistics acquired over eight years at the manufacturing facility, have shown that in cylinders with basically oval distortion shape, piston slap is more likely to occur. The subject engine has average distortion shapes similar to those in figure 6.25 (the shapes are very exaggerated in this figure).

A rank order of cylinder bores in terms of oval shape is as follows:

1) the number 6 cylinder bore  
2) the number 3 cylinder bore  
3) the number 1 cylinder bore  
4) the number 2 cylinder bore  
5) the number 4 cylinder bore  
6) the number 5 cylinder bore
FIGURE 6.25: AVERAGE CYLINDER BORE DISTORTION SHAPE.
Therefore, it is expected that in cylinder 6 there should be more evidence of knock than in cylinder 3 etc. These values are based on aggregate averages and individual engines may differ.

6.9.2 Results of Correlation Against Cylinder Bore

Re-evaluating the results of the "Piston Slap Variable Test" will show quite clearly that the occurrence of piston slap in each cylinder follows the rank order of cylinder bore distortion. This implies that piston slap is still a strong function of bore distortion, a conclusion that is well accepted by the technicians and engineers in the manufacturing facility. This acceptance is valuable and gives support to the method as a measuring tool. It still, unfortunately, does not provide a graduated scale of slap severity. This would require a substantially large sample population, due to the type of subjective analysis of human perception the method must be correlated against. This is beyond the scope of one person's work.

6.10 Piston Slap Variable Test Results

1) Piston slap again manifested itself as sharp peaks usually separated by the angle associated with ignition.
These peaks again occurred in either, or both, the energy envelope of the TDA signal or the variance analysis of that signal.

2) The magnitudes of the MSA results from inaudible piston slap was much lower than that of the audible piston slap. This implies gradation of the severity of piston slap based on these methods is still possible.

3) The contention that bore distortion is still a very important cause of piston slap is quite valid for the subject engine.
VII. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The following list is a summary of the results of this investigation into piston slap detection.

1) The detection of piston slap is best accomplished, in the manufacturing point of view, by the use of certain MSA techniques. These techniques are the energy envelope of the TDA signal and the variance analysis of the signal.

2) Piston slap is usually indicated by sharp peaks in the MSA methods. These peaks typically occur at the crank angles associated with ignition or at the BDC of the piston stroke.

3) Particular cylinders suffering from piston slap can be differentiated from those that are not with these techniques.

4) The most useful transducer for the detection of piston slap is the accelerometer.

5) The best location of the accelerometer is directly over each cylinder wall on the crankcase.
7.2 Recommendations

The following is a list of other work that should be conducted to continue and verify this work.

1) This technique should be applied to other makes of engines. The results indicate that "slapping" is occurring at crank angles associated with ignition and not just at TDC and BDC conditions. This is not consistent with literature [1, 2, 3, 5].

2) The technique should be applied to a large number of engines experiencing piston slap problems. The results of these tests should be correlated against other subjective results. This is suggested in order to develop a database to graduate piston slap severity against the results of MSA techniques.

3) Other transducers, such as intensity probes, should be evaluated.

4) A dedicated, tailor made system should be tested in order to determine the minimum time at which results can be acquired.
5) Other fault problems, such as those listed in the introduction, should now be tackled.
VIII. REFERENCES


APPENDIX A

A Bibliography of Books on Internal Combustion Engines


APPENDIX B

Computer Program Listings
DATA ACQUISITION PROGRAM
10 OPTION BASE 1
20 DEG
30 OUTPUT 2 USING "*K*":CHR$(255),CHR$(75)
40 COM INTEGER Max_rec_size,Type_flag,Line,
50 COM Mes$(80),Tiave$(1),A$(15),Answ$(1),Filthy$(1),Autosngl$(1),Asroot$(15)
60 COM REAL Rec_num,Span,Cutoff,Start,Rpm,Trv,Plug,Cal_fact,Fil_del
70 COM INTEGER Rge,Act,Autosngl_st,Autosngl_end
80 ON ERROR RECOVER Errr
90 ASSIGN #PI TO "TRIGPARA"
100 ENTER #PI,1,A#:Tiave$:Answ$:Rec_num$:Filthy$:Cutoff$:Start$:Rpm$:Rge$:Trv:
110 ASSIGN #PI TO *
120 OFF ERROR
130 ASSIGN @Anx TO 711  'CREATE AN I/O PATH TO THE HP
140 Autosngl$="N"
150 Autosngl_st=1
160 Autosngl_end=1
170 Asroot$=""
180 Variable:  
190 CONTROL 1,13:25
200 Menfl=1
210 ON KEY (1) LABEL "MENU1",12 GOSUB Menu1
220 ON KEY (2) LABEL "MENU2",12 GOSUB Menu2
230 ON KEY (3) LABEL "TESTMENU",12 GOSUB Mainmenu
240 ON KEY (4) LABEL "CHANGE PARAM",12 GOSUB Param
250 ON KEY (5) LABEL "SAVE PARAM",12 GOSUB Spara
260 CONTROL 2,2:1
270 WHILE Wiler<1
280 IF Menfl=1 THEN
290 GOSUB Menu1
300 Menfl=0
310 END IF
320 IF Menfl=2 THEN
330 GOSUB Menu2
340 Menfl=0
350 END IF
360 END WHILE
370 Param:  
380 INPUT "NUMBER OF PARAMETER YOU WISH TO CHANGE",Sel#
390 SELECT Sel#
400 CASE "1"
410 INPUT "ENTER NEW MASS STORAGE SPECIFIER",As#
420 Mes$=""
430 CASE "2"
440 INPUT "DO YOU WANT A TIME AVERAGE",Tiave$:
450 IF Tiave$="Y" THEN Start=0
460 Answ$="N"
470 Mes$=""
480 CASE "3"
490 INPUT "HOW MANY TIME AVERAGES",Tnum
500 Mes$=""
510 CASE "4"
520 INPUT "DO YOU WANT FREE RUN DATA",Answ#
530 Mes$=""
540 IF Tiave$="Y" AND Answ$="N" THEN
550 Answ$="N"
560 Mes$="CAN'T TIME AVERAGE AND FREE RUN AT THE SAME TIME"
570 END IF
580 CASE "5"
590 IF Answ$="N" THEN
600  Message(wiith A WAVE VARIABLE "FREE RUN")","...
610  ELSE
620  INPUT "HOW MANY RECORDS PER FREE RUN",Rec_num
630  Message(""
640  END IF
650  CASE "6"
660  INPUT "ARE YOU USING A FILTER",Filt
670  Message(""
680  CASE "7"
690  INPUT "ENTER THE CUT OFF FREQUENCY FOR THE LOW PASS FILTER",Cutoff
700  Message(""
710  CASE "8"
720  INPUT "ENTER THE ANALYZER FREQUENCY SPAN",Span
730  Message(""
740  CASE "9"
750  IF Tiaves="Y" OR Answer="N" THEN
760  Message(" CAN NOT SET START FREQ UNLESS IN FREE RUN MODE"
770  ELSE
780  INPUT "WHAT IS THE STARTING FREQUENCY",Start
790  Message(""
800  END IF
810  CASE "10"
820  INPUT "WHAT IS THE ENGINE RPM",Rpm
830  Message(""
840  CASE "11"
850  INPUT "THE SETTLED ANALYZER RANGE",Range
860  Act=(Trv/(10*(Range/20)))*100
870  IF ABS(Act)>140 THEN
880  Act=SGN(Act)*140
890  END IF
900  Act=INT(Act)
910  Message(""
920  CASE "12"
930  INPUT "THE TRIGGER VOLTAGE",Trv
940  Act=(Trv/(10*(Range/20)))*100
950  IF ABS(Act)>140 THEN
960  Act=SGN(Act)*140
970  END IF
980  Act=INT(Act)
990  Message(""
1000  CASE "13"
1010  Act=(Trv/(10*(Range/20)))*100
1020  IF ABS(Act)>140 THEN
1030  Act=SGN(Act)*140
1040  END IF
1050  Act=INT(Act)
1060  PRINT TABXY(5,16);"********THEORETICALLY THE TRIGGER PERCENTAGE SHOULD BE":A
1070  PRINT " WHAT PERCENTAGE TO TRIGGER ANALYZER",Act
1080  Message(""
1090  CASE "14"
1100  INPUT "WHAT IS THE ENGINE (BTDC) IN (DEGREES)",Plug
1110  Message(""
1120  CASE "15"
1130  INPUT "WHAT ARE THE VOLTS PER UNIT OF THE TRANSDUCER",Cal_fact
1140  Message(""
1150  CASE "16"
1160  INPUT "WHAT IS THE FILTER CAUSED DELAY",Filt_del
1170  Message(""
1180  CASE "17"
1190  INPUT "DO YOU WANT AUTO_SINGLE FUNCTIONS",Auto_Sngls
1200  IF Auto_Sngls="Y" THEN
1210  Tiaves="N"
1220  Answer="N"
1230  INPUT "WHAT IS THE ROOT NAME",ASroots
1240  INPUT "WHAT IS THE START NUMBER",Auto_num et
1250 INPUTWarn Is INN NUMBER AUTOSNGI_end
1260 END IF
1270 Mes#
1280 END SELECT
1290 Sel=VAL(Sel$)
1300 SELECT Sel
1310 CASE 1 TO 10
1320 Menfil=1
1330 CASE 11 TO 17
1340 Menfil=2
1350 END SELECT
1360 RETURN
1370 Menu1:
1380 OUTPUT 2 USING "$,-K":CHR$(255)&CHR$(75)
1390 FOR I=2 TO 11
1400 PRINT TABXY(I,1);"*":VAL$(I-1);
1410 NEXT I
1420 PRINT TABXY(5,2);"MASS STORAGE IS:";AS$:
1430 PRINT TABXY(5,3);"DO YOU WANT TO AVERAGE TIME DATA:";Tieves$:
1440 PRINT TABXY(5,4);"HOW MANY TIME AVERAGES:";Tnum$:
1450 PRINT TABXY(5,5);"DO YOU WANT FREE-RUN DATA:";Ans$:
1460 PRINT TABXY(5,6);"NO OF RECORDS OF FREE RUN:";Rec_num$:
1470 PRINT TABXY(5,7);"FILTER PRESENT:";Filthy$:
1480 PRINT TABXY(5,8);"CUTOFF FREQUENCY (LP):";Cutoff$:
1490 PRINT TABXY(5,9);"FREQUENCY SPAN:";Span$:
1500 PRINT TABXY(5,10);"FREQUENCY START:";Start$:
1510 PRINT TABXY(5,11);"ENGINE RPM:";Rpm$:
1520 PRINT TABXY(5,17);Mes$:
1530 PRINT TABXY(5,18);"SELECT APPROPRIATE SOFTKEY":"
1540 RETURN
1550 Menu2:
1560 OUTPUT 2 USING "$,-K":CHR$(255)&CHR$(75)
1570 FOR I=12 TO 18
1580 PRINT TABXY(I,1);"*":VAL$(I-1)
1590 NEXT I
1600 PRINT TABXY(5,2);"SETTLED ANALYZER RANGE:";Rge$:
1610 PRINT TABXY(5,3);"TRIGGER VOLTAGE:";Trv$:
1620 PRINT TABXY(5,4);"PERCENTAGE OF RANGE TO TRIGGER:";Act$:
1630 PRINT TABXY(5,5);"BEFORE TOP DEAD CENTER (DEG):";Plug$:
1640 PRINT TABXY(5,6);"THE VOLTS PER UNIT ARE:";Cal_fact$:
1650 PRINT TABXY(5,7);"THE FILTER DELAY IS:";Fil_del$:
1660 PRINT TABXY(5,17);Mes$:
1670 PRINT TABXY(5,18);"SELECT APPROPRIATE SOFTKEY":"
1680 PRINT TABXY(5,8);"AUTOSINGLE:";Autosngl$",";Autosngl_st$",";Autosngl_end$",";Asroot$:
1690 RETURN
1700 Menu:
1710 PURGE "TRIGPARA"
1720 CREATE BDAT "TRIGPARA",1,120
1730 ASSIGN @P1 TO "TRIGPARA"
1740 OUTPUT @P1,1:A:Tieves$;Ans$;Rec_num$;Span$;Filthy$;Cutoff$;Start$;Rpm$;Rge$;Trv$;Act$;Plug$;Cal_fact$;Tnum$;Fil_del$
1750 ASSIGN @P1 TO *
1760 RETURN
1770 MainMenu:
1780 I CONTROL 2.2:0 --- REMEMBER TO INCLUDE THIS AFTER THE START
1790 CALL Measurement(Anz$)
1800 CONTROL 2.2:1
1810 GOSUB Menu
1820 RETURN
1830 Err:
1840 IF ERRL(90)=1 OR ERRL(100)=1 THEN
1850 RESET 7
1860 GOTO 120
1870 END IF
1880 RETURN
I.

1900 SUB Measurement(Anz)
1910 'THIS PROGRAM READS DATA FROM THE HP-3561A
1920 'THE HP MUST BE IN TIME CAPTURE MODE, UP TO 40
1930 'RECORDS, OR 62910 BYTES (2048 BYTES PER RECORD PLUS 350 BYTE HEADER)
1940 'CAN BE READ.
1950 'ALL HP DATA CONTAINS A DATA HEADER. IN TIME CAPTURE MODE, THE HEADER
1960 'IS SENT IN THE FIRST 250 BYTES OF THE TRANSFER. THIS PROGRAM REMOVES
1970 'THE HEADER AND RETURNS THE CALIBRATED TIME DATA.
1980 OPTION BASE 1
1990
2000 REAL Start_t,Stop_t,Str,Rec_size
2010 INTEGER Tag_field(175)
2020 INTEGER Raw_data(100,1,2040)
2030 INTEGER Range,Rang(100)
2040 DIM Cal_fact(16)
2050 ON KEY 1 LABEL "GET DATA",13 GOSUB Get1
2060 ON KEY 3 LABEL "RETURN",13 GOSUB Rtn
2070 OUTPUT 2 USING ":,", "CHRS(125),CHR$(175)
2080 DISP "PICK APPROPRIATE SOFT KEY"
2090 CONTROL 2,21
2100 WHILE Bnk<1
2110 END WHILE
2120 Get1:
2130 Tiave=Ti
2140 DOSUB Tiave
2150 Tiave="N"
2160 Autoasng1="Y"
2170 DOSUB Autoasng1
2180 Autoasng1="N"
2190 DISP "FINISHED COLLECTING DATA"
2200 GOSUB Store_data
2210 GOSUB Return
2220 Rtn:
2230 ASSIGN @Fast TO *
2240 GCLEAR
2250 SUBEXIT
2260
2270 PRINT CHR$(12)
2280 INPUT "HOW MANY RECORDS TO TRANSFER?",Rec_size
2290 IF Tiave="N" AND Ans="N" THEN RESET @Fast
2300 RETURN
2310
2320 Read_data:
2330 1READS DATA FROM HP TO BUFFER. TAKES 0.15 SECONDS
2340 1PER RECORD PLUS .13 SECONDS
2350
2360
2540 IF **flag** = 'y' THEN GOTO 3050
2550 IF **answ** = 'y' THEN
2560 **gs** = **val** (**rec_num**)
2570 **act** = '0'
2580 **type_flag** = 1
2590 GOTO 3510
2600 END IF
2610 IF **filthy** = 'y' THEN
2620 SELECT Cutoff
2630 CASE .01 TO 11.9
2640 **ms** = 'm1'
2650 **fs** = **val** (**int** (**cutoff** + 100))
2660 CASE .1 TO 119
2670 **ms** = 'm2'
2680 **fs** = **val** (**int** (**cutoff** + 10))
2690 CASE 100 TO 1190
2700 **ms** = 'm3'
2710 **fs** = **val** (**int** (**cutoff** / 10))
2720 CASE 10000 TO 110000
2730 GOTO 114
FS=VAL$(INT(Cutoff/100))
END SELECT
IF LEN(FS)<4 THEN
Bbb=4-LEN(FS)
FOR F=1 TO Bbb
FS="0"&FS
NEXT F:
END IF
Fills="F"&FS&"M"
SEND 7,MTA LISTEN 7 DATA "R",.13
Fills="C"&Fills&"G8"&"I0"&"O6"
SEND 7,MTA LISTEN 7 DATA Fills,.13
SEND 7,MTA LISTEN 7 DATA "L",.13
END IF
B$=VAL$(Span)
IF AnsW<"Y" THEN
Start=0
END IF
B2$=VAL$(Start)
B1$=VAL$(Span/2+Start)
OUTPUT @Anz:"CF"&B1$&"HZ"
OUTPUT @Anz:"SF"&B2$&"HZ"
OUTPUT @Anz:"SP"&B2$&"HZ"
PRINT "THEREFORE THERE WILL BE":720*(2.56*Span/(16*Rpm));" SAMP/CY
C"
Total_time=120/Rpm
Rec_num=INT(2.56*Span>Total_time/1024)+1
G=VAL$(Rec_num)
Act=VAL$(Act)
Plug=VAL$(Plug/(16*Rpm)+F1+d1)
PRINT "AT THIS TIME CALIBRATE THE TRANSDUCER".
LOCAL @Anz
DISP "PRESS CONTINUE WHEN FINISHED"
PAUSE
IF AnsW="Y" THEN
OUTPUT @Anz:"UDVU;"
END IF
OUTPUT @Anz:"TRIG"
OUTPUT @Anz:="TRG""
OUTPUT @Anz:="EXT"
IF AnsW="Y" THEN OUTPUT @Anz:"FPR""
IF Tflag<1 THEN OUTPUT @Anz:"TRMA"
OUTPUT @Anz:"TLPR"&Act&"PCT"
OUTPUT @Anz:"DELY ON"
OUTPUT @Anz:"DLY:"&"PPlug&"SEC"
OUTPUT @Anz:"TBUP"
OUTPUT @Anz:"TBST"&"SEC"
OUTPUT @Anz:"TBP:100PCT"
OUTPUT @Anz:"TBNR"&"REC"
IF Tflag=1 THEN GOTO 3750
PRINT "ARM TRIGGER (IF 2 CYCLE DATA) WHEN READY"
OUTPUT @Anz:"SCP"
LOCAL @Anz
3740 PRINT "HIT CONTINUE WHEN FINISHED DATA COLLECTION"
3750 PAUSE
3760 RETURN
3770 Store_data:="I
3780 INPUT "WHAT NAME DO YOU WANT",Name$3790 CREATE BDAT ="HT"&Name$,1,512
3800 CREATE BDAT ="HT"&Name$,1,Fn+1,Rec_num+2048
3810 CREATE BDAT ="HT"&Name$,1,1204
3820 DIM Text$(1:5184)
3830 FOR I=1 TO S
3840 PRINT "ENTER TEXT STRING NUMBER":I
"
LOAD 'LEN', EXIT:
3870 Text(I)=Texts'.5RPTS:',(B4-Tlen)
3900 NEXT I
3930 ASSIGN OP3 TO 'HC&Names.FORMAT OFF
3950 ASSIGN OP2 TO 'HC&Names.FORMAT OFF
3970 ASSIGN OP1 TO 'HI&Names.FORMAT OFF
3990 OUTPUT OP1,1:.TAG_field(*).Total_time=Rpm;Span;Start.Rec_num;pe
_flag,Cal_fact,Rang(*)
3990 FOR I=1 TO FN+1
3995 MAT Slime=Raw_data(I,*)
4010 OUTPUT OP2,I:.Slime(*)
4015 NEXT I
4020 OUTPUT OP3,I:.TextS(*)
4025 ASSIGN OP3 TO *
4030 ASSIGN OP2 TO *
4040 ASSIGN OP1 TO *
4050 DISP "FINISHED STORING DATA"
4060 RETURN

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4070 DIM Tiaverge(10240),Tempaver(10240),Tiaverge2(10240)
4075 INTEGER Tiaverge(10240),Fn,Slime(10240)
4080 INPUT "HOW MANY FILES BESIDES THE AVG DO YOU WANT",Fn
4090 REDIM Rang(Fn+1)
4100 Tiflag=1
4110 Maxf=-10000
4120 GO SUB ANL_set
4130 Rec_size=Rec_num
4140 REDIM Slime(Rec_num*1024)
4150 REDIM Tiaverge(Rec_num*1024)
4160 REDIM Tiaverge2(Rec_num*1024)
4170 REDIM Tempaver(Rec_num*1024)
4180 REDIM Tiaverge3(Rec_num*1024)
4190 REDIM Raw_data(Fn,1,Rec_num*1024)
4200 OUTPUT @Anz:"CRCN OFF"
4210 OUTPUT @Anz:"PSRO ON "
4220 FOR Ijk=1 TO Tinum
4230 CONTROL @Fast,3:1
4240 OUTPUT @Anz:"TMA"
4250 OUTPUT @Anz:"SCAP"
4260 OUTPUT @Anz:"MACM"
4270 B=0
4280 REPEAT
4290 A=SPOLL(@Anz)
4300 B=BIT(A,0)
4310 UNTIL B=1
4320 GO SUB Read_data
4330 GO SUB Read_tag
4340 IF Range>Maxf THEN Maxf=Range
4350 Factor=(4/3)*10^((Range+4.817)/20)/32768/Cal_fact
4360 Req_S=351
4370 CONTROL @Fast,5:Req_S
4380 ENTER @Fast,Tiaverge(*)
4390 MAT Tempaver=Tiaverge
4400 MAT Tiaverge2=Tiaverge*(Factor/Tinum)
4410 MAT Tiaverge=Tempaver+Tiaverge2
4420 :GO SUB Tim_plot
4430 PRINT Ijk1
4440 NEXT Ijk1
4450 OUTPUT @Anz:"CRCN ON"
4460 GO SUB Tim_plot
4470 PAUSE
4480 OUTPUT Z USING "*,-K":CHR$(255),CHR$(75)
4490 Range=Maxf
4500 Factor=(4/3)*10^((Range+4.817)/20)/32768/Cal_fact
4510 MM: M*averag: * M*averag: * Cal.: 1
4520 MAT Raw: data: 1: i = Tiaverag: 1
4530 Range i = Range
4540 RETURN
4550 Tim: plot: 1
4560 DIM Max v(200), Min v(200)
4570 Total pts=2.55±Span±Total time
4580 OUTPUT 2 USING "#,:CHR$(155):CHR$(175)"
4590 GCLEAR
4600 GINIT
4610 ALPHA OFF
4620 GRAPHICS ON
4630 ALPHA ON
4640 VIEWPORT 25,125,28,98
4650 FRAME
4660 Y_max=MAX(Tiaverag(*))
4670 Y_min=MIN(Tiaverag(*))
4680 Max v(I, j, k)=Y_max
4690 Min v(I, j, k)=Y_min
4700 WINDOW 0, Total pts, Y_min, Y_max
4710 LINE TYPE 4
4720 GRID Total pts/12, 0, 0, Y_min
4730 LINE TYPE 1
4740 MOVE 0, Y_min
4750 FOR I, j, k=1 TO Rec_num=1024
4760 IF I, j, k> Total pts THEN GOTO 4790
4770 DRAW I, j, k, Tiaverag(I, j, k)
4780 NEXT I, j, k
4790 CSIZE 3, 5
4800 MOVE 0, Y_max
4810 CLIP OFF
4820 Lab$=VAL$(GROUND(Y_max, 5))
4830 LORG 8
4840 LABEL Lab$
4850 MOVE 0, Y_min
4860 CLIP OFF
4870 Lab$=VAL$(GROUND(Y_min, 5))
4880 LORG 8
4890 LABEL Lab$
4900 FOR I=0 TO 12
4910 Lab$=VAL$(60*I)
4920 MOVE I=Total pts/12, Y_min
4930 LORG 6
4940 CLIP OFF
4950 LABEL USING "#,:Lab$
4960 NEXT I
4970 RETURN
4980 Pitm: 1
4990 GCLEAR
5000 GINIT
5010 ALPHA OFF
5020 GRAPHICS ON
5030 ALPHA ON
5040 VIEWPORT 20,133,28,98
5050 FRAME
5060 Y_max=MAX(Max v(*))
5070 Y_min=MIN(Min v(*))
5080 WINDOW 0, Tinum, Y_min, Y_max
5090 LINE TYPE 1
5100 MOVE 0, 0
5110 FOR I, j, k=1 TO Tinum
5120 DRAW I, j, k, Max v(I, j, k)
5130 NEXT I, j, k
5140 MOVE 0, 0
5150 FOR I, j, k=1 TO Tinum
5160 END DRAW I, j, k, Min v(I, j, k)
S180  MOVE 0,Y_max/2
S190  RETURN
S200  I---------------------------------------------------------------
S210  Auto_snp:
S220  I---------------------------------------------------------------
S230  OUTPUT 2 USING "#,%":CHR$(255),CHR$(75)
S240  INTEGER As1,Rn
S250  T:flag=1
S260  Rec_size=Rec_num
S270  OUTPUT @Anz: "PSAQ ON"
S280  FOR As1=1 TO Fn
S290  Rn=As1+1
S300  PRINT As1
S310  CONTROL @fast,3:1
S320  OUTPUT @Anz: "TRMA"
S330  OUTPUT @Anz: "SCAP"
S340  OUTPUT @Anz: "MARM"
S350  B=0
S360  REPEAT
S370  A=SPOOL(?Anz)
S380  B=BIT(A,0)
S390  UNTIL B=1
S400  GSUB Read_data
S410  GSUB Read_tag
S420  GSUB Convert_data
S430  NEXT As1
S440  CONTROL 2,2:1
S450  T:flag=0
S460  RETURN
S470  SUBEND
ANALYSIS PROGRAM
10  \* THIS IS THE FIRST WORKING VERSION OF AN ACCEPTABLE WORKING
20  \* ANALYSIS PROGRAM
30  OPTION BASE 0
40  COM /A/ R(4095,1), T(4095,1), Rb(4095), File%(20). Span
50  COM /B/ INTEGER Ra(4095), I, J, K, Rc, Tag_field(1:175), Type_flag, Slope(4095), R
range, Nu, Tot_pts, Rn, Rang(1:25)
60  COM /C/ INTEGER Raw(2047, 100), REAL Fact(100), INTEGER Varflag, Fn
70  ON KEY 1 LABEL "FFT", 10 GOSUB Fft
80  ON KEY 2 LABEL "VARIANCE", 10 GOSUB VarFlag
90  ON KEY 3 LABEL "HILB", 10 GOSUB Hilb
100 ON KEY 4 LABEL "PLOT", 10 GOSUB Plot
110 ON KEY 5 LABEL "DUMP", 10 GOSUB Dump
120 REPEAT
130  UNTIL Ixx=1234
140 Fft:
150 OUTPUT 2 USING "+", K:CHR$(255), CHR$(75)
160 CALL Fft(0)
170 DISP "FINISHED FFT"
180 RETURN
190 Variance:
200 OUTPUT 2 USING "+", K:CHR$(255), CHR$(75)
210 CALL Variance
220 DISP "FINISHED VARIANCE"
230 RETURN
240 Hilb:
250 OUTPUT 2 USING "+", K:CHR$(255), CHR$(75)
260 CALL Hilb
270 DISP "FINISHED HILB"
280 RETURN
290 Plot:
300 OUTPUT 2 USING "+", K:CHR$(255), CHR$(75)
310 CALL Plot(1)
320 DISP "FINISHED PLOT"
330 RETURN
340 Dump:
350 CALL Dump
360 RETURN
370 END
380
390 SUB CollData
400
410 OPTION BASE 0
420 ON ERROR RECOVER Err
430 COM /A/ R(4095,1), T(4095,1), Rb(4095), File%(20). Span
440 COM /B/ INTEGER Ra(4095), I, J, K, Rc, Tag_field(1:175), Type_flag, Slope(4095), R
range, Nu, Tot_pts, Rn, Rang(1:25)
450 COM /C/ INTEGER Raw(2047, 100), REAL Fact(100), INTEGER Varflag, Fn
460 DISP "COLLECTING DATA"
470 ASSIGN #1 TO "H1" & File#
480 ASSIGN #2 TO "H2" & File#
490 ENTER #1,1:Tag_field(*)
500 Total_time:Ran:Span:Start:Rec_num:Type_flag:Cal_fact
510 Enter #1,Tot_pts=INT(Total_time/2.55+Span+.5)
520 N_int=INT(Tot_pts/1024)+1
530 Pow_2=INT(LOG10(Tot_pts)/LOG10(2))+1
540 Nu=INT(2^INT(Pow_2+.5)+.5)
550 IF Varflag=1 THEN GOSUB Varcol
551 INTEGER Length
554 REDIM Sline(0:Length/2-1),
555 REDIM R(0:Length/2-1,1),
556 ENTER OP2,Rn:Sline(*),
570 MAT R(*,0)=Sline
580 MAT R=Ra*Factor
590 FOR I=Tot_pts TO Nu-1
600 R(I,0)=R(I-Tot_pts,0)
610 NEXT I
620 ASSIGN OP1 TO *
630 ASSIGN OP2 TO *
540 SUBEXIT
550 Vercol:
560 FOR I=1 TO Fn
570 Fact(I-1)=(4/3)*10*((Rang(I)+4.312)/20)/32768/Ceil_fact
580 ENTER OP2,1:Sline(*)
590 MAT Raw(*,I-1)=Sline
600 NEXT I
610 ASSIGN OP1 TO *
620 ASSIGN OP2 TO *
630 SUBEXIT
740 Err:
750 PRINT ERMA
760 IF ERR(478)=1 OR ERR(490)=1 THEN
770 DISP "ERROR: EITHER WRONG FILE NAME OR INSERT ANOTHER DISK"
780 PAUSE
790 DISP "";
800 GOTO 460
810 END IF
820 SUBEND
830 OPTIONS BASE 0
840 OPTION BASE 1
850 :COM /A/ R(4095,1),T(4095,1),Ra(4095),File$(20),Span,
860 /B/ INTEGER Ra(4095),I,J,K,Rc,Tag_field(1:175),Type_flag,Sline(4095),Rang,
870 Nu,Tot_pts,Rn,Rang(I:26)
880 DISP "REORDERING DATA"
890 MAT Ra=Ra*(0)
900 Const=INT(LOG(Nu)/LOG(2)+.5)
910 FOR I=1 TO Const
920 Valu=2^I
930 Valu=Nu/Valu
940 Va=2^(I-1)
950 FOR K=1 TO Valu/2
960 IF K MOD 2=0 THEN
970 Inc=1
980 ELSE
990 Inc=0
1000 END IF
1010 Aaa=(K-1)*Valu+1
1020 Aaa=Inc*Va
1030 FOR J=0 TO (Valu-1)
1040 Ra(Aaa+J)=Ra(Aaa+J)+Aaa
1050 NEXT J
1060 NEXT K
1070 NEXT I
1080 NEXT I
1090 Aa=Nu=1
1100 FOR I=0 TO Nu/2-1
1110 T(I,0)=R(Ra(I,0))
1120 T(Aa-1,0)=R(Aa-Ra(I,0))
1130 T(I,1)=R(Ra(I,1))
1140 T(Aa-1,1)=R(Aa-Ra(I,1))
1150 NEXT I
1160 SUBEND
1170 !
1180 !
1190 !
1200 !
OPTION BASE 0
COM /A/ R(4095,1), T(4095,1), Ra(4095), File#(20), Span
COM /B/ INTEGER Ra(4095), I, J, K, Rc, Tag_field(1:175), Type_flag, Sline(4095), Range, Nu, Tot_pats, Rn, Rang(1:26)

DISP "TAKING FFT"
Rc=INT(LOG(Nu)/LOG(2)+.5)
Pu=SIGN(2*PI/Nu)
FOR K=1 TO Rc
St=2*K
Ni=2*(Rc+K)
Wi=P*NI
Wl=NU/2**(Rc+K))
FOR J=0 TO Nu/St-1
Wu=J*St
WW=Wi*Wl
FOR I=0 TO 2**(K-1)-1
Ang=Wr*I
NZ=Wu*I
NJ=WW*I
E=T(N3,0)+COS(Ang)-T(N3,1)*SIN(Ang)
F=T(N3,1)+COS(Ang)+T(N3,0)*SIN(Ang)
T(N3,0)=T(N2,0)*E
T(N3,1)=T(N2,1)*F
T(N2,0)=T(N2,0)*E
T(N2,1)=T(N2,1)*F
NEXT I
NEXT J
NEXT K
IF Sign=1 THEN MAT T= T*(2/Nu)
SUBEND

SUB Timeweight(Arg)
1510
COM /A/ R(4095,1), T(4095,1), Ra(4095), File#(20), Span
COM /B/ INTEGER Ra(4095), I, J, K, Rc, Tag_field(1:175), Type_flag, Sline(4095), Range, Nu, Tot_pats, Rn, Rang(1:26)
DISP "DOING TIME WEIGHT"
Rasio=2*PI/Tot_pats
FOR I=0 TO Tot_pats-1
R(I,0)=R(I,0)+I*0.012*(1-COS(Rasio*I))
NEXT I
IF Nu>Tot_pats THEN
Rasio=2*PI/(Nu-Tot_pats)
FOR I=Tot_pats TO Nu-1
R(I,0)=R(I,0)+I*0.012*(1-COS(Rasio*(I-Tot_pats)))
NEXT I
END IF
SUBEND

SUB Fft(Auto)

COM /A/ R(4095,1), T(4095,1), Ra(4095), File#(20), Span
COM /B/ INTEGER Ra(4095), I, J, K, Rc, Tag_field(1:175), Type_flag, Sline(4095), Range, Nu, Tot_pats, Rn, Rang(1:26)
IF Auto<1 THEN
INPUT "WHICH FILE DO YOU WISH AN FFT OF? ", File#
INPUT "WHICH RECORD DO YOU WANT? ", Rn
END IF
CALL Colldata
CALL Timeweight(1)
CALL Reorder
CALL Fort(1)
SUBEND
1820 SUB Subroutine
1830
1840 COM /A/ R(4095,1),T(4095,1),Rb(4095),Files[20],Scan
1850 COM /B/ INTEGER Ra(4095),I,J,K,Re,Tag_field(1:175),Type_flag,Slime(4095),R
gen, Nu, Tot_pts, An, Range(1:26)
1860 INPUT "WHAT FILE DO YOU WISH AN ENVELOPE STUDY OF",Files#
1870 INPUT "WHAT IS THE RECORD NUMBER",Rn
1874 REDIM R(1023,1)
1875 REDIM T(1023,1)
1876 CALL Colldata
1883 CALL Reorder
1884 CALL Fort(1)
1890 MAT R = T*(2)
1900 R(0,0) = R(0,0)/2
1910 FOR I = Nu/2 TO Nu-1
1920 R(I,0) = 0
1930 R(I,1) = 0
1940 NEXT I
1950 CALL Reorder
1960 CALL Fort(-1)
1970 MAT R = R*(0)
1980 FOR I = 1 TO Nu-1
1990 R(I,0) = SQR(T(I,0)*T(I,0)+T(I,0)+T(I,1)*T(I,1))
2000 NEXT I
2009 GOTO 2080 1--------
2010 CALL Plt(1)
2020 CALL Reorder
2030 CALL Fort(1)
2040 FOR I = 0 TO 2
2050 T(I,0) = 0
2060 T(I,1) = 0
2070 NEXT I
2080 SUBEND
2090
2100 SUB Subroutine
2110
2120 COM /A/ R(4095,1),T(4095,1),Rb(4095),Files[20],Scan
2130 COM /B/ INTEGER Ra(4095),I,J,K,Re,Tag_field(1:175),Type_flag,Slime(4095),R
gen, Nu, Tot_pts, An, Range(1:26)
2140 DIM Var(4095),Avg(4095),Avgl(4095)
2150 COM /C/ INTEGER Raw(2047,100),REAL Fact(100),INTEGER Varflag,Fn
2150 Varflag = 1
2170 INTEGER N,St,I,1,Lenh
2180 INPUT "WHAT IS THE FILENAME",Files#
2190 ASSIGN @P1 TO "H2"&Files#
2200 STATUS @P1,3:Fn
2210 STATUS @P1,4:Lenh
2220 ASSIGN @P1 TO *
2230 Lenh = INT(Lenh/2+.5)
2240 REDIM Slime(Lenh-1),Re(Lenh-1)
2250 REDIM R(Lenh-1,1),T(Lenh-1,1),Rb(Lenh-1),Var(Lenh-1),Avg(Lenh-1)
2260 REDIM Avgl(Lenh-1)
2270 REDIM Raw(Lenh-1,Fn-1)
2280 PRINT Lenh
2290 CALL Colldata
2300 DISP "CALCULATING VARIANCE"
2310 MAT Avg = Raw(0,0)
2320 MAT Avg = AvgFact0)
2330 FOR I = 0 TO Fn-2
2340 MAT Var = Raw(I+1)
2350 MAT Var = Varn(Fact(I+1))
2360 MAT Var = Var-Avg
2370 MAT Var = Var * Var
2380 MAT Var = Var(1/(I+1))
2390 MAT Var = Var * Var
2400 MAT Var = Var * Var
2410 MAT Var = Var * Var
2420 MAT Var = Var * Var
2430 MAT Var = Var * Var
2440 MAT Var = Var * Var
2450 MAT Var = Var * Var
2346 MAT Avgl= Avgl+var
2400 NEXT i:
2440 Varflag=0
2450 MAT Ri(+,0)= Avgl
2460 SUBEND
2470:
2480 SUB Plot(Sel)
2490:
2500 COM /A/ R(4095,1),T(4095,1),Rb(4095),File=(20),Scan
2510 COM /B/ INTEGER Ral(4095),I,J,K,Rc,Tag_field(1:175),Type_flag,Size=4095.,Range, Nu,Tot_pts,An,Rang(1:26)
2520 DIM Plt(4095,1)
2530 INPUT "PLAT TIME SEQUENCE OR SPECTRUM (T/S)",Test$
2540 Nu=Nu
2550 Summ=0
2560 IF Test$="S" THEN
2570 Nu=Nu/2-1
2580 MAT Plt= Plt*(0)
2590 FOR I=0 TO Nu
2600 Plt(I,0)=SQRT(T(I,0)+T(I,1)+T(I,1)-T(I,0))
2610 Summ=SQRT(Summ+Plt(I,0)**2)
2620 NEXT I
2630 ELSE
2640 IF Sel$=1 THEN Nu=Tot_pts
2650 MAT Plt= Plt*(0)
2660 MAT Plt= R
2670 FOR I=0 TO Nu
2680 Summ=SQRT(Summ+Plt(I,0)**2)
2690 LinSum=LinSum+Plt(I,0)
2700 NEXT I
2710 END IF
2720 Ymax=MAX(Plt(*));
2730 Ymin=MIN(Plt(*));
2740 INPUT "DO YOU WANT TO SCALE THE GRAPH",Sca$
2750 IF Sca$="Y" THEN
2760 INPUT "MAX VALUE",Ymax
2770 INPUT "MIN VALUE",Ymin
2780 END IF
2790 OUTPUT 2 USING ",,-K":CHR$(255),CHR$(75)
2800 GRAPHICS OFF
2810 SCLEAR
2820 ALPHA OFF
2830 ALPHA ON
2840 GRAPHICS ON
2850 VIEWPORT 20,125,39,99
2860 WINDOW 0,N,Ymin,Ymax
2870 LINE TYPE 4
2880 IF Test$="T" THEN GRID N/12,(Ymax-Ymin)/10,0,Ymin
2890 IF Test$="S" THEN GRID N/10,(Ymax-Ymin)/10,0,Ymin
2900 LINE TYPE 6
2910 FRAME
2920 IF Ymin<0 THEN
2930 MOVE 0,0
2940 DRAW N,0
2950 END IF
2960 MOVE 0,Plt(I,0)
2970 LINE TYPE 1
2980 FOR I=1 TO Nu
2990 DRAW I,Plt(I,0)
3000 NEXT I
3010 CSIZE 3,.5
3020 IF Test$="S" THEN Cunt=10
3030 IF Test$="T" THEN Cunt=12
3040 FOR I=0 TO Cunt
3050 IF Test$="T" THEN Lab=VAL$(60+I)
3070 IF Tests="S" AND I-2 THEN Lab$=VAL$(Labs$+i-1)+"..."
3080 IF Tests="T" THEN MOVE I=N/L2,Ymin
3090 IF Tests="S" THEN MOVE I=N/10,Ymin
3100 LOR 5
3110 CLIP OFF
3120 LABEL USING ";K":Lab$
3130 NEXT I
3140 MOVE -.05*N,Ymin+ABS(Ymax-Ymin)/2
3150 LDIR P1/2
3160 LOR 5
3170 LABEL "AMPLITUDE"
3180 LDIR 0
3190 MOVE N/2,-.1*ABS(Ymax-Ymin)+Ymin
3200 LOR 5
3210 IF Tests="S" THEN LABEL "FREQUENCY (HZ)"
3220 IF Tests="T" THEN LABEL "ANGLE IN DEGREES"
3230 MOVE 0,Ymax
3240 Lab$=VAL$(ROUND(Ymax,4))
3250 LOR 8
3260 CLIP OFF
3270 LABEL Lab$
3280 MOVE 0,Ymin
3290 LOR 8
3300 Lab$=VAL$(ROUND(Ymin,4))
3310 CLIP OFF
3320 LABEL Lab$
3330 IF Tests="S" THEN PRINT TABXY(2,25):Summ,Ymax,ABS(Ymax/Summ)
3340 IF Tests="T" THEN PRINT TABXY(2,25):"AVAR":(ROUND(Linavg/Total,D10.5))
3350 IF Tests="T" THEN PRINT TABXY(32,25):"ANSVAR":Summ
3360 SUBEND
3370 !
3380 SUB Dump$
3390 !
3400 DIM Disp$(99)
3410 DUMP DEVICE IS 701
3420 INPUT "ENTER GRAPH DESCRIPTOR",Disp$
3430 DISP Disp$
3440 CONTROL 1,12:1
3450 DUMP GRAPHICS
3460 CONTROL 1,12:2
3470 DISP **
3480 SUBEND
APPENDIX C

Measurement Equipment Specifications
HP3561A SPECIFICATIONS
### APPENDIX E

**SPECIFICATIONS**

Specifications describe the instrument's warranted performance. Subsequent characteristics are intended to provide information useful in selecting the instrument for given tasks, but non-warranted, performance characteristics are denoted as nominal. Normal to Abbreviations:

<table>
<thead>
<tr>
<th>FREQUENCY and TIME MEASUREMENT MODES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nominal Bandwidth</strong>: 125 kHz to 100 MHz. Frequency range 0 to 400 MHz with sweep trigger and averaging mates are available.</td>
</tr>
<tr>
<td>Phases: Phase spectrum is available with or without triggering. When triggered, phase is referenced to the trigger.</td>
</tr>
<tr>
<td>10 Decades: 0.1 Hz to 10 kHz; see separate Octave section.</td>
</tr>
<tr>
<td>20 Decades: 1 Hz to 30 kHz; see separate Octave section.</td>
</tr>
<tr>
<td>Time: Time measurement of 3 to 500 nsec is available up to 400 MHz. Real-time sweep function is available for sweep settings.</td>
</tr>
<tr>
<td>External Sampling: sweep rate can be externally controlled by the user. Scan time and sweep rate can be varied to meet the needs of the user.</td>
</tr>
<tr>
<td><strong>FREQUENCY SELECTION</strong>: 0 to 10 kHz; Measurement is made over the full frequency range of the instrument.</td>
</tr>
<tr>
<td><strong>Resolution</strong>: 0 to 1 kHz; Measurement is made over the selected frequency. Start or center frequency can be set anywhere in the 0 to 1 kHz range with resolution of 0.1 Hz.</td>
</tr>
<tr>
<td><strong>Sweep</strong>: Measurement frequency steps are provided at 1, 2, 5, 10, 20 Hz. Other steps exist between these intervals.</td>
</tr>
<tr>
<td><strong>Time</strong>: Measurement time can be set from 0.001 second to 851 minutes per sweep. Time setting is readout and agrees with time base sweep.</td>
</tr>
</tbody>
</table>

**AMPLITUDE and INPUT**

<table>
<thead>
<tr>
<th>AMPLITUDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Range: 0 to 10 V; 0 to 100 V; 0 to 1000 V.</td>
</tr>
<tr>
<td>Accuracy: ±0.01% of range or ±1 digit.</td>
</tr>
<tr>
<td><strong>DC Resistance</strong>: With Auto-Cal: 0 to 1000 kΩ.</td>
</tr>
<tr>
<td><strong>Amplitude Measurement Resolution</strong>: 0.001 dB, linear 4 digits.</td>
</tr>
<tr>
<td><strong>Phase Measurement</strong>: ±0.1°, phase is referenced to the trigger point.</td>
</tr>
</tbody>
</table>

**INPUT**

| **Input Impedance**: 10 kΩ ± 5% shunt maximum. |
| **Input Leakage**: 0.1 nA. |
| **Input Noise**: 0.001 V peak-to-peak. |
| **Input Capacitance**: 0.1 pF. |

**Windows**

<table>
<thead>
<tr>
<th><strong>Windows Parameters</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gain</strong>: 0.956, 0.375, 0.25</td>
</tr>
<tr>
<td><strong>Input Freq.</strong>: 1 kHz, 10 kHz, 100 kHz</td>
</tr>
<tr>
<td><strong>Input Noise</strong>: 0.001 V peak-to-peak.</td>
</tr>
<tr>
<td><strong>Input Capacitance</strong>: 0.1 pF.</td>
</tr>
</tbody>
</table>

**Typical Data**

<table>
<thead>
<tr>
<th><strong>Typical Data</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency Range</strong>: 0 to 10 MHz.</td>
</tr>
<tr>
<td><strong>Resolution</strong>: 0.001 Hz.</td>
</tr>
<tr>
<td><strong>Accuracy</strong>: ±0.001%.</td>
</tr>
<tr>
<td><strong>Sweep</strong>: 0 to 1 kHz.</td>
</tr>
<tr>
<td><strong>Time</strong>: 0.001 second to 851 minutes.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Real-Time Spectrum</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time</strong>: 0.001 second.</td>
</tr>
<tr>
<td><strong>Accuracy</strong>: ±0.001%.</td>
</tr>
<tr>
<td><strong>Sweep</strong>: 0 to 1 kHz.</td>
</tr>
<tr>
<td><strong>Time</strong>: 0.001 second.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Typical Data</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency Range</strong>: 0 to 10 MHz.</td>
</tr>
<tr>
<td><strong>Resolution</strong>: 0.001 Hz.</td>
</tr>
<tr>
<td><strong>Accuracy</strong>: ±0.001%.</td>
</tr>
<tr>
<td><strong>Sweep</strong>: 0 to 1 kHz.</td>
</tr>
<tr>
<td><strong>Time</strong>: 0.001 second.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Amplitude Measurement</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Range</strong>: 0 to 10 V; 0 to 100 V; 0 to 1000 V.</td>
</tr>
<tr>
<td><strong>Accuracy</strong>: ±0.01% of range or ±1 digit.</td>
</tr>
<tr>
<td><strong>DC Resistance</strong>: With Auto-Cal: 0 to 1000 kΩ.</td>
</tr>
<tr>
<td><strong>Amplitude Measurement Resolution</strong>: 0.001 dB, linear 4 digits.</td>
</tr>
<tr>
<td><strong>Amplitude Measurement</strong>: ±0.1°, phase is referenced to the trigger point.</td>
</tr>
</tbody>
</table>

**Phase Measurement Resolution**: ±0.1°, phase is referenced to the trigger point.
Octave Analysis

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Averaged</th>
<th>Displaced</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 - 6</td>
<td>51</td>
<td>33</td>
</tr>
<tr>
<td>1 - 3</td>
<td>17</td>
<td>11</td>
</tr>
</tbody>
</table>

1/3 and 1/1 Octave Analysis Parameters:
- Band center: 2kHz, 2kHz
- Frequency Range: 3 kHz to 6kHz
- Octave: 3 kHz to 10 kHz
- Time: 2 sec to 3 sec
- Number of Averages: 13 to 30

Computation Time: 1.3 octaves and 1.1 octave computations are made in less than 0.80 seconds per channel.

Trigger

TRIGGER MODES:
- Free Run: A new measurement is initiated by command of the previous measurement.
- External: A new measurement is initiated by a TTL pulse signal from the rear panel external trigger input.
- Internal: Allows measurements to be initiated by pressing the manual trigger input.
- Internal: Measurement is initiated when the input signal meets the defined trigger level conditions.
- Source: New measurements are synchronized with the internal source.
- External: A new measurement is initiated by sending a trigger signal from an external source over the front panel.

TRIGGER ARM:
- Auto Arm: Measurements are initiated automatically when trigger conditions are met.
- Manual Arm: Enables a single measurement when trigger conditions are met.

TRIGGER LEVEL:
- Triggers can be set to occur when the input signal reaches a user-defined level input. Definitions from 10% to 110% of full range setting. Positive and negative levels and slopes can be set.

TRIGGER DELAY:
- Pre-Trigger: The measurement can be based on input data from 1/1024 to 8 time records before trigger conditions have been met, with resolution of 1/1024 of a record. Time capture mode is used for pre-trigger delays of up to 40 records.
- Post-Trigger: The measurement is initiated from 1/1024 to 1023 time records after trigger conditions have been met. Resolution is 1/1024 of a record.

Measurement Averaging

AVERAGING TYPES:
- RMS: For each calculated frequency point, the displayed amplitude is averaged in a root mean square fashion.
- Peak Hold: Same as RMS, except the maximum amplitude value is held for each frequency, if phase is not available.
- RMS: For each calculated frequency point, the displayed amplitude is averaged in a root mean square fashion.

AVERAGE CONTROL:
- Start: Starts new average of measurement.
- Pause/Continue: Pauses the average. Generally, a value cannot be edited while averaging.
- Stop: Stops averaging mode. The displayed value is not the average of the last n averages, but the average of the last n averages plus the last n averages.
- Manual: Allows setting of the number of averages to be averaged.
- Normal Display: The average is calculated and displayed for each frequency.
- Fast Display: The Fast Display function displays the last n averages of the measurement.
- Level Display: The Level Display function displays the last n averages of the measurement.
- External: A new measurement is initiated by sending a trigger signal from an external source over the front panel.

Source

- Band: 8 band pass band filter and a pseudo-random waveform. The output of the band filter is applied to the rear panel. Output levels are within the range of 0 to 5V, with no attenuation.
- Impedance: 50 ± 5 ohms.

LEVEL AND ACCURACY:
- Sweep: 4 steps: 1mV to 1V, 1V to 10V, 10V to 100V, 100V to 1kV.
- Random Source: 0.1 to 1.0 kHz and 1 to 100 kHz.

PLATEFUSE:
- Sweep: 4 steps: 1mV to 1V, 1V to 10V, 10V to 100V, 100V to 1kV.
- Random Source: 0.1 to 1.0 kHz and 1 to 100 kHz.

ATTENUATION:
- 15 dB step, random, pseudo-random, 40, 50, 100 dB.

XXX
PCB ACCELEROMETER SPECIFICATIONS
- built-in unity-gain amplifier; enhances resolution
- high-level (5V), low impedance (<100 ohm) analog output
- drives long coaxial or 2-wire cables
- inverted, isolated-compression structure
- standardized sensitivity; suppressed resonance
- simplified systems; low per channel cost
- insensitive to cable length or motion

Use Model 302A for routine measurement of vibration and shock in laboratory, field, flight, vehicular and industrial applications.

Model 302A, a precision quartz accelerometer, measures the acceleration aspect of shock and vibration motion from 1g to 500g; over a wide frequency range and under adverse environmental conditions. Sensitivity is standardized at 10 mV/g. Like most quartz transducers, this instrument offers exceptionally good low-frequency response and follows long duration shock events up to 20 milliseconds duration. An optional shock Model 302A02 measures transient events to 0.5 second duration.

Quartz accelerometers are installed by clamping the precision base surfaces in intimate contact with the adjacent structure of the test object, usually by means of an elastic beryllium-copper stud. Adhesive and magnetic mounting bases facilitate quick installation for structure testing. Since the force moving the instrument is transmitted through this interface, it is important that the mating surface be machined flat. For severe shock environments, the optional solder pin connector adaptor has proved more reliable than coaxial components.

For convenience in ordering and portability these instruments are offered in assembled kit form, as illustrated, complete and ready to install by connecting to your readout instrument and operate. Standard options include ground isolation, longer time constant, higher sensitivity and welded hermetic seal. A variety of battery or line power signal conditioners (with or without gain) in single or multi-channel configurations meet most all applications.

### Specifications:

| Model No. | Range, FS (±5 volt output) | Resolution | Sensitivity | Resonant Frequency (mounted) | Discharge Time Constant | Frequency Range (±5%) | Frequency Range (+10%) | Linearity | Overload Recovery | Output Impedance | Strain Sensitivity | Transverse Sensitivity | Temperature Coefficient | Temperature Range | Vibration/Shock (max) | Weight | Excitation |
|-----------|----------------------------|------------|-------------|-----------------------------|-------------------------|-----------------------|-----------------------|----------|------------------|-------------------|------------------|---------------------|---------------------|-------------------|-------------------|-----------|
| 302A      | g                          | 0.01       | 10 ± 30     | 45,000                      | 0.5                     | 1 to 5000             | 0.7 to 10,000         | 1        | <10μs            | <100            | 0.01             | 5                   | 0.03               | -100 to -250      | 2000/5000         | 25       | -VDC/mA         | 18 to 28/20       |

### Optional Models:

- Shock (1C = 10 second) 302A02
- High Sens. (300 mV/g, larger size) 302A03
- Gen Purpose, Grid ISO, 10 mV/g 302A04
- High Freq 10kHz (version of 302A) 302A05
- High Freq 10kHz (version of 302A04) 302A06
- Triaxial 1 inch Cube 306A

Use prefix "H" to specify hermetic sealing - e.g. H302A

### Typical Systems:

K302A battery power kit is shown below. Also available as GX302A with gain. Rechargeable and long life external battery pack options available.

![Typical Systems Diagram]
NICOLET 310 OSCILLOSCOPE SPECIFICATIONS
ROCKLAND FILTER TIME DELAY INFORMATION
<table>
<thead>
<tr>
<th>FREQUENCY (HZ)</th>
<th>TIME DELAY (MICRO SECONDS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>913</td>
</tr>
<tr>
<td>1200</td>
<td>765</td>
</tr>
<tr>
<td>1400</td>
<td>656</td>
</tr>
<tr>
<td>1600</td>
<td>573</td>
</tr>
<tr>
<td>1800</td>
<td>507</td>
</tr>
<tr>
<td>2000</td>
<td>456</td>
</tr>
<tr>
<td>2200</td>
<td>418</td>
</tr>
<tr>
<td>2400</td>
<td>385</td>
</tr>
<tr>
<td>2600</td>
<td>355</td>
</tr>
<tr>
<td>2800</td>
<td>331</td>
</tr>
<tr>
<td>3000</td>
<td>311</td>
</tr>
<tr>
<td>3200</td>
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</tr>
<tr>
<td>3400</td>
<td>273</td>
</tr>
<tr>
<td>3600</td>
<td>259</td>
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<tr>
<td>3800</td>
<td>246</td>
</tr>
<tr>
<td>4000</td>
<td>233</td>
</tr>
<tr>
<td>5000</td>
<td>187</td>
</tr>
<tr>
<td>6000</td>
<td>157</td>
</tr>
<tr>
<td>7000</td>
<td>134</td>
</tr>
<tr>
<td>8000</td>
<td>118</td>
</tr>
<tr>
<td>9000</td>
<td>105</td>
</tr>
<tr>
<td>10000</td>
<td>94</td>
</tr>
<tr>
<td>12500</td>
<td>74</td>
</tr>
<tr>
<td>15000</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>17500</td>
<td>54</td>
</tr>
<tr>
<td>20000</td>
<td>47</td>
</tr>
<tr>
<td>25000</td>
<td>39</td>
</tr>
<tr>
<td>30000</td>
<td>33</td>
</tr>
<tr>
<td>40000</td>
<td>25</td>
</tr>
<tr>
<td>50000</td>
<td>21</td>
</tr>
<tr>
<td>60000</td>
<td>18</td>
</tr>
<tr>
<td>70000</td>
<td>15</td>
</tr>
<tr>
<td>80000</td>
<td>14</td>
</tr>
<tr>
<td>90000</td>
<td>13</td>
</tr>
<tr>
<td>100000</td>
<td>12</td>
</tr>
</tbody>
</table>
APPENDIX D

Additional Data
BASE ENGINE DATA
TDA DATA FROM CYLINDER 1 OF THE BASE ENGINE

TDA DATA FROM CYLINDER 2 OF THE BASE ENGINE
TOA DATA FROM CYLINDER 3 OF THE BASE ENGINE

TOA DATA FROM CYLINDER 4 OF THE BASE ENGINE
VARIANCE DATA FROM CYLINDER 1 OF THE BASE ENGINE

VARIANCE DATA FROM CYLINDER 2 OF THE BASE ENGINE
VARIANCE DATA FROM CYLINDER 3 OF THE BASE ENGINE

VARIANCE DATA FROM CYLINDER 4 OF THE BASE ENGINE
HILBERT DATA FROM CYLINDER 1 OF THE BASE ENGINE

HILBERT DATA FROM CYLINDER 2 OF THE BASE ENGINE
Hilbert data from cylinder 3 of the base engine

Avar = 1.3732
RMSV = 45.379339722

Hilbert data from cylinder 4 of the base engine

Avar = 2.487
RMSV = 77.6498636835
FFT DATA FROM CYLINDER 1 OF THE BASE ENGINE

FFT DATA FROM CYLINDER 2 OF THE BASE ENGINE
FFT DATA FROM CYLINDER 3 OF THE BASE ENGINE

FFT DATA FROM CYLINDER 4 OF THE BASE ENGINE
SECOND FIELD RETURN ENGINE
TOA DATA FROM CYLINDER 1 OF THE SECOND FIELD RETURN ENGINE (FRET2)

TOA DATA FROM CYLINDER 3 OF THE SECOND FIELD RETURN ENGINE (FRET2)
TOA DATA FROM CYLINDER 4 OF THE SECOND FIELD RETURN ENGINE (FRET2)

TOA DATA FROM CYLINDER 6 OF THE SECOND FIELD RETURN ENGINE (FRET2)
VARIANCE DATA FROM CYLINDER 1 OF THE SECOND FIELD RETURN ENGINE (FRET2)

VARIANCE DATA FROM CYLINDER 3 OF THE SECOND FIELD RETURN ENGINE (FRET2)
VARIANCE DATA FROM CYLINDER 4 OF THE SECOND FIELD RETURN ENGINE (FRET2)

AVAR= .1939  
RMSVAR= 0.40492203875

VARIANCE DATA FROM CYLINDER 6 OF THE SECOND FIELD RETURN ENGINE (FRET2)

AVAR= .6367  
RMSVAR= 1.91229981981
HILBERT DATA FROM CYLINDER 1 OF THE SECOND FIELD RETURN ENGINE (FRET2)

HILBERT DATA FROM CYLINDER 2 OF THE SECOND FIELD RETURN ENGINE (FRET2)
HILBERT DATA FROM CYLINDER 4 OF THE SECOND FIELD RETURN ENGINE (FRET2)

HILBERT DATA FROM CYLINDER 6 OF THE SECOND FIELD RETURN ENGINE (FRET2)
FFT DATA FROM CYLINDER 1 OF THE SECOND FIELD RETURN ENGINE (FRET2)

FFT DATA FROM CYLINDER 3 OF THE SECOND FIELD RETURN ENGINE (FRET2)
FFT DATA FROM CYLINDER 4 OF THE SECOND FIELD RETURN ENGINE (FRET2)

FFT DATA FROM CYLINDER 6 OF THE SECOND FIELD RETURN ENGINE (FRET2)
VITA AUCTORIS

1964 Born in Windsor, Ontario, Canada on November 11

1987 Received the Degree of Bachelor of Applied Science in Mechanical Engineering from the University of Windsor, Windsor, Ontario, Canada

Summer 1987 Employed as a Research Engineer by Dyneer Research Inc., Windsor, Ontario, Canada

1987 to 1989 Full Time Graduate Student at the University of Windsor, Windsor, Ontario, Canada

1987 to 1989 Natural Sciences and Engineering Research Council of Canada Post Graduate Scholarship holder