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NOMENCLATURE

$A(\omega)$	Amplitude of the fourier transform of $x(t)$
e_m	Maximum bias error defined by equation (3.1)
e_e	Expected bias error defined by equation (3.2)
f	Frequency in Hertz
f_s	Sampling frequency
Δf	Frequency Bandwidth defined by equation (3.3)
$F(x)$	Probability distribution function defined by equation (4.7)
$F_r(\omega)$	Fourier transform of the rectangular window defined by equation (4.16)
$G_x(\omega)$	Power spectral density defined by equation (4.20)
$\tilde{G}_x(n)$	Smoothed power spectral density defined by equation (4.31)
$I(\omega)$	Imaginary component of the fourier transform of $x(t)$
m	Time lag for the discrete auto correlation function $R(m)$
N	Number of data points for the discrete time history
$P_r(A)$	Probability of occurrence of event A
$p(x)$	Probability density function defined by equation (4.8)
$R(\tau)$	Auto correlation function defined by equation (4.6)
$R(m)$	Discrete auto correlation function defined by equation (4.25)
$R(\omega)$	Real component of the fourier transform of $x(t)$
σ^2	Variance as defined by equation (4.5)
Δt	sampling period
τ	Time lag for the continuous auto correlation function $R(\tau)$
ϕ	Figure of merit defined by equation (4.23)
$\phi(\omega)$	Phase angle of the fourier transform of $x(t)$
$w_r(t)$	Rectangular window as defined by equation (4.15)

NOMENCLATURE (Cont'd)

$W(f)$	GEO spectral window as defined by equation (4.24)
ω	Frequency in radians per second
$x(t)$	Finite, continuous time history
$x(i)$	Finite, discrete time history
\bar{x}	Mean value defined by equation (4.1)
\bar{x}^n	General moments defined by equation (4.2)
\bar{x}^2	Mean square value defined by equation (4.3)
$X(n)$	Fourier transform of $x(i)$ defined by equation (4.13)
$\tilde{X}(n)$	Windowed fourier transform defined by equation (4.28)
$X(\omega)$	Fourier transform of $x(t)$ defined by equation (4.10)
$y(t)$	Infinite, continuous time history

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CHAPTER 1

INTRODUCTION

This investigation is concerned with the design and development of a machinery vibration signal recording system and a computer based processing package for the statistical analysis of the data. The work was conducted in the engineering laboratories of the Sir George Williams campus of Concordia University. The recording system is intended to be the signal acquisition and storage link between vibration sources and the wide variety of equipment that may be used to analyze the signals. The processing package is a series of computer programs, known collectively as VIBPAC, written for a DEC PDP-11 digital computer. VIBPAC provides the capability for analog to digital conversion of the recorded signals, and for further manipulation and handling of the digitized data including necessary statistical analysis of that data.

The acquisition and recording of vibration data on magnetic tape is well documented and the associated problems have been well defined through past experience [1,2,3]. Thus the acquisition and recording system described here is based on fairly rigid requirements. The digital processing of mechanical vibration data, on the other hand, is not so well documented, as it is only in recent years, with the introduction of Fast Fourier Transform techniques that the digital analysis of vibration over a broad frequency range has become a viable proposition. Accordingly, the design of the processing package is based on the characteristic properties of the vibration signals, as well as on consideration of the error sources arising in the various computations and on the limitations of the PDP-11 computer system.

The capability and accuracy of the acquisition and analysis system can be severely compromised if correct recording and handling procedures are not employed. For this reason, the practical aspects of signal conditioning and recording are discussed in some detail.

The use of the VIBPAC processing package has been detailed in Appendix A which has been designed as the VIBPAC user's manual. Although the package is complete in itself, the computational procedures are discussed in sufficient detail to provide enough background for any future development and further deployment of the techniques.

The discussion and specifications for both the analog acquisition system and the VIBPAC processing package centre around the measurement and analysis of rotating machinery vibration. However, the collection of acoustic or shock transient data is also a possible future requirement and this has been borne in mind throughout this development.

CHAPTER 2

PRELIMINARIES

2.1 The Nature of the Vibration Signal

The measurement and analysis of machinery vibration for trouble shooting and maintenance purposes is a fairly well established and accepted technique [4,5,6,7,8]. Usually, vibration signatures of a given machine, taken when it is known to be in good condition, are compared to signatures taken during other times in order to establish the present condition of the machine. This is often performed by transforming the vibration signal from the time domain into the frequency domain and identifying certain characteristic frequencies. These characteristic frequencies are a function of the machine construction and its actual operating condition. For example, imbalance in a rotating shaft generates vibration at rotational speed so the first and most obvious characteristic frequency is the rotational frequency of the shaft, usually known as the fundamental or the first order frequency. Gear meshing frequency (number of teeth times the rotational frequency) is yet another example of such a characteristic frequency. The vibration signal, even from relatively simple machines, is often complex and consists of many different frequencies and many fluctuating amplitudes. This is a result of the modulation and distortion of the characteristic frequencies due to the machine structure and the nature of the contacting surfaces within [9]. It is thus often possible to identify only a few characteristic frequencies through knowledge of the structural aspects of the machine construction. In addition, observation of machinery vibration, both in the time domain and in the frequency domain, appears to indicate

that there is a considerable amount of random behaviour present in the signal! This evidently suggests that there is a lot of information contained in the vibration signal that cannot be obtained by the use of conventional comparative techniques.. Thus the question arises as to how valid information can best be extracted from it. It is postulated that the statistics of the signal should supply adequate information required to determine the condition of the machine and to allow some reliable prediction of its condition for the future.

Once it has been determined that the statistical approach is the one of interest it is helpful to classify the signal to be analysed. Since the finite length of the vibration record to be used for analysis is extremely short, the vibration signal statistics are not expected to change appreciably over the sampling time. This means that the signal may be classified as basically stationary [10]. To further assume that the signal is also ergodic is customary unless there is a compelling physical reason not to do so [10,11,12]. This assumption enables the use of the fact that for such processes the statistics of a single representative time history can replace the statistics of the ensemble of time histories.

Conveniently, the finite record length also helps overcome some mathematical hurdles with regard to the computation of power spectra [13].

2.2 Measurement of Vibration Signals

The first and foremost requirement of any measurement system is that the system should not interfere with or modify the parameter being measured in any unpredictable or unforeseeable manner. This is an obvious requirement but it is one which presents the most difficulties

in practice. The form in which the data is collected must be such that the signal contains the maximum amount of information so that any of a variety of analysis methods may be used. Further, the system design must be such that it minimizes spurious and unwanted inputs into the data.

The most general system for the acquisition of vibration data from rotating machines is one which uses an electrical transducer attached to the vibration source. The transducer changes the physical motion into an electrical signal which is amplified if necessary, then transmitted to a device for either recording or analysis.

The type of measurement and recording to be made depends on the analysis requirements for the data and on the amplitude and frequency content of the signal. Magnetic tape recording is a convenient method since it provides the capability of collecting and storing large amounts of data and does not require the analysis equipment as an integral part of the set-up. It is also capable of recording data in several channels simultaneously so that any form of correlation analysis can be performed without losing the time relationship between the channels. Additionally, magnetic tape recording has a wide dynamic range as well as a wide frequency range.

Once the basic parameters for the system have been determined some thought must be given to the ability of the system for preprocessing the data. Although it has been mentioned that the signal should contain as much information as possible, it may be necessary to preprocess the data under certain circumstances in order to assure compatibility with the analysis equipment. This is discussed in more detail in Chapter 3.

2.3 The Analysis of Vibration Signals

The analysis of vibration signals requires transforming the time domain history into different forms better suited for further study.

It involves, in many cases, certain simplifications in the presentation of the complex vibration signal and provides a mathematical description of its parameters. The main question for the analyst is how best to achieve this and which parameters are the most important. This is often difficult to answer and one must keep in mind that, due to the nature of most data reduction processes, some information is often discarded. In many situations it is the objective of the analysis to remove non-essential information, but that must be established before hand. Quite often it is impossible to reconstruct the raw signal after an analysis has been performed. The form of the reduced data depends upon both the characteristics of the time-history as initially recorded and the ultimate purpose for which the reduced data will be used.

The most common form of reduction is to transform the vibration signal from the time domain into the frequency domain using either electronic filtering or some type of Fourier analysis. Instead of an amplitude-time representation of the signal, an amplitude-frequency spectrum is generated. This type of analysis is the most useful for identification of the characteristic frequencies and often facilitates identification of the vibration source and machine faults. Primarily, it is used on deterministic signals. Where random signals are concerned, frequency analysis does not provide enough valid information.

With the development of Fast Fourier Transform (FFT) algorithms over the last few years, the digital computer has become a very attractive tool for the analysis of vibration data. Besides providing flexibility in the various functions and filters that can be used, it also provides an environment for handling, storing and manipulating large amounts of data. For processing single-channel signals and, more importantly, multi-channel signals, digital processing techniques offer several advantages over analog techniques. In addition to the analysis precision which can be achieved by using an all digital approach, one of the foremost single advantages is that the phase relationship of the data is well preserved. A second advantage is the fact that many other functions are readily derived using FFT because they have a distinct mathematical relationship to either the forward or the inverse transform. For example, the power spectral density can be shown to be the Fourier transform of the correlation function, and hence correlation functions can be computed very rapidly.

Essentially, the functions of interest may be classified into two areas: those which describe and identify the data such as the probability functions, mean, variance, auto correlation function, etc., and those which provide a measure of the mutual properties between signals, such as cross-correlation, coherence functions and cross-spectra.

There are a great variety of probability density and distribution functions that can be derived and used for the description of random processes. One of the most important of these functions is the probability density function for the amplitude values of the process, sometimes designated the first order probability density function.

This function is of considerable practical interest since, if the probability density function turns out to be Gaussian, the process can be completely described by measuring the power spectral density function or the auto-correlation function [14]. The auto-correlation function describes the time domain relationship between a signal and a delayed replica of itself. Among other things it serves as a direct indicator of signal bandwidth and the existence of periodicities [15]. In particular the auto-correlation function has many properties which make it a useful descriptor for vibration signals. See Chapter 4 on vibration signal analysis.

The dual signal functions, cross-spectra, cross-correlation etc are used to explore the cause and effect relationship between signals. Cross-spectra, for example, can be used to identify a system's transfer function provided the input and output signals are available. Cross-correlation is used in recovering signals from noise, in studying time delay mechanisms and transmission paths. Coherence functions are used primarily to verify other functions and to reveal the existence of resonant frequencies.

The processing package VIBPAC developed in this work concentrates on single signal functions. That is those which serve to describe and identify the data; VIBPAC also provides adequate means for handling the vibration data. The computation of the dual signal functions, i.e. those which provide a measure of mutual relationships between signals, has been left for further work but the provision for such computations is inherent in the system.

CHAPTER 3

VIBRATION SIGNAL ACQUISITION

3.1 The Acquisition System

In order to fulfill the requirements outlined, the system shown schematically in Figure 3.1 was designed. The core of the system is a multi-channel instrumentation tape recorder. The vibration signals, describing response in each of three mutually perpendicular directions, are obtained from accelerometers rigidly mounted on the bearing housing of the machine under study. The characteristics of the mounting are such that they will not influence the vibration signals over the frequency range of interest.

The accelerometers themselves (B&K 8302) are a matched set, that is, their sensitivities are within a very small error range. This facilitates comparatively easier system calibration. They may be considered as middle of the range accelerometers in terms of voltage and charge sensitivity and physical size. The vibration signal from the accelerometers is fed through special shielded cables (B&K A00037), 10 feet in length, to the conditioning amplifiers. The conditioning amplifiers (B&K 2626) have several features of special importance to this system, the first of which is the ability to adjust the sensitivity to suit the type of transducer employed. Secondly, they have adjustable High-pass and Low-pass filters, thus allowing the pass band to be limited to the frequency range of interest, so reducing the influence of noise and spurious signals outside this range. They have a frequency response which is flat within 0.25dB up to 10kHz and a large dynamic range (-20dB to +60dB). The amplifiers are also provided with two indicator lights, one which indicates an

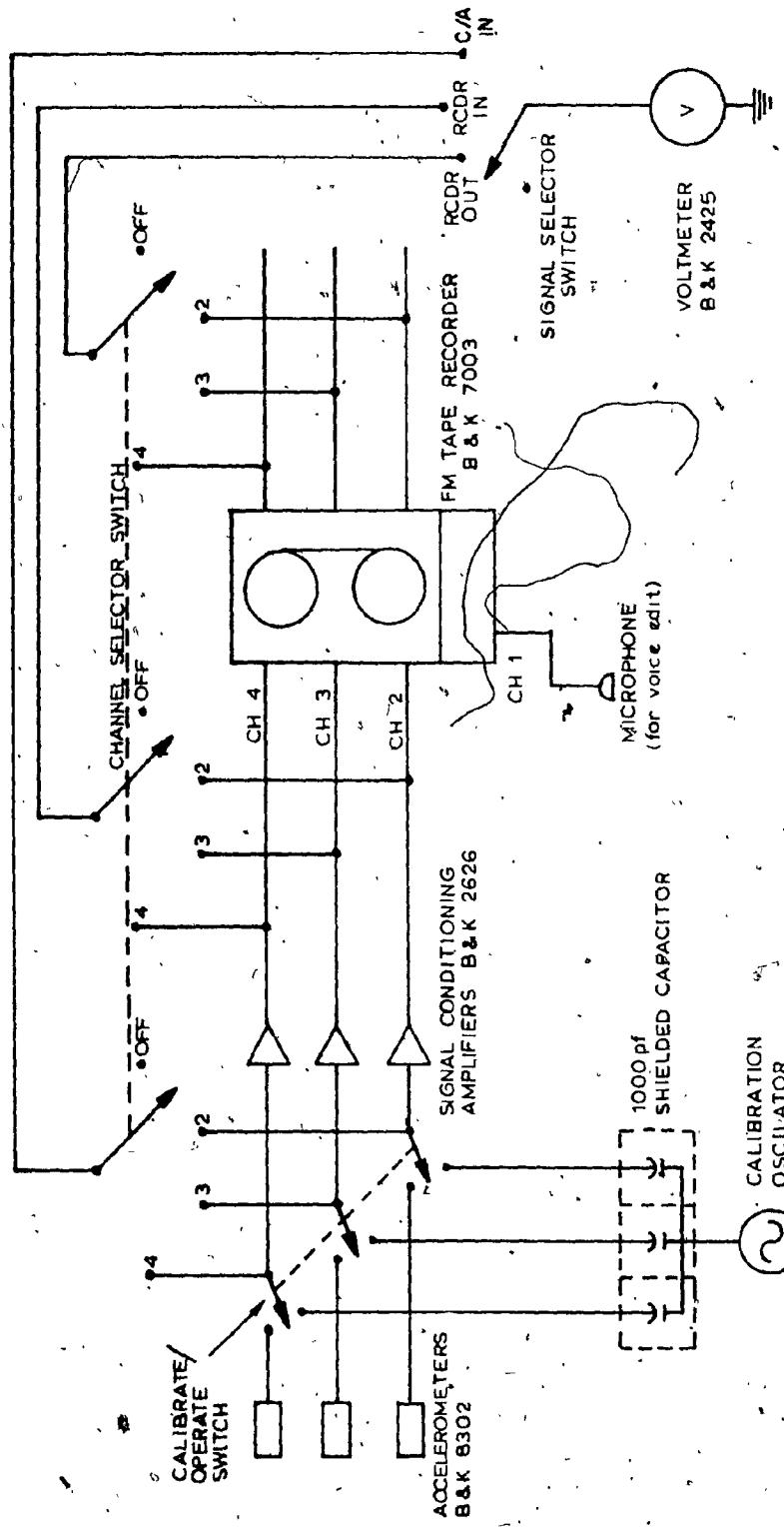


FIGURE 3.1. SCHEMATIC OF VIBRATION & SHOCK DATA ACQUISITION SYSTEM

overload condition and the other which indicates 20dB below overload, so that the best working level may be maintained to minimize noise.

From the conditioning amplifiers the signal is fed to the tape recorder. The tape recorder (B&K 7003) is a multi-channel instrumentation type which allows FM recording on 3 of its 4 channels over a frequency range from DC to 10kHz and direct recording on one channel from 2.5Hz to 50kHz. It has been designed especially for vibration and acoustic recording with great accuracy. The three FM channels are used for the vibration data and have low noise, good linearity and low distortion. The dynamic range is 39dB at a recording speed of 1.5ips and 44dB at 15ips. Each input has a potentiometer adjustment in order to accommodate signal levels from 1 Vrms to 50 Vrms. The output impedance is very low, less than 5Ω , thus allowing use of a wide variety of analysis and measurement equipment. The direct channel is used for recording a voice edit simultaneously with the data using the microphone supplied with the recorder. This feature is used for identification and timing purposes when reproducing the data. Using a suitable editing procedure at the time of recording the data, countdowns, lead-in times etc., the operator is in a position to avoid blanks and switching transients which will always be present on the tape.

The oscillator built into the system is used for internal calibration. A fixed frequency variable amplitude signal can be fed simultaneously into the conditioning amplifiers so that the gain and operation can be checked. The entire system, apart from the accelerometers and low noise cables, can be checked for calibration and correct operation. It is also important that the calibration signal be

recorded on tape so that it may be used during playback for calibration of the measurement or analysis equipment. The oscillator was built to generate a sine wave at a frequency of 100Hz. A schematic is shown in Figure 3.2.

The electronic voltmeter (B&K 2425) was selected for its versatility of measurement and its large frequency and sensitivity ranges. Some of the more notable features are its ability to read positive peak, negative peak, RMS and average indication, as well as a hold function for transient inputs. With this voltmeter and the switching arrangement shown, each of the three channels may be monitored at either input to the conditioning amplifiers, at input to the recorder or at output from the recorder, thus making checks on the system operation and calibration a simple and accurate process.

The entire system is contained in an instrumentation cabinet with special mounting racks for each component. This provides portability, ease of operation and protection from environmental hazards. Figure 3.2 shows the layout.

3.3 Recording, Calibration and Tape Editing

Once the specifications for the recording system have been determined and the system built, the form of the collected data has been fixed. However, it is necessary to follow carefully laid down procedures so that the recorded data can be interpreted and located properly at playback time. Figure 3.4 shows a data sheet used when recording vibration signals from a 1-1/2 kW motor generator set located in the Concordia Engineering Laboratories. All pertinent information regarding the machine, its speed and load, the number of running hours, accelerometer locations etc, are noted. The recording system settings,

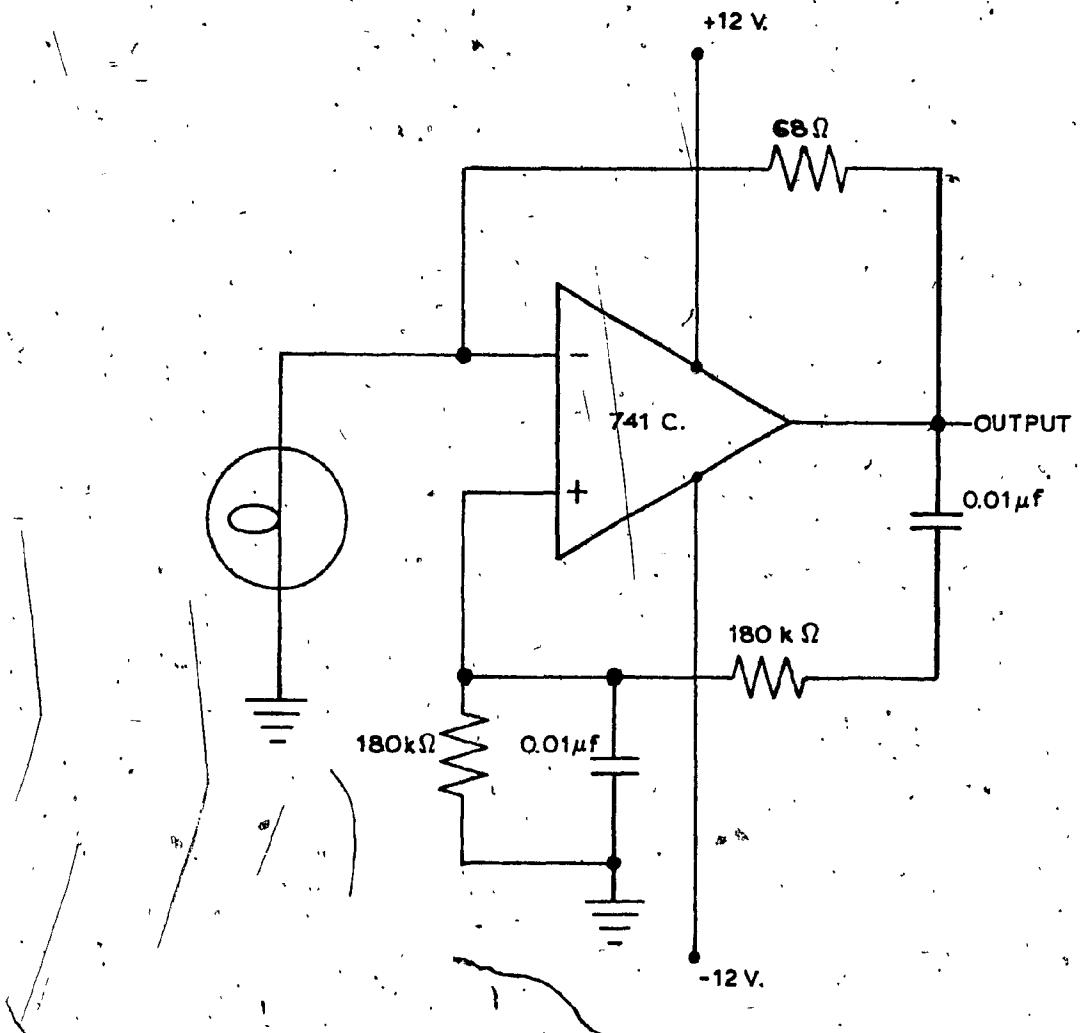


FIGURE 3.2 SCHEMATIC DIAGRAM OF CALIBRATION OSCILLATOR

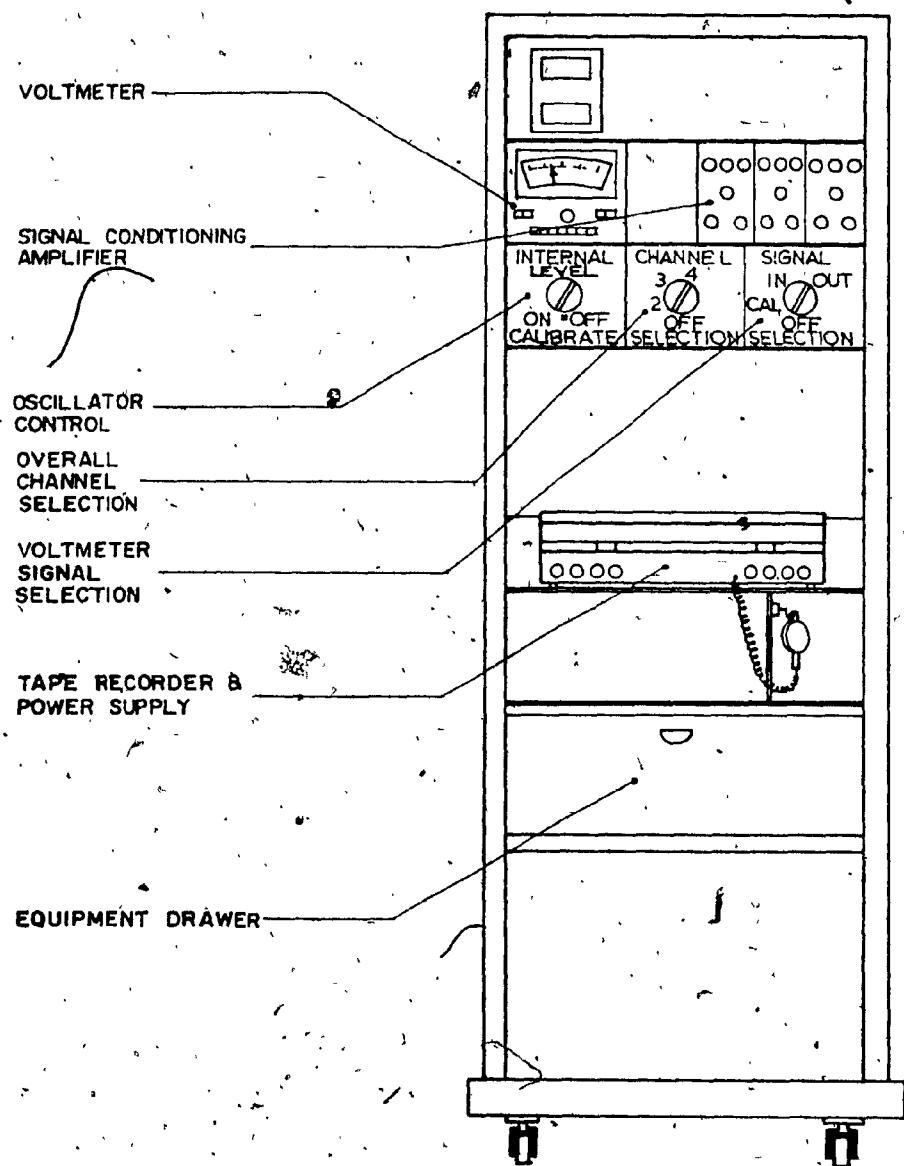


FIGURE 3.3 DATA ACQUISITION RACK

VIBRATION RECORDING DATA SHEET

MACHINE: '1 1/2 hr MC Set
 TAPE SPEED: 15 ips

LOCATION: Rm 0027
 CAL. SIGNAL: _____

LOAD OR CONDITION: _____
 FREQ. BANDWIDTH: Hz to kHz

ACCELEROMETER SPECS: Ch2. Vertical, 10.03pc/g, 9.12mV/g, No. 344820
 Ch3. Horizontal, 10.12pc/g, 8.83mV/g, No. 344817
 Ch4. Axial, 10.16pc/g, 9.16mV/g, No. 344821

RECORDING # TAPE NO.	DATE	RECODER CHANNEL	COUNTER START	C/A SETTING PC/R	V/Z	SYSTEM VOLTAGES (RUS)			COMMENTS	
						INPUT	C/A OUTPUT	CDR OUTPUT	Calibrate Signal	
		2								
		3								
		4								
		2								
		3								
		4								
		2								
		3								
		4								
		2								
		3								
		4								

FIGURE 3.4 VIBRATION RECORDING DATA SHEET

tape speed, bandwidth etc are also noted for each set of data. Each data set is identified by a data set identification number and each data set contains a calibration signal of known frequency and amplitude recorded prior to the recording of the vibration signals.

Suitable spacing is allowed between each signal and locations on the tape are identified by voice edit on Channel 1 and by a tape recorder counter reference on the data sheet.

The correct signal levels are determined by monitoring the 20 dB down light and the overload light on the front of the charge amplifiers. Providing the 20 dB down light is continuously lit and the overload light remains unlit, the signal level is always greater than 20 dB below overload. The high and low pass filters on the charge amplifiers are set prior to recording based on the selection of required bandwidth, usually governed by the analysis to be performed later. The VIBPAC analysis system at present has a maximum frequency limit of 3 kHz and a minimum limit of 10 Hz so the filters are set to this operating range. Charge amplifier output in Volts per g is set to keep the signal in the 20 dB down range and the tape recorder input sensitivity adjusted to suit.

Adherence to these procedures ensures that the data collected has the correct frequency bandwidth and the correct level on the tape. It allows calibration of the vibration signal amplitudes with a known calibration signal and provides a voice edit to identify and locate the signals on tape. Additionally, three simultaneously recorded signals are available for future analysis.

3.3 Analog to Digital Conversion

Once the data has been recorded on tape it may be played back through a variety of analysis instruments. In our case, as a first step to analyzing the data using the VIBPAC computer system, the signal has to be changed from analog to digital form. This is accomplished by feeding the signals simultaneously into the DR-11c analog to digital converter which is under the control of the VIBPAC Vibration Input Routine, VIR (See Appendix A). Conversion takes place by sampling the vibration signals at discrete time intervals so that the signal becomes a real valued array within the computer. Digitizing the data in this fashion leads to several sources of error. In particular there are three important areas worth consideration here.

The first is known as the quantizing error introduced by the finite word size of the computer. Since the word size is restricted to a given number of bits the computer cannot represent any infinite level but only discrete levels. It is the difference between the actual sampled level and the nearest level that the computer can represent that is known as the quantizing error. This is represented in Figure 3.5. Once the computer word size reaches 8 bits or more this error becomes extremely small [16]. For the DEC PDP-11 computer, the word size is 16 bits so the quantizing error is insignificant. The second and third sources of error arise due to the sampling rate itself.

For a given sampling rate, $f_s = \frac{1}{\Delta t}$; where Δt is the sampling interval; the Nyquist sampling theorem states that only frequency components less than $f_s/2$ can be detected. Frequency components greater than $f_s/2$ (known as the Nyquist or aliasing frequency) are

folded back or aliased into the range $0, f_s/2$, as shown in Figure 3.6. Thus a convenient method of determining a reasonable sampling frequency is to define the band-limiting properties of the data acquisition system and preprocess the data during recording. If a sampling frequency of twice the maximum frequency of the recording system were to be used the large number of data points required for a reasonable bandwidth could become excessive.

A sampling rate of twice the maximum expected frequency contained in the signal is adequate for a frequency analysis but is not adequate for computation of functions in the time domain, due to bias error.

The simplest peak detection technique is to search the digitized time signal for the maximum value and assume that this maximum is the true peak. Figure 3.7 shows how such errors can arise. The maximum bias error for a sinusoidal signal will occur when the true maximum is halfway between two samples. The maximum percentage error can be shown to be [17].

$$e_m = 100 \left(1 - \cos \frac{\pi f}{f_s} \right) \quad (3.1)$$

Thus for a sampling rate of twice the highest frequency the maximum possible error is 100%. If a probabilistic approach is taken then the percentage expected error becomes [17]

$$e_e = 100 \left(1 - \frac{\sin \pi f/f_s}{\pi f/f_s} \right) \quad (3.2)$$

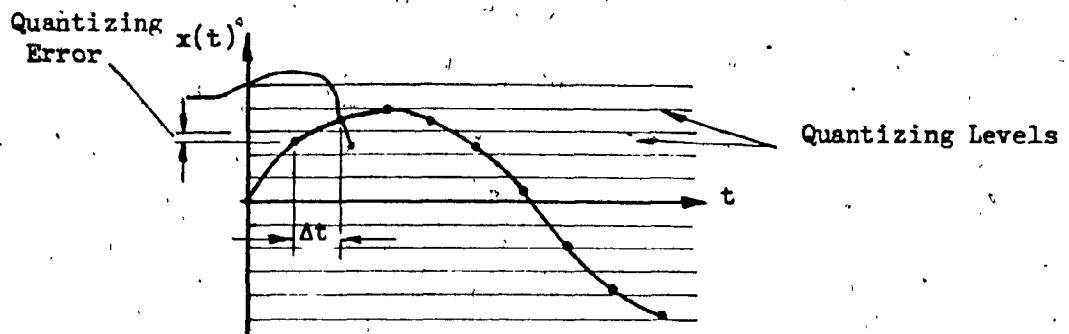


FIGURE 3.5 QUANTIZING ERROR

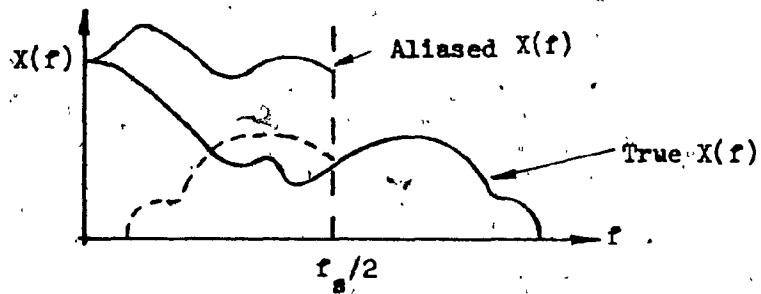


FIGURE 3.6 ALIASING ERROR DUE TO INSUFFICIENT SAMPLING RATE

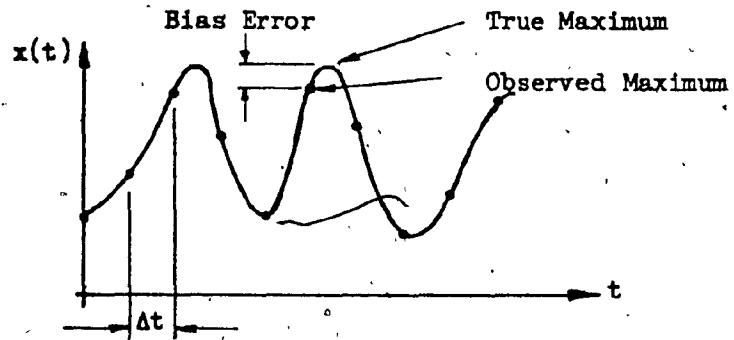


FIGURE 3.7 BIAS ERROR

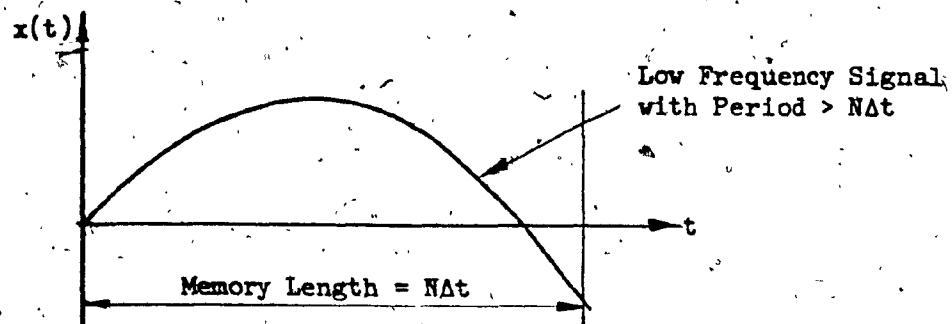


FIGURE 3.8 LOW FREQUENCY CONTAMINATION OF DATA

and the maximum expected error for a sampling rate of twice the highest frequency is 36 percent. For a sampling ratio of ten times the highest frequency equation (3.2) yields an expected error of 1.6% and equation (3.1) yields a maximum possible error of 4.9%.

It is clear from the foregoing that the selection of the sampling rate in relation to the frequency content of the signal to be analyzed is an extremely important factor with regard to the accuracy of the results. The selection of the sampling rate is further complicated by other factors, namely the degree of resolution required, the lowest frequency in the signal and by the available digital memory of the analysis equipment. It may be shown that the effective bandwidth Δf , is given by [18]:

$$\Delta f = \frac{1}{N\Delta t} \quad (3.3)$$

where N = number of samples of the time history.

N is obviously limited by the available digital memory and it is determined by the degree of accuracy required in the analysis. The lowest frequency contained in the sampled signal is equal to the bandwidth Δf . If frequencies lower than this are contained in the time history they will contaminate the sampled data as illustrated in Figure 3.8.

On analysis the signal shown will yield statistics other than those associated with a periodic signal. Thus the time history must not contain signals of frequency less than Δf . By preference the lowest frequency contained in the history should be several times this.

It is seen that the selection of sampling rates is dependent on many often conflicting criteria so that it becomes a matter of judgement as to what sampling rate is appropriate. The sample results generated by VIBPAC in Appendix B demonstrate the use of two sampling rates for the same data. Twice the highest frequency is used for frequency analysis so that a good resolution is obtained and nine times the highest frequency is used for accuracy when time based computations are performed. These choices were made necessary due to the limited memory capacity of the DEC PDP-11 computer used in the analysis.

CHAPTER 4

VIBRATION SIGNAL ANALYSIS

4.1 Preliminary Concepts

As mentioned earlier, the vibration time history contains a great deal of complex information and is basically of a random nature. The use of a statistical approach in characterizing and describing the signal offers many advantages and is, of course, the only valid option when dealing with random data.

In mechanical vibration analysis, the parameters of interest are the mean, mean square, variance of the process, the auto correlation, probability density, probability distribution and power spectral density functions. The intention here is to present a brief introduction to these statistical parameters, and to show how their respective computations are handled by the VIBPAC programs.

4.1(a) Mean Value, Mean Square and Variance

Since the continuous signal $x(t)$ is to be digitized the resulting array consists of N discrete observations of $x(t)$, designated $x(i) \quad i = 1, 2, \dots, N$
then the mean or expected value is given by [19]:

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x(i) \quad (4.1)$$

Equation (4.1) can be written in a more general form [20]:

$$\bar{x}^n = \frac{1}{N} \sum_{i=1}^N x^n(i) \quad (4.2)$$

which is the expression for the general moments of a series of observations.

The most important of these moments are for $n = 1$, giving the mean value, and $n = 2$ which yields the mean-square value.

$$\bar{x}^2 = \frac{1}{N} \sum_{i=1}^N x^2(i) \quad (4.3)$$

The importance of the mean square value lies in the fact that it is proportional to the average power (or energy) contained in the signal, as for example, the mean square value of average power dissipated by a resistor. The square root of \bar{x}^2 is known as the rms or effective value of the signal.

An extension of equation (4.2) is used to define the central moments of a series of observations [20]:

$$(x - \bar{x})^n = \frac{1}{N} \sum_{i=1}^N (x(i) - \bar{x})^n \quad (4.4)$$

The central moment for $n=1$ is zero. For $n=2$ the central moment is known as the variance and is symbolized by σ^2 . That is,

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^N (x(i) - \bar{x})^2 \quad (4.5)$$

The variance can be thought of as proportional to the average energy of the AC components of a signal. For zero mean value it can be seen that equation (4.5) reduces to equation (4.3) and thus the variance becomes equal to the mean square value.

4.1 (b) The Auto Correlation Function

The examination of the correlation between two signals or the correlation of a signal with itself provides extremely important information when dealing with random signals. The amount of correlation is characterized by what is known as a correlation function. If the variables used to compute this function are from two different signals it is known as the cross-

correlation function and if the variables are from the same signal then it is known as the auto correlation function. For our purposes it will suffice to consider the auto correlation function, which for a stationary time domain signal sampled over a finite time interval is defined to be [21]:

$$R(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_{-T}^{T} x(t)x(t + \tau)dt \quad (4.6)$$

Effectively, this function describes how a particular instantaneous amplitude depends upon previously occurring amplitudes. In the case of an ideal gaussian process the auto correlation function would consist of an infinitely narrow impulse function around zero since the amplitude at any given time is independent of amplitudes at any other times. In practice, the auto correlation function associated with mechanical vibration signals cluster around $\tau=0$ and the function rapidly approaches zero as τ increases [22]. A typical auto correlation function is shown in Appendix B as the result of VIBPAC analysis on the vibration from a small motor generator set. The following list, Table 4.1, shows some of the more important properties of auto correlation functions and helps illustrate why this function is so useful.

1. $R(0) = \bar{x}^2$ The value of the auto correlation function at $\tau=0$ is equal to the mean square value of the process.
2. $R(\tau) = R(-\tau)$ The function is an even function of τ . The largest value always occurs at $\tau=0$.
4. If $x(t)$ has a mean component, then $R(\tau)$ will have a mean component.
5. If $x(t)$ has a periodic component, then $R(\tau)$ will have a periodic component of the same period.
6. If $x(t)$ is ergodic with a zero mean then $R(\tau)=0$.
7. $R(\tau)$ cannot have an arbitrary shape.

TABLE 4.1. PROPERTIES OF THE AUTO-CORRELATION FUNCTION [21]

4.1 (c) Probability Functions

The future behaviour of a random vibration signal cannot be predicted so that a probabilistic approach has to be used to describe the signal. Thus it becomes necessary to attach some physical significance to the concept of probability. Probability may be defined as the chance of a particular event occurring out of the total of all possible events. If $P_r(A)$ designates the probability of event A then the properties of probabilities may be summarized as follows:

1. $0 \leq P_r(A) \leq 1$
2. $P_e(A) + P_r(B) + \dots + P_r(M) = 1$, for a complete set of mutually exclusive events
3. If an event is impossible $P_r(A) = 0$
4. If an event is certain $P_r(A) = 1$

Taking the above concept a step further it is possible to determine the probability that an observed vibration amplitude is less than or equal to a given value. This is accomplished by means of the probability distribution function for a random process, as defined by [23]:

$$F(x) = P_r(X \leq x) \quad (4.7)$$

The significance of the probability distribution function is in the fact that it is a probability and therefore must satisfy similar requirements to those listed above. Also since it is a function of x, the possible values of the random amplitude X, it must be defined for all values of x. Thus the following statements apply:

$$1. \quad 0 \leq F(x) \leq 1 \quad -\infty < x < \infty$$

$$2. \quad F(x_1 < x \leq x_2) = F(x_2) - F(x_1)$$

$$3. \quad F(-\infty) = 0$$

$$4. \quad F(\infty) = 1$$

Although the distribution function contains the information required it is not in the most convenient form for all types of analysis. The derivative of the distribution function, known as the probability density function, is often used when dealing with random signals. In equation form this is written as [23]:

$$p(x) = \frac{dF(x)}{dx} \quad (4.8)$$

The corresponding properties associated with $p(x)$ may be summarized as shown:

$$1. \quad p(x) \geq 0 \quad -\infty < x < \infty$$

$$2. \quad \int_{-\infty}^{\infty} p(x) dx = 1$$

$$3. \quad F(x) = \int_{-\infty}^x p(u) du$$

$$4. \quad \int_{x_1}^{x_2} p(x) dx = F(x_2) - F(x_1)$$

The physical interpretation of the density function in terms of random vibration signals may be made in terms of the element $p(x) dx$. This can be shown to be:

$$p(x) dx = \Pr(x < X \leq x + dx) \quad (4.9)$$

Equation (4.9) states that $p(x) dx$ is the probability that an observed amplitude X lies in the range of possible values between x and $x + dx$.

In statistical work it is usual to normalize the probability density and distribution functions in order to standardize the presentation of them. It is often performed either by dividing by the variance of the data or by dividing by the total number of occurrences and expressing the result as a percentage. VIBPAC computations use the latter method.

4.1 (d) The Fourier Transform

In order to transform the vibration signal from the time domain to the frequency domain the Fourier integral is used. The Fourier integral permits the representation of an arbitrary function, $x(t)$ by a single expression in the frequency domain [25]:

$$X(\omega) = \int_{-\infty}^{\infty} x(t)e^{-i\omega t} dt \quad (4.10)$$

If this integral exists for every real value of ω , it defines a function $X(\omega)$ known as the Fourier Transform of $x(t)$. In general $X(\omega)$ is complex.

$$X(\omega) = R(\omega) + I(\omega) = A(\omega)e^{j\phi(\omega)} \quad (4.11)$$

Where $A(\omega)$ is called the Fourier spectrum of $x(t)$ and $\phi(\omega)$ is its phase angle.

Similarly, the inverse transform is given by [25]:

$$x(t) = \int_{-\infty}^{\infty} X(\omega)e^{i\omega t} d\omega \quad (4.12)$$

$x(t)$ and $X(\omega)$ are known as a Fourier Transform pair and a one to one relationship exists between them. Mathematically there are certain restrictions on the existence of these integrals but in practice these restrictions are far broader than necessary [26].

Since the vibration record to be used for analysis will be a finite digitized sample of a time domain signal equations (4.10) and (4.11) are better expressed in discrete form [27]:

$$X(n) = \frac{1}{N} \sum_{i=0}^{n-1} x(i) e^{-\frac{\omega ni}{N}} \quad (4.13)$$

and

$$x(i) = \sum_{n=0}^{N/2} X(n) e^{\frac{\omega ni}{N}} \quad (4.14)$$

In doing this some of the mathematical restrictions on the existence of the transform pair are removed. Detailed information on these restrictions and their removal by considering a discrete, finite record may be found in the literature, particularly [13], [27] and [28]. Other than the effects of sampling rate which are discussed in detail in Chapter 3, there is one problem which is created by sampling over a finite interval. This is the problem commonly identified as windowing the data.

In order to appreciate the problem created by sampling over a finite record first consider the Fourier transform of a rectangular function $W_r(t)$, shown in Figure 4.1(a), defined by:

$$W_r(t) = \begin{cases} 1 & -T < t < T \\ 0 & \text{otherwise} \end{cases} \quad (4.15)$$

The Fourier transform is found using equation (4.10).

$$F_r(\omega) = \int_{-\infty}^{\infty} W_r(t) e^{-i\omega t} dt = \int_{-\infty}^{\infty} e^{-i\omega t} dt = 2 \frac{\sin \omega T}{\omega} \quad (4.16)$$

and is shown in Figure 4.1(b). Any finite record $x(t)$ may be thought of as the product of a record of infinite length $y(t)$ and the rectangular function $W_r(t)$ shown in Figure 4.2.

$$x(t) = y(t)W_r(t) \quad (4.17)$$

and the Fourier transform of $x(t)$ is

$$X(\omega) = \int_{-\infty}^{\infty} y(t)W_r(t) e^{-i\omega t} dt \quad (4.18)$$

Using the convolution theorem [29] equation (4.18) becomes:

$$X(\omega) = \int_{-\infty}^{\infty} Y(\omega') F_r(\omega' - \omega) d\omega' \quad (4.18)$$

Thus for a finite record length, the Fourier transform of $y(t)$ is modified by the Fourier transform of the rectangular function. This is analogous to looking at the Fourier transform of $y(t)$ through a filter of shape $F_r(\omega)$. Clearly, if a function other than $W_r(t)$ is used to modify the finite record, a different filter shape results in the frequency domain. This result is employed to produce filter shapes of desirable frequency domain characteristics. This is discussed further in Section 4.2, on Data Windows.

A second consideration is the practical aspects of computations using equations (4.13) and (4.14). Although these formulations are straightforward, problems arise if no attention

is paid to the computational aspects. As an illustration consider a discrete record of 4096 data points, the number used by VIBPAC. Effectively $N \times N$ complex multiplication and addition operations are required in the evaluation of equation (4.13). Assuming an operation time of 250×10^{-6} sec the total computational time is $(4096)^2 \times 250 \times 10^{-6} = 1.2$ hours. A recursion method of computing sines and cosines can be used to reduce this time but errors build up rapidly [30]. It is for this reason that a fast Fourier transform (FFT) algorithm is used by VIBPAC. Effectively an FFT is any Fourier transform algorithm that reduces the computational time to such an extent that computation involving large numbers of data points becomes practical. Typically, the number of operations is reduced from N^2 to $2N$ which for the above hypothetical example yields a computational time of 2.05 seconds, a speed increase in the order of 2000 times. The particular FFT algorithm used by the VIBPAC system is discussed in more detail in Section 4.3.

4.1 (e) Power Spectral Density

The objective of spectral analysis is to determine the variation of vibration amplitude, either in acceleration, velocity or displacement units, with frequency and to relate the amplitude to the energy content of the signal. In fact, the power spectral density (PSD) or power spectrum is an extension of the concept of variance which was discussed earlier. It may be shown that the power spectral density $G_x(\omega)$ is given by [13,31]:

$$G_x(\omega) = \lim_{T \rightarrow \infty} \frac{2}{T} \left| \int_{-T/2}^{T/2} x(t) e^{-i\omega t} dt \right|^2 \quad (4.20)$$

$$\text{and from equation (4.9): } \int_{-T/2}^{T/2} x(t) e^{-i\omega t} dt = X(\omega)$$

Thus:

$$G_x(\omega) = \frac{2}{T} |X(\omega)|^2 \quad (4.21)$$

so that the power spectral density may be thought of as the contribution to the mean square value of each frequency.

Mathematically it can be shown that the use of the direct Fourier method, i.e. equation (4.20), to evaluate the PSD for a stochastic process is not valid. This is based on arguments relating to the existence of the Fourier transform, and on the statistical variation of the results [31]. Also without the use of an FFT routine there is the computational objection to using equation (4.20). In order to overcome these objections the classical approach in the past has been to use the Wiener-Khintchine relationship which allows calculation of the PSD from the auto-correlation function [13]:

$$G(\omega) = 2 \int_{-\infty}^{\infty} R(\tau) e^{-i\omega\tau} d\tau \quad (4.22)$$

where $R(\tau)$ is the auto-correlation function defined by equation (4.6).

One of the major reasons for using this relationship was computational efficiency since a satisfactory spectrum could be obtained from a truncated auto correlation function. That is, for a digital time series of N data points and a correlation function of M time lags a Fourier transform could be computed in about Nm operations rather than N^2 . Before the advent of FFT algorithms the computational aspects of the direct approach were

cumbersome and consequently the practical problems of its implementation were never thoroughly dealt with. The speed of modern FFT algorithms now make the direct approach a viable proposition. Providing a suitable data window is selected and proper smoothing of the estimates is carried out, the results obtained by the direct approach are, for all practical purposes, identical to the results that would be obtained by using the classical Wiener-Khintchine method [13].

In smoothing the estimates the concern is with reducing the uncertainty in the PSD measurement due to the amount of data used, the underlying stochastic nature of the data and the method used to determine the PSD. It may be shown for the direct FFT approach that the standard deviation of the PSD is greater than or equal to the quantity being estimated [32]. Clearly with such a large possible error the PSD would be of little use as a descriptor for the process. However, if the data being analyzed is Gaussian it may be shown that the PSD, $G_x(\omega)$ defined by equation (4.26), is a chi-squared variable with two degrees of freedom [32]. As the number of degrees of freedom of a chi-squared variable increases, the confidence-limits on the variance of the estimate improve [33, 34]. Thus if the number of degrees of freedom of the PSD can be increased by averaging a number of contiguous estimates the variance of the estimate can be improved at the expense of resolution. Figure 4.3 illustrates the relationship between variability of the estimate, number of degrees of freedom and confidence limits.

4.2 Data Windows

As discussed in Section 4.1(d) the effect of sampling a continuous signal over a finite time interval and obtaining its Fourier transform is to introduce a rectangular weighting in the time domain and a $\frac{\sin \omega t}{\omega}$ weighting in the frequency domain.

The side lobes introduced by this weighting are referred to as frequency leakage and the width of the filter as frequency smearing. The question to be considered is how best to reduce these effects by suitable window selection. In addition, some of the conditions for variability, bias characteristics and smoothing of PSD's can be improved by selection of a suitably shaped window. In essence, many of the requirements for a data window are contradictory, i.e. improved resolution can only be achieved by having larger side lobes and vice versa. Many windows have been developed, each with its own characteristics [36], hence selection becomes a difficult task. Figure 4.4 shows two of the better known windows, both in the time domain and in the frequency domain.

If viewed from a time domain point of view, the object of applying the data window is to round-off potential discontinuities at each end of the finite segment. The effect in the frequency domain is that of a filter. There is no reason, however, why the application of a window cannot be made as effectively in the frequency domain as in the time domain and computationally there is little to choose between the methods.

Most often data windows are selected on the basis of arbitrary judgement and this requires a clear knowledge of the characteristics of many different windows. One window in particular that has been

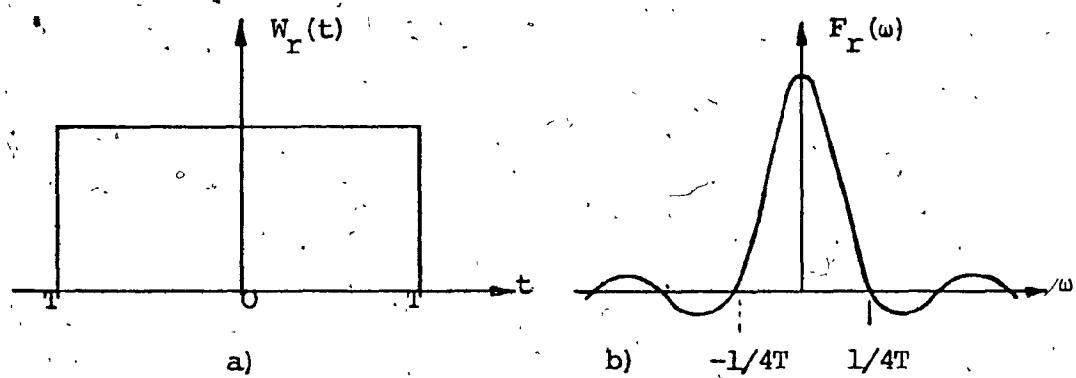


FIGURE 4.1 THE RECTANGULAR WINDOW a) Time Domain b) Freq. Domain

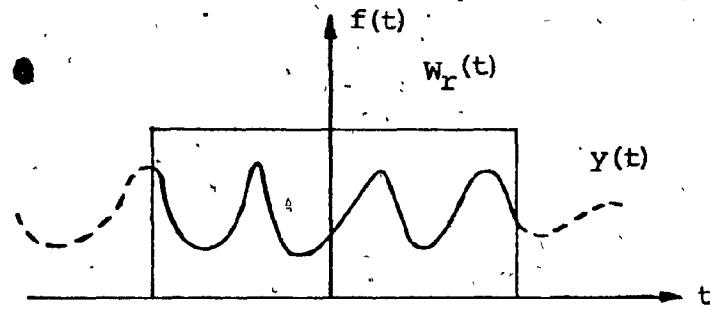


FIGURE 4.2 THE FINITE RECORD

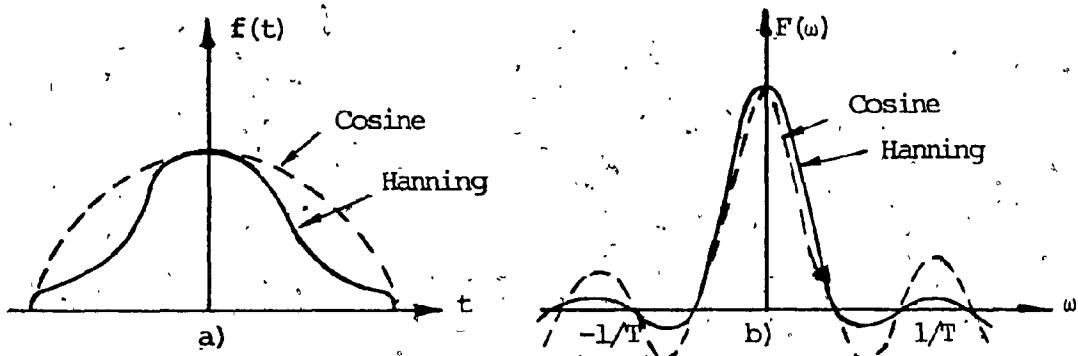


FIGURE 4.4 DATA WINDOWS a) Time Domain b) Frequency Domain

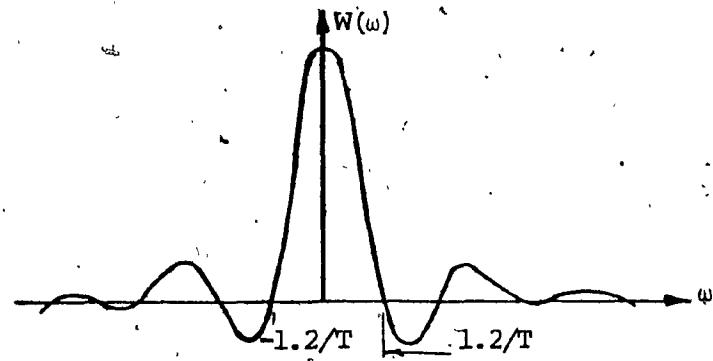


FIGURE 4.5 THE GEC SPECTRAL WINDOW

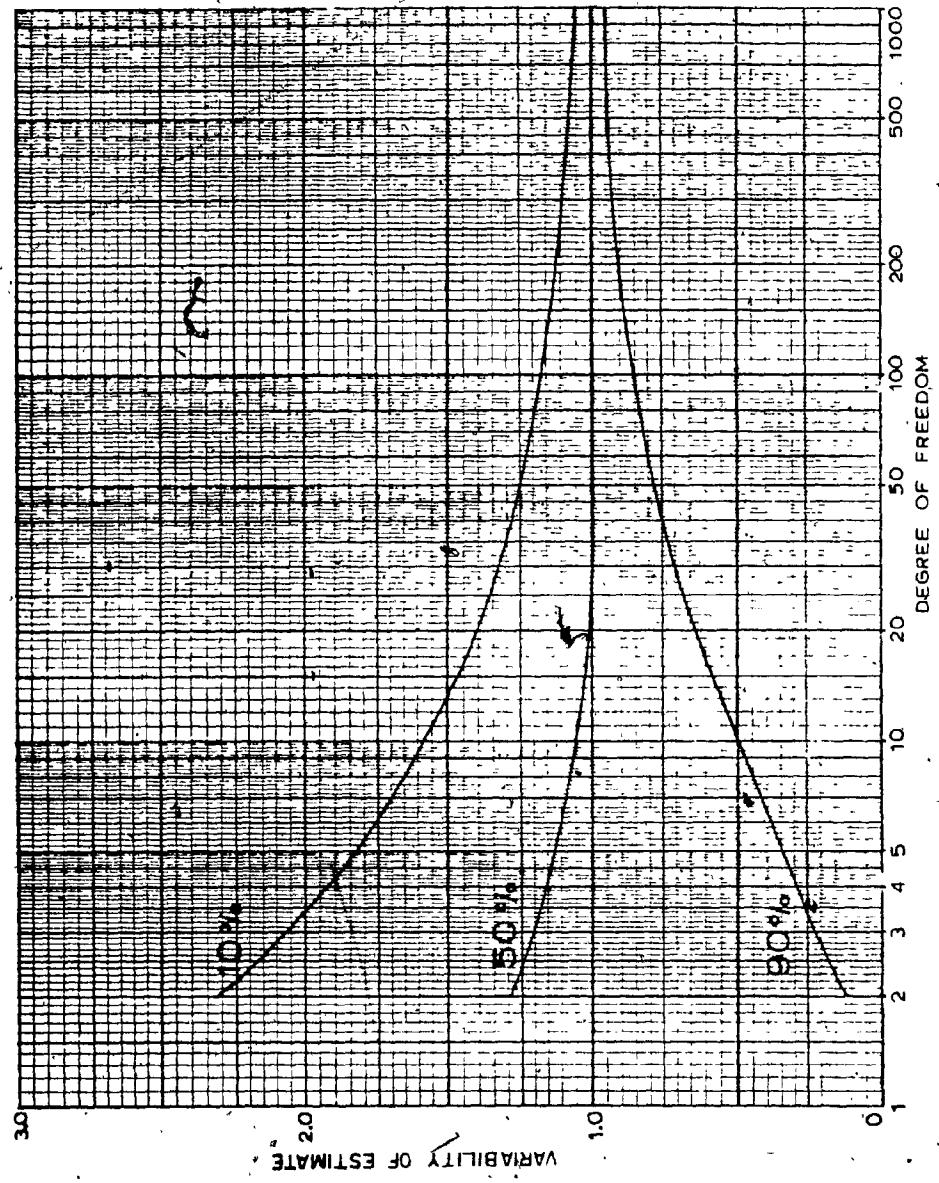


FIGURE 4.3 DEGREES OF FREEDOM VERSUS VARIABILITY OF THE ESTIMATE [35]

purposely designed for good resolution and smoothing characteristics is the GEO spectral window [37]. This window has been designed for application in the frequency domain and the exact form computed to yield an optimum figure of merit ϕ , which is defined by:

$$\phi = \frac{n}{\gamma} \quad (4.23)$$

where n = number of estimates to be smoothed

and γ = number of degrees of freedom of the estimate

The window shape is given by [37]:

$$W(\omega) = \sum_{k=-M}^{M} A_k \frac{\sin [\pi N \omega (1 - \frac{k}{N})]}{N \sin [\pi \omega (1 - \frac{k}{N})]} \quad (4.24)$$

and is shown in Figure 4.5.

This window offers some desirable characteristics for PSD estimates, its width is narrow, side lobe suppression is fairly good, the variance of the estimate is unchanged and at the crossover point the attenuation is only 25%. This means that frequencies which are not integral multiples of the bandwidth Δf , as defined by equation (3.3), are only attenuated by a maximum of $20 \log (1 - 0.25) = -2.5$ db.

Table 4.2 shows some major features of the GEO window along with those for the windows illustrated in Figure 4.4 and the rectangular window. It is seen that the GEO window has a higher side lobe characteristic than both the Hanning and Cosine windows. However, the superior roll-off characteristics and lower maximum attenuation at the crossover point of the GEO window more than compensate for the higher side lobe.

	Highest Side Lobe dB	Roll-off dB/octave	Max. Atten. at Crossover Point dB
GEO	-16	24	-2.5
RECTANGLE	-13	6	-3.92
HANNING	-32	18	-3.18
COSINE	-23	12	-3.01

TABLE 4.2 COMPARISON OF DATA WINDOWS [36]

The GEO window is utilized by the VIBPAC PSD program VPS and its application discussed in Section 4.3(a), on Power Spectrum Computations.

4.3 Analysis Computations

4.3 (a) Mean, Mean Square and Variance Computations

The mean, mean square and variance of the digitized vibration data are computed directly from equations (4.1), (4.3) and (4.5) respectively. The computations are carried out in a single subroutine known as STATS under the VIBPAC system. No estimates of the computational error have been made since these will be due primarily to the bias error inherent in the sampling rate.

4.3 (b) Auto Correlation Computations

The computation of the auto correlation function is performed by the VIBPAC subroutine AUTO by evaluating directly the discrete equivalent of equation (4.6) [21].

$$R(m) = \frac{1}{N-(m-1)} \sum_{i=0}^{N-m-1} x(i)x(i+m) \quad (4.25)$$

Where $m = 0, 1, \dots, M$ & $i = 1, 2, \dots, N$

It is only necessary to compute $R(\tau)$ for positive τ since the function is even about the origin. The number of lags taken is variable but is always very much less than N . Otnes and Enochson [38] suggest that the number of lags can be as high as 20% of N but for large N this would require considerable computing time. The error arising from the use of equation (4.25) is not easy to evaluate but Cooper & McGillam [21] offer the following equation as an approximation to the variance of the estimate.

$$\text{VAR}[R_x(m)] \leq \frac{2}{N} \sum_{k=1}^{M-1} R_x^2(k) \quad (4.26)$$

where M = number of lags to be taken

N = number of data points

and $R(m)$ is obtained from equation (4.25).

After computation of $R(m)$ subroutine AUTO evaluates equation (4.26) on the basis that the maximum possible RMS error cannot be greater than $\text{VAR}[R_x(m)]$. A complete listing of subroutine AUTO is contained in Appendix A. The computational time for this subroutine is quite large when it is used for $M = 50$ and $N = 4096$, the present specification for the VIBPAC programs. However, the root mean square error is generally less than 2% as calculated by equation (4.26) and is essentially unbiased providing the sampling rate held to at least 8 times the maximum frequency content of the signal. Utilization of the Wiener-Khintchine relationship, equation (4.22), is possible to improve computational speed but a considerable increase in computer memory requirements would result.

4.3. (c) Probability Function Computations

Both the probability density function and the probability distribution function are computed by subroutine PDF. The maximum and minimum values of the input array $x(i)$ are found and the range between them divided into the number of intervals that is consistent with statistical requirements. The number of occupancies in each interval are then counted and, for the probability density function, normalized to a percentage of the total number of data points. The number of occupancies is cumulatively summed to produce the probability distribution function.

Based on the assumption that the data are Gaussian distributed and a confidence level of 95% is required it can be shown that [39]:

$$\text{Number of Intervals} = 1.87(N-1)^{2/5} - 2 \quad (4.27)$$

where N = number of data points.

For VIBPAC where $N = 4096$ the number of intervals required is $52.09 - 2 \approx 50$. Thus subroutine PDF is designed to divide the data range into 50 intervals. The statistical validity of the results yielded by subroutine PDF should be examined in the light of equation (4.27) if more than or less than 4096 data points are used.

A complete listing of subroutine PDF is contained in Appendix A.

4.3 (d) Fourier Transform Computations

The finite discrete Fourier transform and the fast Fourier transform were discussed in Section 4.1(d). In general, an FFT algorithm is written to deal with the Fourier transform for a

complex array. This means that two storage locations are required for each point. For a real data array, such as, the digitized vibration time history that we are interested in; the imaginary locations and imaginary computations can be dispensed with. The FFT algorithm [40] used by the VIBPAC system is a modification of one which eliminates the redundant operations entirely. Consequently the amount of computer memory used is only half that which would be required by a routine which evaluated both the real and imaginary components. This is of considerable benefit when utilizing a computer with limited memory such as the DEC PDP-11. The routines used by VIBPAC are designated FFA, for the Fourier transform and FFS for the inverse Fourier transform.

Subroutine FFA evaluates equation (4.13)

$$X(n) = \frac{1}{N} \sum_{i=0}^{N-1} x(i) e^{-\frac{\omega n i}{N}} \quad (4.13)$$

where $x(i)$ is real, $X(n)$ is complex and $i = 0, 1, \dots, N - 1$
and $n = 0, 1, \dots, \frac{N}{2}$

Subroutine FFS evaluates equation (4.14), the inverse of the forward transform:

$$x(i) = \sum_{n=0}^{N/2} X(n) e^{\frac{\omega n i}{N}} \quad (4.14)$$

The Fast Fourier Transform routine is called FFA(M,X) where X is the array of N terms and $N = 2^m$, $m = 3, 4, \dots, 19$. The real vector $x(i)$ is replaced with its finite discrete Fourier transform $X(n)$. The dc ($X(0)$) term is stored in $X(1)$ and the

folding frequency coefficient in $X(2)$. All other terms are returned with the real part in $X(2i+1)$ and the imaginary part in $X(2i+2)$.

The subroutine FFS is the one to one inverse of this procedure and returns the real array where X is entered as described above. It is called as FFS(M, X). Complete listings of these subroutines and the reordering and iteration routines that are required by them are contained in Appendix A.

4.3 (e) Power Spectral Density Computations

These are performed by the VIBPAC program VPS (Vibration Power Spectrum) which makes use of the above mentioned FFA subroutine. The power spectral density is computed in a direct manner with the result being normalized by dividing it by the variance of the input data. Frequency smoothing is employed to improve the variance of the estimates. Essentially, the computational procedure employed is as follows:

- (1) For an $N = 2^P$, $P = 12$ array the finite Fourier transform is computed using the FFA subroutine.
- (2) The GFO spectral window is applied to the raw Fourier transform $X(n)$ using a reformulation of equation (4.24), that is,

$$\tilde{X}(n) = X(n) + \sum_{i=1}^3 a_i (X(n-i) + X(n+i)) \quad (4.28)$$

where $n = 0, 1, \dots, (\frac{N}{2} - 1)$

$$a_1 = -0.1817$$

$$a_2 = -0.1707$$

$$a_3 = -0.1476$$

at the end of the transform the periodicity is used

$$X\left(\frac{N}{2} + n\right) = X(n) \quad (4.29)$$

for values of $(k \pm i)$ less than zero and greater than $N/2$.

(3) The raw power spectral estimates are then computed from

$$G_X(n) = \frac{2}{N} |X(n)|^2 \quad n = 0, 1, \dots, \frac{N}{2} - 1 \quad (4.30)$$

and adjusted for the scale factor by multiplying by $\frac{1}{1.17}$

(4) $G_X(n)$ is then normalized to produce an amplitude which is a measure of its contribution to the variance.

(5) Smoothed estimates are then obtained by averaging ℓ raw estimates to yield:

$$\tilde{G}_X(n) = \frac{1}{\ell} \sum_{j=-(\ell-1)/2}^{(\ell-1)/2} G_X(n+i) \quad (4.31)$$

the spectrum centre frequencies being interpreted as at

$$n = \frac{\ell}{2}, \frac{3\ell}{2}, \dots, \frac{(\ell-1)\ell}{2} \text{ with frequency steps of } \frac{\ell}{N\Delta t} \text{ Hz.}$$

It is worth noting that this procedure lends itself quite readily to the computation of cross spectra and the auto-correlation function. The listing of VPS appears in Appendix A.

In this chapter, a brief introduction is provided on the theory underlying the statistical computations carried out by VIBPAC and a description is included regarding how the individual routines perform their respective computations. In the following chapter the VIBPAC system and the RT-11 software, which is required to operate and run VIBPAC on the DEC PDP-11 computer, is described.

CHAPTER 5

THE 'VIBPAC' SYSTEM

5.1 General Description

The design of VIBPAC was undertaken to provide accurate computation of vibration signal statistics for the study of machinery health monitoring and diagnostic techniques. VIBPAC is a series of computer programs created to provide for the analog to digital conversion, manipulation, storage and statistical analysis of mechanical vibration signals. As well as furnishing the signal statistics the system provides a sound basis for the future development of advanced vibration analysis techniques. A particularly useful feature of the system is that where required the VIBPAC analysis programs communicate with the user to allow control over the analysis parameters. This feature ensures that the accuracy of the results is not compromised as a result of the different characteristics of the input signals.

Vibration signals which are input by analog to digital conversion can be calibrated and integrated to provide data for analysis both in calibrated acceleration units, cm/sec^2 and in calibrated velocity units, cm/sec . VIBPAC provides the capability for operation on any of the data files and its analysis capability includes mean, variance, probability distribution and probability density functions, auto correlation and Power Spectral density. A very important feature of VIBPAC is the fact that all its programs deal with 3 data channels in a form which introduces no time or phase shift between them. This means that the data are in a form which allows the computation of cross-correlation or cross-spectra etc.

The principles used in the design of the analysis programs are those for the analysis of stochastic signals (refer to Chapter 4) and in general the programs have been designed for accuracy of results rather than spectral resolution and range.

The system contains its own library of subroutines, known as VIBLIB, for those which are peculiar to the VIBPAC system. This library is in addition to the FORTRAN and Scientific Subroutine libraries, that are provided with the operating software.

The entire system is contained on one magnetic disc from which the computer can be bootstrapped. The disc is completely self-contained and input to the computer from other discs is not required, even to alter the disc contents.

A users manual has been prepared and is presented in Appendix A. It contains all necessary instructions and information for use of VIBPAC. Figure 5.1 shows the organization of the VIBPAC system and demonstrates the inter-action between the programs, the user, the system data files and the computer system peripherals.

5.2 Operating Environment

VIBPAC has been designed for a DEC PDP-11 computer utilizing the RT-11 (real time) operating software. The system requires the use of the Teletype, Video screen, line printer, DR-11C analog-to digital convertor and one auxiliary disc drive. The VIBPAC system along with all necessary RT-11 programs such as the device handlers, keyboard monitor, Fortran compiler, program editor etc, are contained on the VIBPAC magnetic disc. A master disc, as a back-up, contains copies of the entire system and is designed for use only when problems are experienced with the user disc or when it is necessary to record a copy of a program on it for back-up purposes.

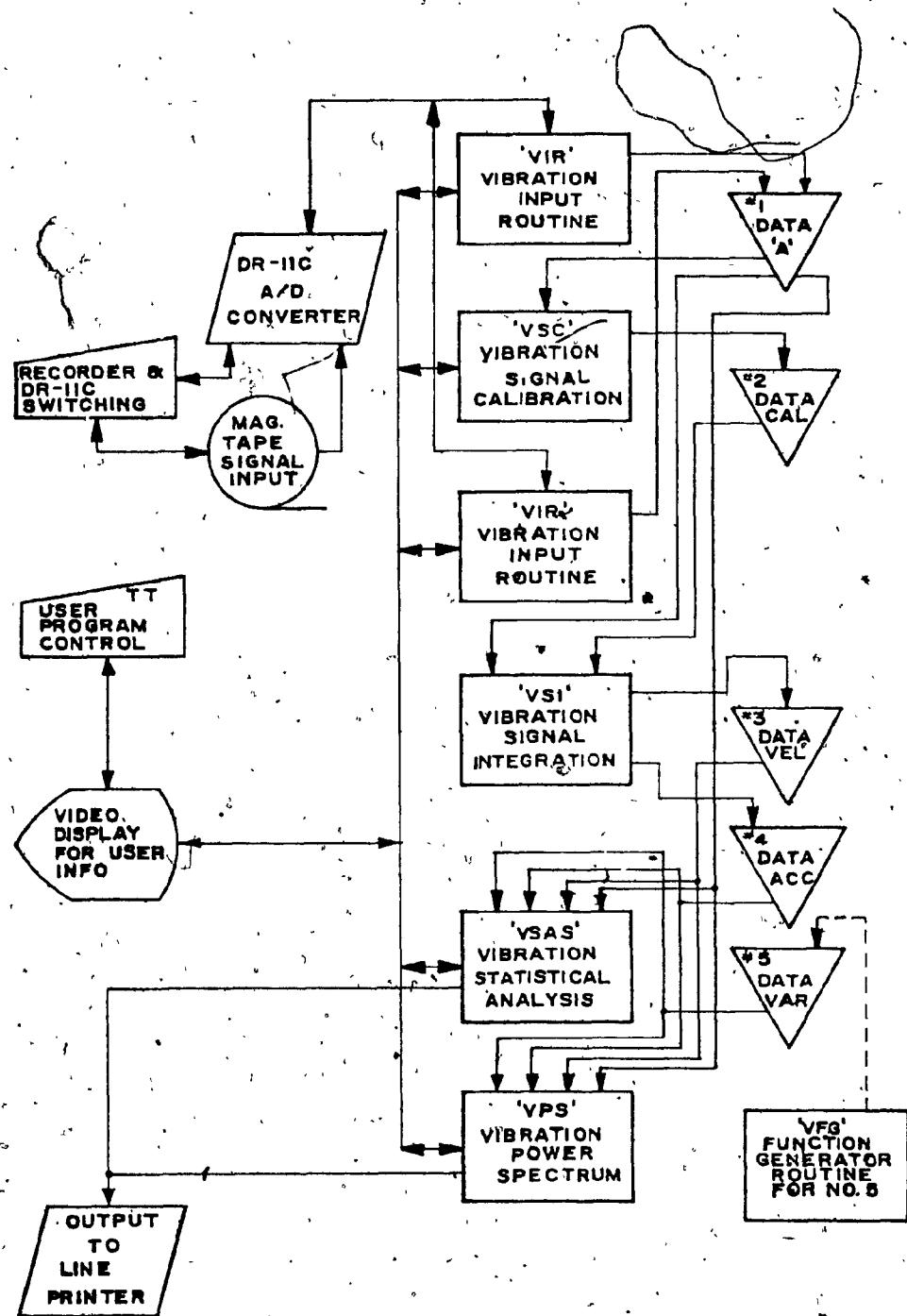


FIGURE 5.1 RT-II VIBPAC SYSTEM ORGANIZATION

The use of a single disc for the entire system reduces the complexity of operational commands, providing the system is bootstrapped from this disc. All communication takes place through the Video screen.

VIBPAC operates in a single job environment which allows full use of all the available PDP-11 memory. This amounts to 28K after approximately 4K has been deducted for device handlers. Each VIBPAC program uses virtually all the core available and this is the only major restriction on the range of the analysis.

5.3 User Features

The VIBPAC system allows the user to input analysis parameters prior to running a program and thus provides versatility of operation. For example, the user communication routine, UCOM contained in the system library is run each time VSAS or VPS is run. The user inputs the number of the file the program is required to operate on, the number of data points for analysis, the running hours of the machine under analysis, a data set identification and decides whether the results should be plotted on the line printer. If a file number is entered that does not contain valid data for that type of analysis an error message is displayed on the video screen and the program is terminated. This error message is show in Figure 5.2.

```
*****  
ANALYSIS ATTEMPTED ON ILLEGAL FILE # 8  
PROGRAM TERMINATED  
*****
```

FIGURE 5.2 ERROR MESSAGE FOR ILLEGAL FILES

The Vibration Signal Calibration program, VSC, requires only that the user input the calibration signal level for each of the three channels. This is because VSC operates only on the raw data file and sets up the calibration data file. The Vibration Signal Integration program, VSI, is the only one which does not require any user input since it is designed only to take raw data operate on it with calibration information from the calibration data file and integrate it.

In addition to this communication with the user subroutine PDF and subroutines PLOT and PLOT3 contain scaling routines. If the input data amplitude is outside the maximum scale value an error message is printed and the program continues with the next computation.

ERROR IN FULL SCALE VALUES-SUBROUTINE PLOT TERMINATED

FIGURE 5.3 TYPICAL ERROR MESSAGE FOR SCALING

At the start of any analysis, i.e. each time the VIBPAC disc is bootstrapped, the user is required to input the current date using the RT-11 system monitor. This date is required by all VIBPAC system analysis programs that output to the line printer VIZ; VSAS, VPS, VSC and VSI. In addition the RT-11 system uses the date to log file access. Complete instructions for using VIBPAC are contained in Appendix A along with source program listings. Enough information is

furnished to allow a user to operate the entire system providing the RT-11 system manuals [41, 42, 43] have been studied.

5.4 Transfer to Other Environments

All programs are written in ASSEMBLER or FORTRAN so that their use on other computer systems is possible. The only changes that may be required are the device numbers and the file names depending on what the conventions employed by the new system are. All program and subroutine names would have to be checked against the list of reserved words. This does not apply to FORTRAN supplied functions. The RT-11 system subroutines DAT and ASSIGN may have to be replaced by their equivalent names on the new system.

The compile and link procedures for the VIBPAC programs are unique to the RT-11 system. Thus the vibration subroutine library VIBLIB would certainly have to be recompiled on a new system because the library structure would be different in terms of entry points and look-up. Since all programs are included on the disc in source form, none of these alterations should pose a serious problem to a user familiar with the new system.

The only program which would not be usable on another system is the Vibration Input Routine, VIR, since this program is written to control the DR-11C analog to digital converter attached to the PDP-11 system. A program would have to be designed to suit the system and its analog to digital convertor. For the remainder of the VIBPAC programs to be usable the output data file structure must remain the same. The transfer of the system to another environment should only be undertaken by a user who is familiar with both the VIBPAC system and the new environment.

CHAPTER 6

DISCUSSION OF RESULTS AND FUTURE DEVELOPMENT

6.1 Selected Results

The VIBPAC system has been subjected to numerous checks for accuracy and correct operation using both deterministic and random test data. The analysis programs VSAS and VPS produced correct and accurate results in all cases. Due to the limitation of space and since the user of VIBPAC will want to test the system with data designed for that purpose, only some selected results have been included for illustration purposes. These results, for a square wave test signal and for some typical vibration data, are contained in

Appendix B.

The square wave test signal was selected because it has very distinctive characteristics associated with its auto-correlation function and its power spectrum. The autocorrelation function is triangular with the same period as the square wave and has an amplitude of A^2 , where A is the amplitude of the square wave. The power spectral density for a square wave exhibits frequency components at 1, 3, 5..... etc times the fundamental frequency with an amplitude attenuation of 12 db/octave. The square wave (data set: TST1) used to produce the results in Appendix B was generated by a program written for this purpose. This was to ensure as great an accuracy as possible for the test signal. Examination shows that VSAS and VPS produce the correct results within very reasonable limits. For example, the standard deviation of a square wave of amplitude 1000 is also 1000. VSAS computes this as 1000.12 showing an error of only 0.012 per cent. The probability density function shows, correctly,

that 50% of all amplitudes occur at -1000 and that 50% occur at +1000. The probability distribution function shows that there is a constant probability of 0.5 that an amplitude will be less than any value between -1000 and +1000. The autocorrelation coefficient function is of the typical triangular form and has the same period as the test signal of 0.56 msec. Its amplitude at $\tau = 0$ is unity, having been normalized by dividing it by the variance, σ^2 . Thus $\sigma^2 = A^2$ which is seen to be correct within the calculated maximum RMS error of 1.3 per cent.

The results from VPS use the same square wave of amplitude 1000 but with the period increased from 0.56 msec to 2.64 msec (data set: TST2). This maintains a similar analysis bandwidth of approximately 5 Hz to 3 kHz and ensures that at least four components of the fundamental frequency appear in the results. It may be seen that VPS produces frequency components at 378.8, 1134.9, 1891.0 and 2647.1 Hz, whose amplitudes do not fall-off at exactly 12 dB/octave. The actual components occur at 378.8, 1136.4, 1893.9 and 2651.5 Hz. The differences are due to the averaging performed by VPS, which results in the filter centre frequencies not coinciding exactly with the actual components. Despite this, however, the amplitude attenuation is still fairly accurate, giving a loss of only 2 dB at 35 dB below the fundamental amplitude. Figure 6.1 illustrates this.

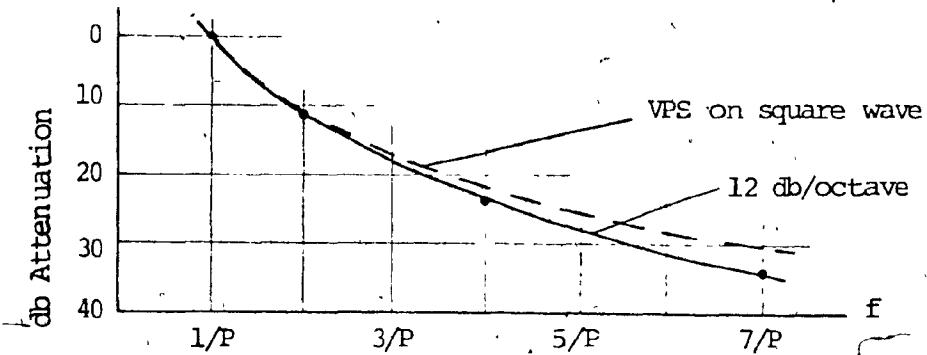


FIGURE 6.1 AMPLITUDE ATTENUATION PRODUCED BY VPS

The vibration data (data set: MG7) was taken from a bearing housing of a 1-1/2 kW motor generator set. The MG set is known to be in good condition as a result of a major overhaul when the unit was fitted with new bearings, balanced and carefully aligned. Data set: MG7 was recorded after 2112 hours of machine operation at a full load of 1500 watts, using the acquisition system described in Chapter 3. Machine operating speed was 1760 RPM and recording speed was 15 ips. The high and low pass filters on the charge amplifiers were used to preprocess the data for a frequency bandwidth of 10 Hz to 3 kHz.

Analysis of the data shows the typical mixture of random and periodic components that one expects from any rotating machinery. The probability density function is almost gaussian in shape with the addition of the 'humps' associated with periodic amplitudes. The probability distribution function confirms the gaussian nature of the data. Insufficient resolution prevents identification of the periodic amplitudes however. The auto correlation coefficient function, as indicated in Chapter 4, is a series of rapidly decaying periodic components indicating less and less correlation in the data as τ increases from zero. The power spectrum shows that a broad range of frequencies, principally between 1 kHz and 2kHz, contribute to the signal variance and that no frequency stands out as being clearly characteristic. This is to be expected for two reasons. The first, is that if the machine is in good condition then there are no faults to produce high amplitudes of vibration at a particular frequency. The second reason is that the spectrum is averaged over adjacent frequencies in order to reduce the variability of the estimate. It is also worth noting that this averaging process precludes the sum of the contributions to the variance totalling 100 per cent.

6.2 Future Development

The vibration analysis capability of the VIBPAC programs is adequate to provide basic statistical parameters but is restricted in range and frequency resolution. As discussed earlier this is due to the limited memory available for the DEC PDP-11 computer. In order to utilize the full potential of the VIBPAC system a considerable increase in computer memory is required. It is envisaged that 100k, rather than the present 28k, would be adequate. This would allow a frequency analysis range of up to approximately 10kHz, an improvement of three times the present capability.

The use of the line printer for analysis program outputs generates a considerable number of pages. This could become a disadvantage if a large number of signals were to be analyzed. The use of a digital plotter, such as the Calcomp 663, for the program outputs would improve this situation. The extremely fine resolution of this type of plotter would allow the output to be plotted on two pages or less without a loss of accuracy. Thus for a three channel analysis only 6 or 7 pages would be generated rather than the present twenty two pages.

Further development of the diagnostic capability of the VIBPAC system is foreseen in the form of programs written to furnish more functions. For example second order probability distributions, cross-correlation, cross-spectra, etc. In addition the versatility of the system can be improved by providing a new program to handle the input of velocity or displacement vibration data. The present structure of VIBPAC makes the provision of additional programs straightforward since they need only be written to operate on the existing data files.

Development of the VIEPAC system along the lines suggested is recommended to improve versatility and to provide a more comprehensive system for the study and analysis of mechanical vibration signals.

REFERENCES

1. Davies, G.L., "Magnetic Tape Instrumentation". McGraw-Hill Book Company, Inc. New York, 1961.
2. Magrab, E.B. and Blomquist, D.S., "The Measurement of Time Varying Phenomena". John Wiley and Sons, Inc. Toronto, 1971.
3. Pear, C.B., "Magnetic Recording in Science and Industry". Reinhold Publishing Corporation New York, 1967.
4. Glew, C.A.W. and Watson, D.C., "Vibration Analysis as a Maintenance Tool in the Royal Canadian Navy". Trans. of the Institute of Marine Engineers, Canadian Div., Supplement No. 32, June 1968.
5. Xistris, G.D., "Vibration Monitoring of a 750kW Gas Turbine Generator". SAE Paper 730932, 1973.
6. Danlow, M.S. and Badgley, R.H., "Early Detection of Defects in Rolling-Element Bearings". SAE Paper 750209, 1975.
7. Nittinger, R.H., "Vibration Monitoring and Analysis as a Maintenance Tool". ASME Paper 70.PET-2, 1970.
8. Glew, C.A.W., "The Octave Band Analyser as a Machinery Defect Indicator". ASME Paper 71.DE.47, 1971.
9. Sankar, T.S. and Osman, M.O.M., "Profile Characteristics of Manufactured Surfaces using a Random Function Excursion Technique". J. Eng. Ind. ASME, Vol. 97 pp. 190 - 202, 1975.
10. Cooper, G.R. and McGillam, C.D., "Probabalistic Methods of Signal and System Analysis". Holt, Reinhart and Winston, Inc. New York, 1970, pp. 95 - 100.
11. Harris, C.M. and Crede, C.E., "Shock and Vibration Handbook". Second Edition, McGraw-Hill Book Company, Inc. New York, 1976.,
p 27 - 7.

REFERENCES (Cont'd)

12. Crandall, S.H. and Mark, W.D., "Random Vibration in Mechanical Systems". Academic Press, Inc. New York, 1963, p22.
13. Stens, R.K. and Enochson, L., "Digital Time Series Analysis". John Wiley and Sons. New York, 1972, p23.
14. Broch, J.T., "Mechanical Vibration and Shock Measurements". Brüel and Kjaer, Denmark, 1972, p256.
15. IBID 10, p114
16. Kelly, R.D. and Richman, G., "Principles and Techniques of Shock Data Analysis". The Shock and Vibration Information Centre. United States Department of Defence, 1969, pp 121 - 122.
17. IBID 16, pp 150 - 153
18. IBID 16, p 123
19. IBID 13, p 4
20. IBID 10, pp 43 - 44
21. IBID 10, pp 107 - 116
22. IBID 14, p 23
23. IBID 10, P 37
24. IBID 10, pp 27 - 43
25. Papoulis, A., "The Fourier Integral and its Applications". McGraw-Hill Book Company, Inc. Toronto, 1962, p 7.
26. IBID 13, pp 11 - 22
27. Cooley, J.W., Lewis, P.A.W. and Welch, P.D., "The Finite Fourier Transform". IEEE Transactions on Audio and Electro Acoustics. Vol. AU-17, No. 2 June. 1969.

REFERENCES (Cont'd)

28. Jenkins, G.M. and Watts, D.G., "Spectral Analysis and its Applications". Holden-Day, Inc. San Francisco, 1967, pp 17 - 25.
29. IBID 10, p 18
30. IBID 13, p 139
31. IBID 28, pp 209 - 211
32. IBID 13, pp 206 - 217
33. IBID 28, pp 252 - 255
34. IBID 13, pp 6 - 11
35. IBID 28, p 82
36. Harris, F.J., "Windows, Harmonic Analysis and the Discrete Fourier Transform". IEEE Proceedings, August 1976.
37. IBID 13, pp 286 - 297
38. IBID 13, p 227
39. IBID 13, p 381
40. Bergland, G.D., "A Radix - Eight Fast Fourier Transform Subroutine for Real-Valued Series". IEEE Transactions on Audio and ElectroAcoustic. Vol. AU-17, No. 2, June 1969.
41. RT-11 System Reference Manual. DEC-11-DRUGA-C-D. Digital Equipment Corporation. Massachusetts, 1975.
42. RT-11 Fortran Compiler and Object Time System: Users Manual. DEC-11-LRFFPA-A-D. Digital Equipment Corporation. Massachusetts, 1974.
43. PDP-11 Fortran Language Reference Manual. DEC-11-LFLRA-A-D. Digital Equipment Corporation. Massachusetts, 1974.

APPENDIX A

VIBPAC

USER'S MANUAL AND PROGRAM DOCUMENTATION

VIBPAC

USER'S MANUAL AND PROGRAM DOCUMENTATION

PROGRAMS AND VIBPAC SYSTEM DESIGN BY R.J. WILSON

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MONTREAL

1977

INTRODUCTION

This manual is designed to provide the necessary information and program listings to enable use of VIBPAC, the vibration data analysis and processing package; on the DEC PDP-11 computer. It is assumed that the user is familiar with the PDP-11 computer and the RT-11 operating environment. Familiarity with the following list of references is suggested as a minimum requirement before use of the VIBPAC system.

(1) RT-11 SYSTEM REFERENCE MANUAL (Chapters 1 through 7)

DEC-11 ORUGA-C-D, Digital Equipment Corporation,
Massachusetts, June 1975.

(2) RT-11 FORTRAN Compiler and Object Time System Reference
Manual. DEC-11-LRFPA-A-D.

And Addendum DEC-11-LRFPA-A-DN1, Digital Equipment
Corporation, Massachusetts, June 1974.

(3) PDP-11 FORTRAN Language Reference Manual

DEC-11-LFLRA-A-D, Digital Equipment Corporation,
Massachusetts, June 1974.

(4) Wilson, R.J. The Design and Development of an
Acquisition System and a Computerized Processing Package for
the Study of Machinery Vibrations. A Thesis in the Faculty
of Engineering. Concordia University, Montreal, 1977.

VIBPAC has been designed specifically for the handling and analysis of mechanical vibration data. Three channels of data are handled simultaneously so that correlation between channels is always possible. Either acceleration or velocity data can be analyzed while the vibration input to the analog to digital converter has to be in the form of acceleration. If it is desired to input velocity or displacement data new handling and calibration programs will be required to supplement the present VSI and VSC. The analysis programs and subroutines remain the same, as does the file structure. The analysis programs output to the line printer and make use of the condensed type option. They also communicate with the user and request information when necessary, through the video screen. Most programs contain error messages to inform the user of excessive amplitudes in the data. In general, all programs which deal with data files use unformatted direct access read and/or write statements. Table A1 lists all the programs and subroutines of which VIBPAC is comprised. Figure A1 shows schematically how the analysis programs, data files and peripherals are interrelated.

The VIBPAC system is contained on a single disc (#16) along with all necessary software for system operation. A second disc (#15) contains a complete copy of disc #16. This disc is the back-up and should NEVER be used to run programs or operate the system. The use of a single disc for VIBPAC greatly simplifies the operation and the command structure necessary to run computer programs, providing the computer is bootstrapped from the disc located in unit RK 1: In the discussions that follow the conventions adopted are those of the PDP-11 system manuals. User response is not underlined while that of the computer is.

TABLE A1 RT-11 VIBPAC PROGRAM DIRECTORY

(1) EXECUTABLE PROGRAMS - prefix V. RT-11 default extension .SAV

VIR.SAV	Vibration Input Routine
VSC.SAV	Vibration Signal Calibration Routine
VSI.SAV	Vibration Signal Integration Routine
VSAS.SAV	Vibration Statistical Analysis Routine
VPS.SAV	Vibration Power Spectrum Routine
V1.SAV	VIBRATION Data File #1 Disposition Routine

V5.SAV	VIBRATION Data File #5 Disposition Routine
--------	--

(2) SOURCE PROGRAMS Prefix V. Extension FIN

All programs require linking with

VIBLIB and FORLIB unless otherwise noted.

PCMVO2.FIN Programmed channel Multiplexer Version 2 used to build VIR.SAV when linked.

VSC.FIN Vibration Signal Calibration Main program. Does not require linking to VIBLIB.

VSI01.FIN Vibration Signal Integration and data manipulation using subroutine IFFT. Option 1 to build VSI.SAV

VSI02.FIN Vibration Signal Integration and data manipulation using subroutine IQSF. Option 2 to build VSI.SAV.

VSAS2.FIN Vibration Statistical Analysis Version 2 used to build VSAS.SAV.

TABLE A1 (cont'd)

<u>VPS.FIN</u>	Vibration Power Spectrum used to build <u>VPS.SAV.</u>
<u>VFILE.FIN</u>	Vibration File #1 Disposition used to build <u>VI.SAV.</u>
<u>VFILE5.FIN</u>	Vibration File #5 Disposition used to build <u>VI.SAV.</u>
(3) OBJECT LIBRARIES	Extension <u>.OBJ</u> . These libraries are required for the <u>LINK</u> procedures after source program compilation.
<u>VIBLIB.OBJ</u>	VIBPAC system library contains all subroutines that are peculiar to VIBPAC (see listing below).
<u>FORLIB.OBJ</u>	RT-11 FORTRAN subprogram library
<u>SSPGT.OBJ</u>	RT-11 Scientific subroutine package and graphics support library.
(4) SUBROUTINES -	source versions are on disc with either a .FIN or .ASS extension. Object versions are contained in <u>VIBLIB.OBJ</u> .
<u>FFA.FIN</u>	Fast Fourier Analysis used by VPS and <u>VSI01</u> .
<u>FFS.FIN</u>	Fast Fourier Synthesis used by <u>VSI01</u>
<u>R2TR.FIN</u>	Radix 2 Iteration subroutine used by FFA and FFS
<u>R4TR.FIN</u>	Radix 4 Iteration Subroutine used by FFA

TABLE A1 (cont'd)

R8TR.FTN	Radix 8 Iteration Subroutine used by FFA
R4SYN.FTN	Radix 4 Synthesis subroutine used by FFS
R8SYN.FTN	Radix 8 Synthesis subroutine used by FFS
ORD 1.FTN	Reordering subroutine No. 1 used by FFA and FFS
ORD 2.FTN	Reordering subroutine No. 2 used by FFA and FFS
PLOT.FTN	Line printer plotting routine. Single channel used by VSAS
PLOT3.FTN	Line printer plotting routine. Three channels.
INPUT.FTN	Sampling parameter user communication routine. Used by VIR.
ADJUST.FTN	Sampling parameter adjustment routine used by VIR.
STP.ASS	Analog to digital convertor control routine used by VIR
TITLE.ASS	Title input subroutine used by VIR
LBUF.FTN	Line printer buffer clearance routine. (Required in some programs due to an existing fault in the RT-11 LP Handler (LP-SYS) which occasionally does not output buffer contents at completion of print operations).

TABLE A1 (cont'd)

MGSET.FIN	Title page format routine used by VSAS and VPS
AUTO.FIN	Auto correlation coefficient function routine used by VSAS.
UCOM.FIN	Analysis parameter user communication routine used by VSAS and VPS
STATS.FIN	Statistical computation routine. Used by VSAS, VPS, IFFT and IQSF.
PDF.FIN	Probability Density and Probability Distribution function computation routine. Used by VSAS.
IFFT.FIN	Integration routine VIA Fast Fourier Transform. Used by VSIØ1.
IQSF.FIN	Integration routine via RT-11 system subroutine QSF. Used by VSIØ2.

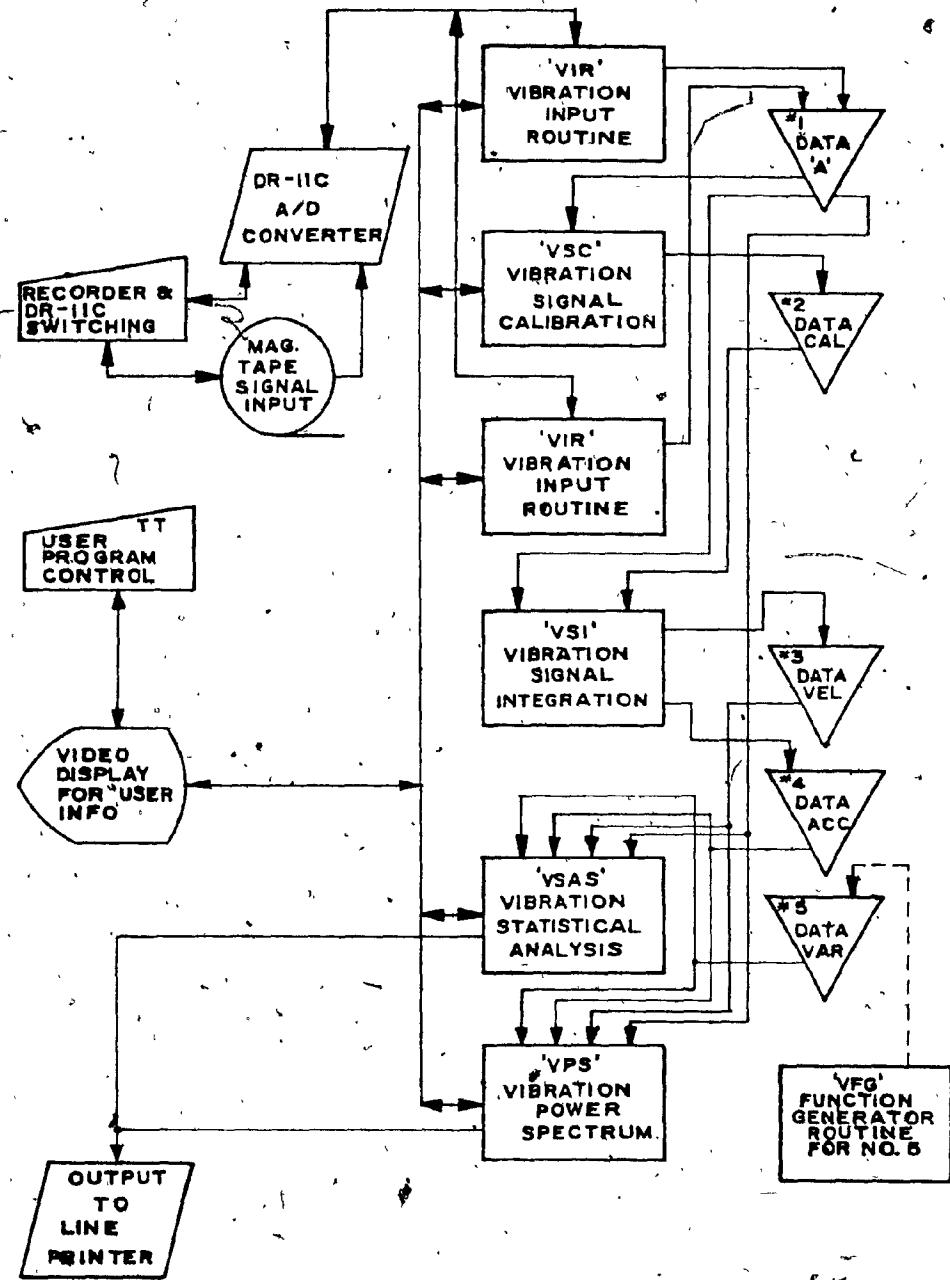


FIGURE A.1 RT-II VIBPAC SYSTEM ORGANIZATION

BOOTSTRAPPING PROCEDURE

The following procedure should be followed whenever VIBPAC is to be used. If this is carried out as shown the VIBPAC disc will be

- mounted correctly for data file designation and
- any executable program can be run by using the command format; R name.

1. Press HALT
2. Mount disc on RK0:
3. Enter address 773010
4. Raise HALT
5. Press START
6. Terminal should respond with:

RT-11SJ V02B-05

7. In response to the keyboard monitors dot enter R PIP
8. Terminal should type *
9. Remove disc from RK0: and mount on RK1:/
10. Enter RK1:/0
11. Terminal again responds with:

RT-11SJ V02B-05

the computer is now bootstrapped from RK1:

12. Enter GT ON in response to keyboard monitors dot, all display will be directed to the video screen.
13. Enter the current date viz:

DAT 22-APR-77

Note that internally the date is required by all VIBPAC programs and is used to record access to files.

DATA INPUT

Data is input by running the Vibration Input Routine, VIR.

Input signals can be from any source but generally will be from playback of the tape recorder. Signal inputs are connected to the interface unit which is wired directly to the analog to digital convertor. The channel selection switch on this unit should be set to the highest input channel number. Note that channels are numbered 0 through 7 on the interface while VIR numbers channels 1 through 8 . The ready/go switch should be set in the 'ready' position. VIR can handle up to 8 channels of data. The maximum sampling frequency is 80 kHz if a single channel is used and 26.6 kHz if three channels are used. VIR will request, through the video screen, the number of channels to be input and the sampling interval, in microseconds, for each channel. After the user has input these VIR will pause until the ready/go switch on the interface is switched to 'go'. If the switch was previously at, 'go' VIR will commence sampling immediately whether there is a signal present or not. After sampling has finished the user has the option of entering a title. The sampled data is stored on disc in file #1, DATA.A in the format shown in Figure A2.

R VIR

NUMBER OF CHANNELS (MAX, 8)=3

PERIOD (MICRO-SEC) CHANNEL# 1 = 38

PERIOD (MICRO-SEC) CHANNEL# 2 = 38

PERIOD (MICRO-SEC) CHANNEL# 3 = 38.

ADJUSTED PARAMETERS:

SAMPLING PERIOD CHANNEL# 1 = 37.50 MICRO-SEC
-- FREQ' -- = 26.67 KHZ

SAMPLING PERIOD CHANNEL# 2 = 37.50 MICRO-SEC
-- FREQ' -- = 26.67 KHZ

SAMPLING PERIOD CHANNEL# 3 = 37.50 MICRO-SEC
-- FREQ' -- = 26.67 KHZ

DATA IS ON DISK. YOU CAN WRITE YOUR COMMENTS NOW.
WHEN FINISHED TYPE (ESC) AND RETURN.

CALIBRATE SIGNALS FOR DATA SET MG1.

CALIBRATE SIGNALS FOR DATA SET MG1.

R V1

CALIBRATE SIGNALS FOR DATA SET MG1.

NOCH = 3

ADDRESS = 600

ADDRESS = 5605

ADDRESS = 5606

ADDRESS = 10604

ADDRESS = 10605

ADDRESS = 15600

INTERVAL = 37.50

INTERVAL = 37.50

INTERVAL = 37.50

FIGURE A2 VIBPAC DATA FILE STRUCTURE

Applicable to all data files used by VIBPAC

Record size: 2 words

RECORD NO.

CONTENTS

1 - 100	Title or Comments
101 - 499	Unused
500 - 507	Volts/g (For File #2, DATA.CAL only)
508 - 549	Unused
550 - 567	Start & End Addresses for Channels 1 through NOCH (Maximum 8). Consecutive Viz: Start Address CH1 End Address CH1 Start Address CH2 etc.
568 - 569	Unused
570 - 577	Sample Periods (Microseconds for Channels 1 through NOCH (Maximum 8). Consecutive
578 - 579	Unused
580	Number of Channels Used. NOCH
581 - 599	Unused
600 - 15600	DATA. Starting with Channel 1 and evenly divided between all channels used. Number of records depends on number of channels. If only one channel is used then file contains 15000 data points. (NB: File #2, DATA.CAL ends at record 600).

SIGNAL CALIBRATION

Signal calibration is accomplished by first establishing a data file which contains the necessary information required for calibration of further incoming signals. This file, #2 - DATA.CAL is created by running VSC (Vibration Signal Calibration). VSC expects file #1 DATA.A to contain three channels of a sinusoidal calibration signal. On request the user enters the peak level of these signals in 'g' units ($1g = 980.61 \text{ cm/sec/sec}$) VSC then uses this input with the contents of file #1 to establish a calibration factor for each channel in volts/g. File #2 is then created using these calibration factors. These factors will be used to calibrate all future incoming signals unless VSC is used again. On completion VSC outputs the following to the line printer:

RT-11 VIBPAC VIBRATION SIGNAL CALIBRATION V01-A

DATA FILE # 2 NOW CONTAINS THE FOLLOWING PARAMETERS:

CHANNEL 1	1.036	VOLTS PER G
CHANNEL 2	1.056	VOLTS PER G
CHANNEL 3	1.036	VOLTS PER G

The second step in calibration of the signals is achieved by running VSI (VIBRATION SIGNAL INTEGRATION). VSI assumes that File #1 contains three channels of raw vibration data and that File #2 contains valid calibration factors for each channel. VSI then uses this information to create calibrated acceleration in File #3 'DATA.ACC' with units cm/sec/sec. This calibrated acceleration data is then integrated and stored in File #4, DATA.VEL with units of cm/sec. It should be noted that VSI removed the mean from both the velocity and acceleration signals, since any mean that is present is solely due to sampling and is not a signal characteristic. VSI requires no user input and on completion outputs the following message to the line printer:

RT-11 VIBPAC VIBRATION SIGNAL INTEGRATION V02-A.

DATA FILE #3 NOW CONTAINS CALIBRATED ACCELERATION SIGNAL UNITS CM/SEC/SEC
DATA FILE #4 NOW CONTAINS CALIBRATED VELOCITY SIGNAL UNITS CM/SEC

There are two integration subroutines available for compilation with VSI, each of which has its own advantages and disadvantages. These are IQSF and IFFT both are contained in the VIBPAC system library VIBLIB. Subroutine IQSF uses the scientific subroutine package (SSPGT) integration routine which involves a variation of Simpsons Rule and requires at least twice the memory requirements of the array being integrated.

Subroutine IFFT on the other hand requires half the memory space although it is somewhat slower than IQSF. IFFT uses the VIBPAC Fast Fourier Analysis and Fast Fourier Synthesis routines to perform the integration. At present VSI is compiled using IQSF and is probably the best one to use until such time that the number of data points become too large.

SIGNAL ANALYSIS

Once the data files have been created and calibrated using VIR, VSC and VSI analysis can be performed upon them. The two VIBPAC analysis programs are VSAS (Vibration Statistical Analysis) and VPS (Vibration Power Spectrum). In order that the frequency bandwidth remain the same these programs require that the sampling interval between data points be different. The sampling interval for VPS must be between 4 and 5 times that used for VSAS. This is necessary to maintain accuracy in the absence of a large computer memory. Effectively this means running VIR & VSI prior to use of VSAS and again prior to VPS.

(i) Statistical Analysis

This is accomplished by running VSAS on either File #3 or File #4. (File #1 and File #5 are also valid options for VSAS but caution should be exercised in calling for an analysis on them). VSAS requests that the user enter certain parameters. These are:

- (a) File number
- (b) Data set identification
- (c) The number of machinery running hours
- (d) The number of data points to be analyzed and
- (e) Whether plotting is desired on the line printer

If analysis on file #5, DATA.VAR is requested VSAS will ask for the contents to be verified before proceeding.

VSAS will provide an analysis of three data channels and if the plotting option is included it will produce 22 pages of line printer output. Running time is approximately 25 minutes. The analysis consists of maximum, minimum, mean, standard deviation, probability density function, probability distribution function and the auto correlation coefficient function for each channel.

(ii) Power Spectrum

This is accomplished by running VPS on either File #3 or File #4. VPS uses the same user communication routine as VSAS and except for plotting on the line printer has the same options open to it. Output is directed to the line printer and produces four pages for a complete three channel analysis. Running and output time is approximately 5 minutes. The power spectrum amplitude is the averaged contribution to the variance of the vibration signal in percent and is computed via FFT.

R VSAS

ENTER DATA SET IDENTIFICATION.FMT A4
MG7

ENTER MACHINE RUNNING HOURS.FMT F7.1
2112.0

ENTER FILE NUMBER.FMT I2
4

ENTER NUMBER OF DATA POINTS.FMT I6
4096

IF YOU WISH TO PLOT RESULTS ON LP ENTER 1

1

COMPILE AND LINK PROCEDURES

The compilation and link procedures required to produce an executable program on disc are greatly simplified by the existence of the VIBPAC subroutine library VIBLIB. All VIBPAC subroutines are contained in this library. Essentially the procedure is to run the compiler required e.g. FORTRAN on the source program and then to link the resulting object module with VIBLIB, as shown by the following example.

TO CREATE THE VIBRATION INPUT ROUTINE:

```
.R FORTRAN  
*VIR=PCMVO2.FTN  
*^C  
  
.R LINK  
*VIR=VIR,VIBLIB/F  
  
*^C
```

The RT-11 scientific subroutine package and the graphics support package are contained in one library, SSPGT, so that if graphics capability is added to the VIBPAC system in the future no other libraries are required. Only one VIBPAC program at present requires linking to SSPGT. This is the vibration signal integration routine VSI02.FIN.

TO CREATE THE VIBRATION SIGNAL INTEGRATION ROUTINE:

```
.R FORTRAN  
*VSI=VSI02.FTN  
*^C  
  
.R LINK  
*VSI=VSI,VIBLIB,SSPGT/F
```

RT II - VIBPAC, VIBLIB DIRECTORY

MODULE	ENTRY/CSECT	ENTRY/CSECT	ENTRY/CSECT
RANGE	RANGE		
RBSYN	RBSYN		
R4SYN	R4SYN		
FFA	FFA		
R2TR	R2TR		
R4TR	R4TR		
R8TR	R8TR		
ORD1	ORD1		
ORD2	ORD2		
PLOT3	PLOT3		
INPUT	INPUT		
ADJUST	ADJUST		
PCW8	STP		
MAIN	TITLE		
LBUF	LBUF		
FFS	FFS		
MSET	MSET		
AUTO	AUTO		
UCOM	UCOM		
STATS	STATS		
PLOT	PLOT		
PDF	PDF		
IFFT	IFFT		
IQSF	IQSF		

RT-II VIBPAC, USER DISC DIRECTORY

30-APR-77			
STP ASS	5	LP LST	0 19-MAR-77
TITLE ASS	2	PDF FTN	3 17-APR-77
TSLK RJM	2	PLOT FTN	6 17-APR-77
TSLK FTN	2	LIBFOR OBJ	237 2-APR-77
RANGE FTN	2	SYSLIB DBJ	37 2-APR-77
PLOT3 FTN	7	DATA A	122 9-APR-77
DATA CAL	5 9-APR-77	DATA ACC	115 9-APR-77
VSC FTN	4 16-JAN-77	R2TR FTN	1 9-APR-77
VSC SAV	58 16-JAN-77	R4TR FTN	1 9-APR-77
MONITR SYS	45 12-JAN-77	ORD1 FTN	1 9-APR-77
DP SYS	2 12-JAN-77	ORD2 FTN	3 9-APR-77
RK SYS	2 12-JAN-77	VSITDS BUG	5 8-APR-77
RF SYS	2 12-JAN-77	STATS FTN	1 9-APR-77
TT SYS	2 12-JAN-77	VSI SAV	94 30-APR-77
LIP SYS	2 12-JAN-77	R8TR FTN	9 9-APR-77
BK SYS	6 12-JAN-77	VPS FTN	7 17-APR-77
DX SYS	2 12-JAN-77	VPS TST	7 17-APR-77
BT SYS	2 12-JAN-77	DATA VEL	115 9-APR-77
CR SYS	3 12-JAN-77	VPSTST SAV	87 17-APR-77
RKMFB SYS	2 12-JAN-77	VSI01 FTN	4 30-APR-77
HT SYS	6 12-JAN-77	VSI02 FTN	4 30-APR-77
MM SYS	6 12-JAN-77	VSAS2 FTN	9 30-APR-77
PR SYS	2 12-JAN-77	WIR SAV	84 30-APR-77
PP SYS	2 12-JAN-77	WFILI FTN	2 17-APR-77
CT SYS	5 12-JAN-77	WFIL5 FTN	2 17-APR-77
DS SYS	2 12-JAN-77	VSAS2 TST	9 17-APR-77
FORTRAN SAV	92 12-JAN-77	FUNGEN FTN	3 17-APR-77
PIP SAV	13 12-JAN-77	DATA VAR	103 17-APR-77
LINK SAV	25 12-JAN-77	R8SYN FTN	9 17-APR-77
LIBR SAV	15 12-JAN-77	RASYN FTN	1 17-APR-77
EDIT SAV	18 12-JAN-77	FFA FTN	2 17-APR-77
MACRO SAV	31 12-JAN-77	IFFT FTN	1 30-APR-77
SYSMAC SRL	18 12-JAN-77	IOSF FTN	1 30-APR-77
ROLLIN SAV	28 12-JAN-77	VIBLIB OBJ	163 30-APR-77
TT AMP	1 19-JAN-77	< UNUSED > 1703	
TT A E	1 19-JAN-77	93 FILES, 3083 BLOCKS	
INPUT FTN	2 22-JAN-77	1703 FILE BLOCKS	
ADJUST FTN	2 22-JAN-77		
POW01 FTN	6 22-JAN-77		
FORCIB V2	136 23-JAN-77		
FORLIB V2S	137 23-JAN-77		
SUCOM1 FTN	4 26-JAN-77		
LBUF FTN	1 26-JAN-77		
NOSET FTN	3 27-JAN-77		
FFS FTN	2 12-FEB-77		
VI SAV	17 16-FEB-77		
SSPGFT DBJ	616 12-FEB-77		
FORLIB OBJ	136 12-FEB-77		
VSATST SAV	72 17-APR-77		
AUTO FTN	1 23-FEB-77		
UCOM FTN	4 23-FEB-77		
TT LST	0 23-FEB-77		
PCMVO3 FTN	5 23-FEB-77		
PCMVO2 FTN	5 23-FEB-77		
VPS SAV	89 30-APR-77		
V5 SAV	17 17-APR-77		
FUNGEN SAV	15 17-APR-77		
VSAS1 FTN	13 23-FEB-77		
VSAS SAV	74 30-APR-77		

VIRGINIA PER PETRA 191-9

15. TIME '12, 120, 204)
NET, NO. 1 (P1), (A11), (D1), (E1), (F1),
PARENT, (A2), (B2), (C2), (D2), (E2), (F2), (G2),
1, (H2), (I2), (J2), (K2), (L2), (M2), (N2), (O2),
CENTRE STOP
END

APR 26 VINTAGE FIBER OPTIC FILE 95-1
LSD KEN "JULIE" AND "TRAIL"
P.J. MOLIN, RECORDER, 1746
INTERVIEW AT 4106 PINEWOOD, ST. LOUIS, MO 63113, 913, 9013, 913
DATA 913(1), 913(2), 913(3), / / /
TAPERED RECORD, CHM, FILE
PAGE 31
CALL DATE(MAY)
NOTE 16, 100) ERPOSE, INT

FORM 11(1)(1) **SECTION 11**

NETTIE CASES 1962-1972

CENTRE

卷之三

31774-9 MURKIN, JAMES T
MURKIN, JAMES T

[1] विजयनाथ

BRIEFING PAPER | 31

卷之三

THE PEOPLE'S RECORD 13

THE MUSICAL TIMES

$F(X) = \{1, 2, 3, 4, 5\}$

REVIEW

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卷之三

NETTE(4,10) L.G.D.A
SWEET

10 RECENT U.S. CHANGES 1974

WITTEL (601) PL 81(1), P.C.
REGISTRED TRADE MARK
IN THE UNITED KINGDOM

17.2. KICKED IN, M. TELLER
17.3. FILLED IN, FILTA BURN

CALL STATISTICA, 1400, 1500, 1600, 1700, 1800
21

卷之三

A21

A23

```

      RTS PC          NOV 100, INCR
      JMP STICK      NOV 0200, INCR ! NOV 0000
      DEI             NOV 001, INCR
      NOV 000, INCR
      RTS PC          RTS PC

      RTS PC          NOV 100, INCR
      JUMP           NOV 0200, INCR ! NOV 0000
      DEI             NOV 001, INCR
      NOV 000, INCR
      RTS PC          RTS PC

      SUBROUTINE      INPUT/TYPE, INCR.
      DURATION PER(1)
      DO 20 1=1,1
      PER(1)=0
      CONTINUE
      INTEGER# PER MN
      FREQ=0
      WRITE(3,150)
      FORMAT(12H NUMBER OF CHANNELS)
      READ(13,153) NOCH
      FORMAT(12)
      DO 18 1=1,NOCH
      WRITE(3,152)
      READ(13,153) PER(1)
      FREQ=FREQ+1000*PER(1)
      IF (18 .GT. 21) 22,22,22
      WRITE(3,155)
      FORMAT(12H TOTAL FREQUENCY)
      20  GO TO 12
      IF (2500 .GT. PER(1)) 14,18,18
      14,  WRITE(3,154)
      FORMAT(12H MAX PERIOD--2500
      18,  CONTINUE
      HALT
      22  GO TO 13
      FORMAT(11)
      13,  PRINT(15)
      18,  CONTINUE
      HALT
      25  1=1,NOCH
      IF (18 .GT. PER(1)) 15,25,25
      15,  NOCH
      25,  CONTINUE
      RETURN
      END

      RTS PC          NOV 003, INCR
      NOV 000, INCR
      JSF PC, RUM
      RTS PC          HALT
      RTS PC          NOV 003, INCR
      NOV 002, INCR
      NOV 000, INCR
      RTS PC          RTS PC

```


SUBROUTINE RPT(A,N,S1)

SUBROUTINE A11

END

REAL LINE N,MM
 DIMENSION LINE(101),A(90),F1(15),B(11),SCOLE(50),M(5),MM(10)
 DATA M(1),MM(1),M(2),MM(2),M(3),MM(3)/0,-11,-12,-13,-14/
 DATA M(4),MM(4),M(5),MM(5),M(6),MM(6),M(7),MM(7),M(8),MM(8),
 DATA MM(9),MM(10)/5,-16,-17,-18,-19/
 DATA BLANKS DOT 1,BP1//
 TOP=0
 DOT1=1,20
 IF (ABS(M1)) LE TOP GO TO
 TOP=M1+1,M2=1
 CONTINUE
 A11=M1-1,B1R
 CONTINUE
 CALL F1H,A1
 DOT1=M1,N2
 DOT2=M1+2,N2=1/BS1//
 M1=M1+1,N1=M1+1,N2=N2+1/BS1//
 M2=M1+2,N2=M2+1/BS1//
 CONTINUE
 A12=M2+1,N2=P1
 CALL F1H,A1
 DOT1=M1,N2
 M1=M1+1,N2=N2+1
 CONTINUE
 END
 END
 END

CALL F1H,A1
 DOT1=M1,N2
 M1=M1+1,N2=N2+1
 CONTINUE
 RETURN
 END

IF (FRP.GT.PS1) AND TOP LE FS1=M1+1/BS1//

CONTINUE

WRITE(6,100)

FORMAT(2I,10)

FORMAT(2I,10,*,10)

SUBROUTINE RPS1(A,L,N)

SUBROUTINE A11

END

SUBROUTINE RPS1(A,Z,N)

SUBROUTINE A11

END

A26

SUBROUTINE PFA(X, Y, HLL, LD, CR, PL, FL)
SUBROUTINE REL(X, Y, LD, CR, PL)(X1, Y1, X2, Y2)

REAL X1, Y1, X2, Y2, LD, CR, PL(2)
INTEN(X1, Y1), DPER(X1, Y1, PL(2))
CALL STATUS(X, Y, LD, CR, PL, HLL)
IF (LD < 0.0) STOP 'NEGATIVE LENGTH'
TDX=LD*PL(1)
DTP=PL(2)*LD

20 FS(1)=0
FS(2)=0
FS(3)=0.1
FS(4)=0.2
FS(5)=0.5
FS(6)=0.75
FS(7)=1.0
FS(8)=1.25
FS(9)=1.5
FS(10)=2.0
FS(11)=2.5
FS(12)=3.0
FS(13)=4.0
FS(14)=5.0
FS(15)=6.0
FS(16)=8.0
FS(17)=10.0
FS(18)=15.0
FS(19)=20.0
FS(20)=25.0
FS(21)=30.0
FS(22)=40.0
FS(23)=50.0
FS(24)=100.0
FS(25)=150.0
FS(26)=200.0
FS(27)=250.0
FS(28)=300.0
FS(29)=400.0
FS(30)=500.0
FS(31)=1000.0
FS(32)=1500.0
FS(33)=2000.0
FS(34)=2500.0
FS(35)=3000.0
FS(36)=4000.0
FS(37)=5000.0
FS(38)=6000.0
FS(39)=7000.0
FS(40)=8000.0
FS(41)=9000.0
FS(42)=10000.0
FS(43)=12000.0
FS(44)=14000.0
FS(45)=16000.0
FS(46)=18000.0
FS(47)=20000.0
FS(48)=25000.0
FS(49)=30000.0
FS(50)=40000.0
FS(51)=50000.0
FS(52)=60000.0
FS(53)=70000.0
FS(54)=80000.0
FS(55)=90000.0
FS(56)=100000.0
FS(57)=120000.0
FS(58)=140000.0
FS(59)=160000.0
FS(60)=180000.0
FS(61)=200000.0
FS(62)=250000.0
FS(63)=300000.0
FS(64)=350000.0
FS(65)=400000.0
FS(66)=450000.0
FS(67)=500000.0
FS(68)=600000.0
FS(69)=700000.0
FS(70)=800000.0
FS(71)=900000.0
FS(72)=1000000.0
FS(73)=1200000.0
FS(74)=1400000.0
FS(75)=1600000.0
FS(76)=1800000.0
FS(77)=2000000.0
FS(78)=2500000.0
FS(79)=3000000.0
FS(80)=3500000.0
FS(81)=4000000.0
FS(82)=4500000.0
FS(83)=5000000.0
FS(84)=6000000.0
FS(85)=7000000.0
FS(86)=8000000.0
FS(87)=9000000.0
FS(88)=10000000.0
FS(89)=12000000.0
FS(90)=14000000.0
FS(91)=16000000.0
FS(92)=18000000.0
FS(93)=20000000.0
FS(94)=25000000.0
FS(95)=30000000.0
FS(96)=35000000.0
FS(97)=40000000.0
FS(98)=45000000.0
FS(99)=50000000.0
FS(100)=60000000.0
FS(101)=70000000.0
FS(102)=80000000.0
FS(103)=90000000.0
FS(104)=100000000.0
FS(105)=120000000.0
FS(106)=140000000.0
FS(107)=160000000.0
FS(108)=180000000.0
FS(109)=200000000.0
FS(110)=250000000.0
FS(111)=300000000.0
FS(112)=350000000.0
FS(113)=400000000.0
FS(114)=450000000.0
FS(115)=500000000.0
FS(116)=600000000.0
FS(117)=700000000.0
FS(118)=800000000.0
FS(119)=900000000.0
FS(120)=1000000000.0
FS(121)=1200000000.0
FS(122)=1400000000.0
FS(123)=1600000000.0
FS(124)=1800000000.0
FS(125)=2000000000.0
FS(126)=2500000000.0
FS(127)=3000000000.0
FS(128)=3500000000.0
FS(129)=4000000000.0
FS(130)=4500000000.0
FS(131)=5000000000.0
FS(132)=6000000000.0
FS(133)=7000000000.0
FS(134)=8000000000.0
FS(135)=9000000000.0
FS(136)=10000000000.0
FS(137)=12000000000.0
FS(138)=14000000000.0
FS(139)=16000000000.0
FS(140)=18000000000.0
FS(141)=20000000000.0
FS(142)=25000000000.0
FS(143)=30000000000.0
FS(144)=35000000000.0
FS(145)=40000000000.0
FS(146)=45000000000.0
FS(147)=50000000000.0
FS(148)=60000000000.0
FS(149)=70000000000.0
FS(150)=80000000000.0
FS(151)=90000000000.0
FS(152)=100000000000.0
FS(153)=120000000000.0
FS(154)=140000000000.0
FS(155)=160000000000.0
FS(156)=180000000000.0
FS(157)=200000000000.0
FS(158)=250000000000.0
FS(159)=300000000000.0
FS(160)=350000000000.0
FS(161)=400000000000.0
FS(162)=450000000000.0
FS(163)=500000000000.0
FS(164)=600000000000.0
FS(165)=700000000000.0
FS(166)=800000000000.0
FS(167)=900000000000.0
FS(168)=1000000000000.0
FS(169)=1200000000000.0
FS(170)=1400000000000.0
FS(171)=1600000000000.0
FS(172)=1800000000000.0
FS(173)=2000000000000.0
FS(174)=2500000000000.0
FS(175)=3000000000000.0
FS(176)=3500000000000.0
FS(177)=4000000000000.0
FS(178)=4500000000000.0
FS(179)=5000000000000.0
FS(180)=6000000000000.0
FS(181)=7000000000000.0
FS(182)=8000000000000.0
FS(183)=9000000000000.0
FS(184)=10000000000000.0
FS(185)=12000000000000.0
FS(186)=14000000000000.0
FS(187)=16000000000000.0
FS(188)=18000000000000.0
FS(189)=20000000000000.0
FS(190)=25000000000000.0
FS(191)=30000000000000.0
FS(192)=35000000000000.0
FS(193)=40000000000000.0
FS(194)=45000000000000.0
FS(195)=50000000000000.0
FS(196)=60000000000000.0
FS(197)=70000000000000.0
FS(198)=80000000000000.0
FS(199)=90000000000000.0
FS(200)=100000000000000.0
FS(201)=120000000000000.0
FS(202)=140000000000000.0
FS(203)=160000000000000.0
FS(204)=180000000000000.0
FS(205)=200000000000000.0
FS(206)=250000000000000.0
FS(207)=300000000000000.0
FS(208)=350000000000000.0
FS(209)=400000000000000.0
FS(210)=450000000000000.0
FS(211)=500000000000000.0
FS(212)=600000000000000.0
FS(213)=700000000000000.0
FS(214)=800000000000000.0
FS(215)=900000000000000.0
FS(216)=1000000000000000.0
FS(217)=1200000000000000.0
FS(218)=1400000000000000.0
FS(219)=1600000000000000.0
FS(220)=1800000000000000.0
FS(221)=2000000000000000.0
FS(222)=2500000000000000.0
FS(223)=3000000000000000.0
FS(224)=3500000000000000.0
FS(225)=4000000000000000.0
FS(226)=4500000000000000.0
FS(227)=5000000000000000.0
FS(228)=6000000000000000.0
FS(229)=7000000000000000.0
FS(230)=8000000000000000.0
FS(231)=9000000000000000.0
FS(232)=10000000000000000.0
FS(233)=12000000000000000.0
FS(234)=14000000000000000.0
FS(235)=16000000000000000.0
FS(236)=18000000000000000.0
FS(237)=20000000000000000.0
FS(238)=25000000000000000.0
FS(239)=30000000000000000.0
FS(240)=35000000000000000.0
FS(241)=40000000000000000.0
FS(242)=45000000000000000.0
FS(243)=50000000000000000.0
FS(244)=60000000000000000.0
FS(245)=70000000000000000.0
FS(246)=80000000000000000.0
FS(247)=90000000000000000.0
FS(248)=100000000000000000.0
FS(249)=120000000000000000.0
FS(250)=140000000000000000.0
FS(251)=160000000000000000.0
FS(252)=180000000000000000.0
FS(253)=200000000000000000.0
FS(254)=250000000000000000.0
FS(255)=300000000000000000.0
FS(256)=350000000000000000.0
FS(257)=400000000000000000.0
FS(258)=450000000000000000.0
FS(259)=500000000000000000.0
FS(260)=600000000000000000.0
FS(261)=700000000000000000.0
FS(262)=800000000000000000.0
FS(263)=900000000000000000.0
FS(264)=1000000000000000000.0
FS(265)=1200000000000000000.0
FS(266)=1400000000000000000.0
FS(267)=1600000000000000000.0
FS(268)=1800000000000000000.0
FS(269)=2000000000000000000.0
FS(270)=2500000000000000000.0
FS(271)=3000000000000000000.0
FS(272)=3500000000000000000.0
FS(273)=4000000000000000000.0
FS(274)=4500000000000000000.0
FS(275)=5000000000000000000.0
FS(276)=6000000000000000000.0
FS(277)=7000000000000000000.0
FS(278)=8000000000000000000.0
FS(279)=9000000000000000000.0
FS(280)=10000000000000000000.0
FS(281)=12000000000000000000.0
FS(282)=14000000000000000000.0
FS(283)=16000000000000000000.0
FS(284)=18000000000000000000.0
FS(285)=20000000000000000000.0
FS(286)=25000000000000000000.0
FS(287)=30000000000000000000.0
FS(288)=35000000000000000000.0
FS(289)=40000000000000000000.0
FS(290)=45000000000000000000.0
FS(291)=50000000000000000000.0
FS(292)=60000000000000000000.0
FS(293)=70000000000000000000.0
FS(294)=80000000000000000000.0
FS(295)=90000000000000000000.0
FS(296)=100000000000000000000.0
FS(297)=120000000000000000000.0
FS(298)=140000000000000000000.0
FS(299)=160000000000000000000.0
FS(300)=180000000000000000000.0
FS(301)=200000000000000000000.0
FS(302)=250000000000000000000.0
FS(303)=300000000000000000000.0
FS(304)=350000000000000000000.0
FS(305)=400000000000000000000.0
FS(306)=450000000000000000000.0
FS(307)=500000000000000000000.0
FS(308)=600000000000000000000.0
FS(309)=700000000000000000000.0
FS(310)=800000000000000000000.0
FS(311)=900000000000000000000.0
FS(312)=1000000000000000000000.0
FS(313)=1200000000000000000000.0
FS(314)=1400000000000000000000.0
FS(315)=1600000000000000000000.0
FS(316)=1800000000000000000000.0
FS(317)=2000000000000000000000.0
FS(318)=2500000000000000000000.0
FS(319)=3000000000000000000000.0
FS(320)=3500000000000000000000.0
FS(321)=4000000000000000000000.0
FS(322)=4500000000000000000000.0
FS(323)=5000000000000000000000.0
FS(324)=6000000000000000000000.0
FS(325)=7000000000000000000000.0
FS(326)=8000000000000000000000.0
FS(327)=9000000000000000000000.0
FS(328)=10000000000000000000000.0
FS(329)=12000000000000000000000.0
FS(330)=14000000000000000000000.0
FS(331)=16000000000000000000000.0
FS(332)=18000000000000000000000.0
FS(333)=20000000000000000000000.0
FS(334)=25000000000000000000000.0
FS(335)=30000000000000000000000.0
FS(336)=35000000000000000000000.0
FS(337)=40000000000000000000000.0
FS(338)=45000000000000000000000.0
FS(339)=50000000000000000000000.0
FS(340)=60000000000000000000000.0
FS(341)=70000000000000000000000.0
FS(342)=80000000000000000000000.0
FS(343)=90000000000000000000000.0
FS(344)=100000000000000000000000.0
FS(345)=120000000000000000000000.0
FS(346)=140000000000000000000000.0
FS(347)=160000000000000000000000.0
FS(348)=180000000000000000000000.0
FS(349)=200000000000000000000000.0
FS(350)=250000000000000000000000.0
FS(351)=300000000000000000000000.0
FS(352)=350000000000000000000000.0
FS(353)=400000000000000000000000.0
FS(354)=450000000000000000000000.0
FS(355)=500000000000000000000000.0
FS(356)=600000000000000000000000.0
FS(357)=700000000000000000000000.0
FS(358)=800000000000000000000000.0
FS(359)=900000000000000000000000.0
FS(360)=1000000000000000000000000.0
FS(361)=1200000000000000000000000.0
FS(362)=1400000000000000000000000.0
FS(363)=1600000000000000000000000.0
FS(364)=1800000000000000000000000.0
FS(365)=2000000000000000000000000.0
FS(366)=2500000000000000000000000.0
FS(367)=3000000000000000000000000.0
FS(368)=3500000000000000000000000.0
FS(369)=4000000000000000000000000.0
FS(370)=4500000000000000000000000.0
FS(371)=5000000000000000000000000.0
FS(372)=6000000000000000000000000.0
FS(373)=7000000000000000000000000.0
FS(374)=8000000000000000000000000.0
FS(375)=9000000000000000000000000.0
FS(376)=10000000000000000000000000.0
FS(377)=12000000000000000000000000.0
FS(378)=14000000000000000000000000.0
FS(379)=16000000000000000000000000.0
FS(380)=18000000000000000000000000.0
FS(381)=20000000000000000000000000.0
FS(382)=25000000000000000000000000.0
FS(383)=30000000000000000000000000.0
FS(384)=35000000000000000000000000.0
FS(385)=40000000000000000000000000.0
FS(386)=45000000000000000000000000.0
FS(387)=50000000000000000000000000.0
FS(388)=60000000000000000000000000.0
FS(389)=70000000000000000000000000.0
FS(390)=80000000000000000000000000.0
FS(391)=90000000000000000000000000.0
FS(392)=100000000000000000000000000.0
FS(393)=120000000000000000000000000.0
FS(394)=140000000000000000000000000.0
FS(395)=160000000000000000000000000.0
FS(396)=180000000000000000000000000.0
FS(397)=200000000000000000000000000.0
FS(398)=250000000000000000000000000.0
FS(399)=300000000000000000000000000.0
FS(400)=350000000000000000000000000.0
FS(401)=400000000000000000000000000.0
FS(402)=450000000000000000000000000.0
FS(403)=500000000000000000000000000.0
FS(404)=600000000000000000000000000.0
FS(405)=700000000000000000000000000.0
FS(406)=800000000000000000000000000.0
FS(407)=900000000000000000000000000.0
FS(408)=1000000000000000000000000000.0
FS(409)=1200000000000000000000000000.0
FS(410)=1400000000000000000000000000.0
FS(411)=1600000000000000000000000000.0
FS(412)=1800000000000000000000000000.0
FS(413)=2000000000000000000000000000.0
FS(414)=2500000000000000000000000000.0
FS(415)=3000000000000000000000000000.0
FS(416)=3500000000000000000000000000.0
FS(417)=4000000000000000000000000000.0
FS(418)=4500000000000000000000000000.0
FS(419)=5000000000000000000000000000.0
FS(420)=6000000000000000000000000000.0
FS(421)=7000000000000000000000000000.0
FS(422)=8000000000000000000000000000.0
FS(423)=9000000000000000000000000000.0
FS(424)=10000000000000000000000000000.0
FS(425)=12000000000000000000000000000.0
FS(426)=14000000000000000000000000000.0
FS(427)=16000000000000000000000000000.0
FS(428)=18000000000000000000000000000.0
FS(429)=20000000000000000000000000000.0
FS(430)=25000000000000000000000000000.0
FS(431)=30000000000000000000000000000.0
FS(432)=35000000000000000000000000000.0
FS(433)=40000000000000000000000000000.0
FS(434)=45000000000000000000000000000.0
FS(435)=50000000000000000000000000000.0
FS(436)=60000000000000000000000000000.0
FS(437)=70000000000000000000000000000.0
FS(438)=80000000000000000000000000000.0
FS(439)=90000000000000

2501117 VIBRATION SIGNAL GENERATION 151-3
 C LINK WITH 'VIL13' AND 'FIR13'
 C P. J. WILSON NUMBER 1976
 C INSTRUCTION A1(MP6),S1(3),S1T(3),C1(MP3)
 C VIBRATION S1(20),M1(20),M1T(3)
 DATA M1(1),M1(2),M1T(3)
 D1TEEN RECORD, CHW
 CALL ASSIST(1,'MP1 DATA A')
 CALL ASSIST(2,'MP1 DATA ACC')
 CALL ASSIST(4,'MP1 DATA VEL')
 CALL ASSIST(3,'MP1 DATA ACCELERATION')
 DEFINE FILE1(20000,2,1,MPC1)
 DEFINE FILE2(400,2,1,MPC2)
 DEFINE FILE3(20000,2,1,MPC3)
 DEFINE FILE4(20000,2,1,MPC4)
 MP1.2
 MP2=4*M
 CALL/VATE(MPC1)
 WRITE(1,100) DAT
 RECORD=1
 D011=4,399
 READ(1,RECORD) C11
 RECORD=RECORD+1
 CONTINUE
 RECORD=1
 D021=1,399
 WRITE(1,RECORD) C11
 WRITE(1,RECORD) C11
 RECORD=RECORD+1
 CONTINUE
 RECORD=50
 D021=1,3
 READ(1,RECORD) CHW1
 RECORD=RECORD+1
 CONTINUE
 D021=1,3
 RECORD=RECORD+2
 RECORD=RECORD+1
 READ(1,RECORD) VPAK1
 WRITE(7,101) VPAK1
 201 FORMAT(2I,1,V PER G ,16,3)
 5 CONTINUE
 DATA=1,3
 RECORD=CHW1
 D021=1,3
 READ(1,RECORD) A11
 A11=INT(1)/MPU(1)*PSL(1)*PSL(2)
 RECORD=RECORD+1
 CONTINUE
 RECORD=CHW1

2501117 VIBRATION SIGNAL GENERATION 151-3
 4 WRITE(1,RECORD) A11
 CONTINUE
 S1T(1)=S1T(1)+1
 CALL FFT(16,N,SUM)
 RECORD=CHW1
 D021=1,3
 RECORD=RECORD+1
 READ(1,RECORD) VPAK1
 5 CONTINUE
 DATA=1,3
 RECORD=CHW1
 D021=1,3
 RECORD=RECORD+1
 READ(1,RECORD) A11
 A11=INT(1)/MPU(1)*PSL(1)*PSL(2)
 S6=S1A11
 CONTINUE
 SP/VA
 RECORD=CHW1
 D021=1,3
 RECORD=RECORD+1
 WRITE(3,RECORD) A11
 6 CONTINUE
 S1T(1)=S1T(1)+1
 CALL TUF(15,1,L,W)
 RECORD=CHW1
 D021=1,3
 RECORD=RECORD+1
 WRITE(4,RECORD) Z11
 STOP
 END
 C 7512511 VIBRATION SIGNAL GENERATION 152-1
 C LINK WITH 'VIL13', 'SP/VA' AND 'FIR13'
 C P. J. WILSON NUMBER 1976
 C DIMENSION A1(MP6),S1(3),S1T(3),C1(MP3)
 C DIMENSION B1(10),B1(10),INT(3)
 C DATA DAT(1),DAT(2),DAT(3)
 C INTEGER RECORD, CHW
 C CALL ASSIST(1,'MP1 DATA A')
 C CALL ASSIST(2,'MP1 DATA ACC')
 C CALL ASSIST(4,'MP1 DATA VEL')
 C CALL ASSIST(3,'MP1 DATA ACCELERATION')
 C DEFINE FILE1(20000,2,1,MPC1)
 C DEFINE FILE2(400,2,1,MPC2)
 C DEFINE FILE3(20000,2,1,MPC3)
 C DEFINE FILE4(20000,2,1,MPC4)
 C RECORD=1
 C D011=1,399
 C READ(1,RECORD) C11
 C RECORD=RECORD+1
 C CONTINUE
 C RECORD=1
 C D021=1,399
 C WRITE(1,RECORD) C11
 C RECORD=RECORD+1
 C CONTINUE
 C RECORD=50
 C D021=1,3
 C READ(1,RECORD) CHW1
 C RECORD=RECORD+1
 C CONTINUE
 C D021=1,3
 C RECORD=RECORD+2
 C RECORD=RECORD+1
 C READ(1,RECORD) VPAK1
 C WRITE(7,101) VPAK1
 C 201 FORMAT(2I,1,V PER G ,16,3)
 C 5 CONTINUE
 C DATA=1,3
 C RECORD=CHW1
 C D021=1,3
 C READ(1,RECORD) A11
 C A11=INT(1)/MPU(1)*PSL(1)*PSL(2)
 C RECORD=RECORD+1
 C CONTINUE
 C RECORD=CHW1

```

SUBROUTINE DSCRTCH(15,16,17,18)
      INTEGER INT(2)
      DATA(7,10)
      FORMAT(1//,21,'ENTER DATA SET IDENTIFICATION FMT #4'1)
      ACCEPT 210, DATA1D
      210  FORMAT(4A1)
      WRITE(7,111)
      111 FORMAT(1//,21,'ENTER MACHINE NUMBER FMT #4'1')
      ACCEPT 211, MS
      211 FORMAT(5,1)
      WRITE(7,100)
      100 FORMAT(1//,21,'ENTER FILE NUMBER FMT #4'1')
      ACCEPT 206, FILE
      206 FORMAT(12)
      WRITE(7,101)
      101 FORMAT(1//,21,'ENTER NUMBER OF DATA POINTS FMT #4'1')
      ACCEPT 201, N
      201 FORMAT(16)
      WRITE(7,102)
      102 FORMAT(1//,21,'IF YOU WISH TO PLOT RESULTS OR UP ENTER 1')
      ACCEPT 202, INP
      202 FORMAT(11)
      IF(ILE EQ 1)OPEN(1
      IF(ILE EQ 2)OPEN(2
      IF(ILE EQ 3)OPEN(3
      IF(ILE EQ 4)OPEN(4
      WRITE(7,103) FILE
      103 FORMAT(10/1,50*'1',/21,'ANALYSIS ATTEMPTED ON ILLUM. FILE #4'1
      12, /41,'PROGRAM TERMINATED',/50*'1',/21/1)
      PSS=999
      SOTIA
      1. WRITE(11,104)
      104 FORMAT(40,10)  UNITS VOLTE 1
      SOTIS
      2. WRITE(14,105)
      105 FORMAT(40,10)  UNITS CM/SEC/E
      SOTIS
      2. WRITE(14,106)
      106 FORMAT(40,10)  UNITS CM SEC/1
      SOTIS
      4. WRITE(17,107) FILE
      107 FORMAT(10/1,50*'1',/21,'CAUTION - ANALYSIS ON VARIABLE DATA FIL
      IE #4'1,12, /21,'VERIFY CONTENTS BEFORE PROCESSING #4'1,10/1)
      PAUSE
      108 7 FORMAT(40,10)  UNITS ??
      5. WRITE(16,109) FILE, DATA, HGS
      109 FORMAT(21,'DATA FILE NUMBER : ',12,20,'DATA SET : ',10,20,'RUNNING
      1. HOURS. #4'1)
      PSS=0
      RETURN
      END

```

RT-II VIBPAC VIBRATION STATISTICAL ANALYSIS VOZ-A PAGE 21 17-APR-77

AUTOCORRELATION COEFFICIENT FUNCTION			
LAG MSEC	R(T) MSEC	LAG MSEC	R(T) MSEC
0.000	1.000	0.038	0.750
0.225	-0.499	0.262	-0.750
0.450	-0.001	0.498	0.250
0.675	0.501	0.712	0.251
0.900	-1.000	0.937	-0.750
1.125	0.499	1.163	0.750
1.350	0.001	1.389	-0.249
1.575	-0.501	1.612	-0.251
1.800	1.000	1.837	0.750
			1.875 0.501

MAXIMUM RMS ERROR 1.3 PER CENT

RT-11 VIBPAC VIBRATION STATISTICAL ANALYSIS V02-A PAGE 22
AUTOCORRELATION COEFFICIENT FUNCTION 17-APR-72

-2.0 -1.6 -1.2 -0.8 -0.4 0.0 0.4 0.8 1.2 1.6 2.0

00.18

00.37

00.56

00.75

00.93

01.12

01.31

01.50

01.68

B9

RT-11 VIBPAC VIBRATION POWER SPECTRUM VOL-A PAGE 1 17-NPR-77
DATA FILE NUMBER. 5 ANALYSIS ON VARIABLE DATA UNITS ?
DATA SET TST2 RUNNING HOURS 0.0

CHANNEL 3 OF 3

AVERAGED CONTRIBUTION TO VARIANCE

FREQUENCY AMPLITUDE HZ							
5 9	0 00	16 3	0 00	26 6	0 00	37 0	0 00
68 1	0 00	78 4	0 00	88 8	0 00	99 1	0 00
130 2	0 00	140 6	0 00	150 9	0 00	161 3	0 00
192 4	0 00	202 7	0 00	213 1	0 00	223 4	0 00
254 5	0 00	264 9	0 00	275 2	0 00	285 6	0 00
316 6	0 00	327 0	0 00	337 4	0 00	347 7	0 00
378 8	11 72	389 1	0 00	399 5	0 00	409 9	0 00
440 9	0 00	451 3	0 00	461 6	0 00	472 0	0 00
503 1	0 00	513 4	0 00	523 8	0 00	534 2	0 00
565 2	0 00	575 6	0 00	585 9	0 00	596 3	0 00
627 4	0 00	637 7	0 00	648 1	0 00	658 4	0 00
689 5	0 00	699 9	0 00	710 2	0 00	720 6	0 00
751 7	0 00	762 0	0 00	772 4	0 00	782 7	0 00
813 8	0 00	824 2	0 00	834 5	0 00	844 9	0 00
875 9	0 00	886 3	0 00	896 7	0 00	907 0	0 00
938 1	0 00	948 4	0 00	958 8	0 00	969 2	0 00
1000 2	0 00	1010 6	0 00	1021 0	0 00	1031 3	0 00
1062 4	0 00	1072 7	0 00	1083 1	0 00	1093 5	0 00
1124 5	0 00	1134 9	1 42	1145 2	0 03	1155 6	0 00
1186 7	0 00	1197 0	0 00	1207 4	0 00	1217 7	0 00
1248 8	0 00	1259 2	0 00	1269 5	0 00	1279 9	0 00
1311 0	0 00	1321 3	0 00	1331 7	0 00	1342 0	0 00
1373 1	0 00	1383 5	0 00	1393 8	0 00	1404 2	0 00
1435 3	0 00	1445 6	0 00	1456 0	0 00	1466 3	0 00
1497 4	0 00	1507 8	0 00	1518 1	0 00	1528 5	0 00
1559 5	0 00	1589 9	0 00	1580 3	0 00	1590 6	0 00
1621 7	0 00	1632 0	0 00	1642 4	0 00	1652 8	0 00
1683 8	0 00	1694 2	0 00	1704 5	0 00	1714 9	0 00
1746 0	0 00	1756 3	0 00	1766 7	0 00	1777 0	0 00
1808 1	0 00	1818 5	0 00	1828 8	0 00	1839 2	0 00
1870 3	0 00	1880 6	0 00	1891 0	0 62	1901 3	0 03
1932 4	0 00	1942 8	0 00	1953 1	0 00	1963 5	0 00
1994 6	0 00	2004 9	0 00	2015 3	0 00	2025 6	0 00
2056 7	0 00	2067 1	0 00	2077 4	0 00	2087 8	0 00
2118 8	0 00	2129 2	0 00	2139 6	0 00	2149 9	0 00
2181 0	0 00	2191 3	0 00	2201 7	0 00	2212 1	0 00
2243 1	0 00	2253 5	0 00	2263 8	0 00	2274 2	0 00
2305 3	0 00	2315 6	0 00	2326 0	0 00	2336 4	0 00
2367 4	0 00	2377 8	0 00	2388 1	0 00	2398 5	0 00
2429 6	0 00	2439 9	0 00	2450 3	0 00	2460 6	0 00
2491 7	0 00	2502 1	0 00	2512 4	0 00	2522 8	0 00
2553 9	0 00	2564 2	0 00	2574 6	0 00	2584 9	0 00
2616 0	0 00	2626 4	0 00	2636 7	0 00	2647 1	0 00
2678 1	0 00	2688 5	0 00	2698 9	0 00	2709 2	0 00
2740 3	0 00	2750 7	0 00	2761 0	0 00	2771 4	0 00
2802 4	0 00	2812 8	0 00	2823 2	0 00	2833 5	0 00
2864 6	0 00	2874 9	0 00	2885 3	0 00	2895 7	0 00
2926 7	0 00	2937 1	0 00	2947 4	0 00	2957 8	0 00
2988 9	0 00	2999 2	0 00	3009 6	0 00	3019 9	0 00

RT-11 VIBPAC VIBRATION STATISTICAL ANALYSIS V02-A PAGE 1 30-APR-77
DATA FILE NUMBER 3 ANALYSIS ON ACCELERATION DATA UNITS CM/SEC/SEC
DATA SET MG7 RUNNING HOURS 212.0

VIBRATION SIGNALS RECORDED FROM A 1 1/2 KW MOTOR GENERATOR SET LOCATED IN RM 0027

ACCELEROMETERS LOCATED ON MOTOR FREE END BEARING HOUSING. WITH MOTOR AXIS HORIZONTAL

MACHINE OPERATING CONDITIONS

MACHINE SPEED 1800 RPM
MACHINE LOAD 1500 WATTS

RECORDING SPECIFICATIONS

TAPE SPEED 15 IPS
FREQUENCY BANDWIDTH 10 HZ TO 3 KHZ

CHANNEL 1 (RCDR CH 2) RADIAL VERTICAL ACCELEROMETER B&K #344820 SENSITIVITY 10.03 PC/G & 9.12 MV/G
CHANNEL 2 (RCDR CH 3) RADIAL HORIZONTAL ACCELEROMETER B&K #344170 SENSITIVITY 10.12 PC/G & 8.83 MV/G
CHANNEL 3 (RCDR CH 4) AXIAL HORIZONTAL ACCELEROMETER B&K #344821 SENSITIVITY 10.16 PC/G & 9.16 MV/G

CHANNEL 2 OF 3

SAMPLE INTERVAL = 37.5 MICROSECS
 NUMBER OF DATA POINTS ANALYSED = 4096
 MAXIMUM VALUE = 1034.25

SAMPLING FREQUENCY = 26.67 KHZ
 MINIMUM VALUE = -1112.46
STANDARD DEVIATION = 312.90

BANDWIDTH = 6.51 HZ TO 3.00 KHZ
 SIGNAL LENGTH = 0.154 SECONDS
 MEAN = -0.00

INPUT SIGNAL											
MSEC	VALUE	MSEC	VALUE	MSEC	VALUE	MSEC	VALUE	MSEC	VALUE	MSEC	VALUE
0.000	-182.07	0.038	-100.38	0.075	67.55	0.113	203.70	0.150	240.01	0.188	253.63
0.225	212.78	0.263	167.39	0.300	212.78	0.338	253.63	0.375	321.70	0.413	398.86
0.450	335.32	0.488	153.78	0.525	-59.53	0.562	-272.84	0.600	-404.46	0.638	-413.53
0.675	-340.92	0.713	-204.76	0.750	-32.30	0.788	162.86	0.825	303.55	0.863	385.24
0.900	403.40	0.938	317.16	0.975	203.70	1.013	72.09	1.050	-82.22	1.088	-163.92
1.125	-204.76	1.163	-204.76	1.200	-182.07	1.238	-177.53	1.275	-127.61	1.313	-36.84
1.350	49.39	1.388	190.09	1.425	262.70	1.463	194.63	1.500	140.16	1.538	135.63
1.575	108.39	1.613	90.24	1.650	22.16	1.688	-95.84	1.725	-222.92	1.763	-345.46
1.800	-499.76	1.838	-617.76	1.875	-572.38	1.913	-422.61	1.950	-145.76	1.988	190.09
2.025	457.86	2.063	621.24	2.100	664.63	2.138	571.32	2.175	371.63	2.213	108.39
2.250	-186.61	2.288	-399.92	2.325	-458.92	2.363	-445.30	2.400	-363.61	2.438	-222.92
2.475	-5.07	2.513	176.47	2.550	240.01	2.588	208.24	2.625	72.09	2.663	-127.61
2.700	-191.15	2.738	-141.22	2.775	13.09	2.813	217.32	2.850	371.63	2.888	412.47
2.925	344.40	2.963	185.55	3.000	-5.07	3.038	-154.84	3.075	-182.07	3.113	-159.38
3.150	-191.15	3.188	-154.84	3.225	-141.22	3.263	-77.68	3.300	-9.61	3.338	13.09
3.375	94.78	3.413	194.63	3.450	167.39	3.488	155.63	3.525	-45.91	3.563	-195.68
3.600	-136.68	3.638	-123.07	3.675	-86.76	3.713	53.93	3.750	85.70	3.788	35.78
3.825	76.62	3.863	22.16	3.900	13.09	3.938	67.55	3.975	-5.07	4.013	-27.76
4.050	-68.61	4.088	-236.53	4.125	-340.92	4.163	-436.23	4.200	-377.22	4.238	-195.68
4.275	-14.15	4.313	181.01	4.350	385.24	4.388	465.09	4.425	512.32	4.463	521.40
4.500	407.93	4.538	208.24	4.575	58.47	4.613	-95.84	4.650	-290.99	4.687	-449.84
4.725	-522.46	4.763	-508.84	4.800	-399.92	4.838	-227.45	4.875	-82.92	4.913	13.09
4.950	72.09	4.988	90.24	5.025	44.86	5.063	44.86	5.100	40.32	5.138	94.78
5.175	199.16	5.213	230.93	5.250	230.93	5.288	112.93	5.325	-45.91	5.363	-191.15
5.400	-327.30	5.398	-413.53	5.475	-399.92	5.513	-309.15	5.550	-177.53	5.588	-141.22
5.625	-136.68	5.663	-132.15	5.700	-154.84	5.738	-145.76	5.775	-86.76	5.813	-32.30
5.850	76.62	5.888	144.70	5.925	176.47	5.963	230.93	6.000	221.86	6.038	240.01
6.075	253.63	6.113	217.32	6.150	226.39	6.188	199.16	6.225	76.62	6.263	-32.30
6.300	-91.30	6.338	-168.45	6.375	-281.92	6.413	-295.53	6.450	-263.76	6.488	-241.07
6.525	-127.61	6.563	-0.53	6.600	44.86	6.638	153.78	6.675	212.78	6.713	176.47

RT-11 VIBPAC VIBRATION STATISTICAL ANALYSIS VO2-A PAGE 10 30-APR-77

-1000 0 -800 0 -600 0 -400 0 -200 0 0.0 200 0 400 0 600 0 800 0 1000 0

INPUT SIGNAL

00.18

00.37

00.56

00.75

00.93

01.12

01.31

01.50

01.68

28363

B14

RT-11 VIBPAC VIBRATION STATISTICAL ANALYSIS. V02-A
PROBABILITY FUNCTIONS

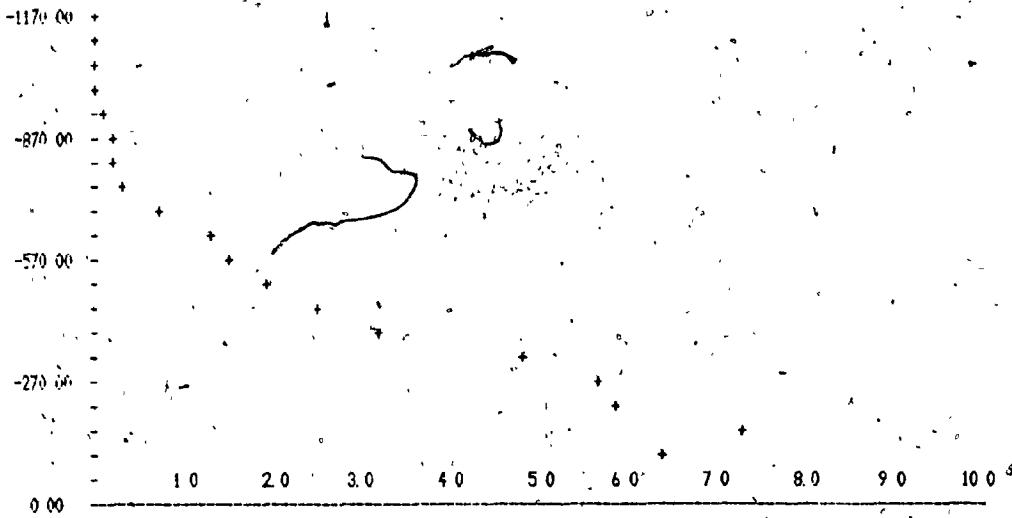
PAGE: 11

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HIGH	LOW	CEN	FUNCTION	
			P(X)	F(X)
-1440.00	-1500.00	-1470.00	0.00	0.00
-1380.00	-1440.00	-1410.00	0.00	0.00
-1320.00	-1380.00	-1350.00	0.00	0.00
-1260.00	-1320.00	-1290.00	0.00	0.00
-1200.00	-1260.00	-1230.00	0.00	0.00
-1140.00	-1200.00	-1170.00	0.00	0.00
-1080.00	-1140.00	-1110.00	0.02	0.00
-1020.00	-1080.00	-1050.00	0.05	0.00
-960.00	-1020.00	-990.00	0.00	0.00
-900.00	-960.00	-930.00	0.12	0.00
-840.00	-900.00	-870.00	0.24	0.00
-780.00	-840.00	-810.00	0.17	0.01
-720.00	-780.00	-750.00	0.29	0.01
-660.00	-720.00	-690.00	0.73	0.02
-600.00	-660.00	-630.00	1.27	0.03
-540.00	-600.00	-570.00	1.51	0.04
-480.00	-540.00	-510.00	1.90	0.06
-420.00	-480.00	-450.00	2.51	0.09
-360.00	-420.00	-390.00	3.22	0.12
-300.00	-360.00	-330.00	4.81	0.17
-240.00	-300.00	-270.00	5.74	0.23
-180.00	-240.00	-210.00	5.88	0.28
-120.00	-180.00	-150.00	7.35	0.36
-60.00	-120.00	-90.00	6.40	0.42
0.00	-60.00	-30.00	7.89	0.50
60.00	0.00	30.00	7.25	0.57
120.00	60.00	90.00	7.03	0.64
180.00	120.00	150.00	6.69	0.71
240.00	180.00	210.00	7.03	0.78
300.00	240.00	270.00	5.08	0.83
360.00	300.00	330.00	4.13	0.87
420.00	360.00	390.00	3.59	0.91
480.00	420.00	450.00	2.69	0.94
540.00	480.00	510.00	2.34	0.96
600.00	540.00	570.00	1.51	0.97
660.00	600.00	630.00	0.95	0.98
720.00	660.00	690.00	0.54	0.99
780.00	720.00	750.00	0.22	0.99
840.00	780.00	810.00	0.04	1.00
900.00	840.00	870.00	0.22	1.00
960.00	900.00	930.00	0.07	1.00
1020.00	960.00	990.00	0.07	1.00
1080.00	1020.00	1050.00	0.02	1.00
1140.00	1080.00	1110.00	0.00	1.00
1200.00	1140.00	1170.00	0.00	1.00
1260.00	1200.00	1230.00	0.00	1.00
1320.00	1260.00	1290.00	0.00	1.00
1380.00	1320.00	1350.00	0.00	1.00
1440.00	1380.00	1410.00	0.00	1.00
1500.00	1440.00	1470.00	0.00	1.00

RI-11 VIBPAC VIBRATION STATISTICAL ANALYSIS. VO2-A PAGE 12
PROBABILITY DENSITY, %

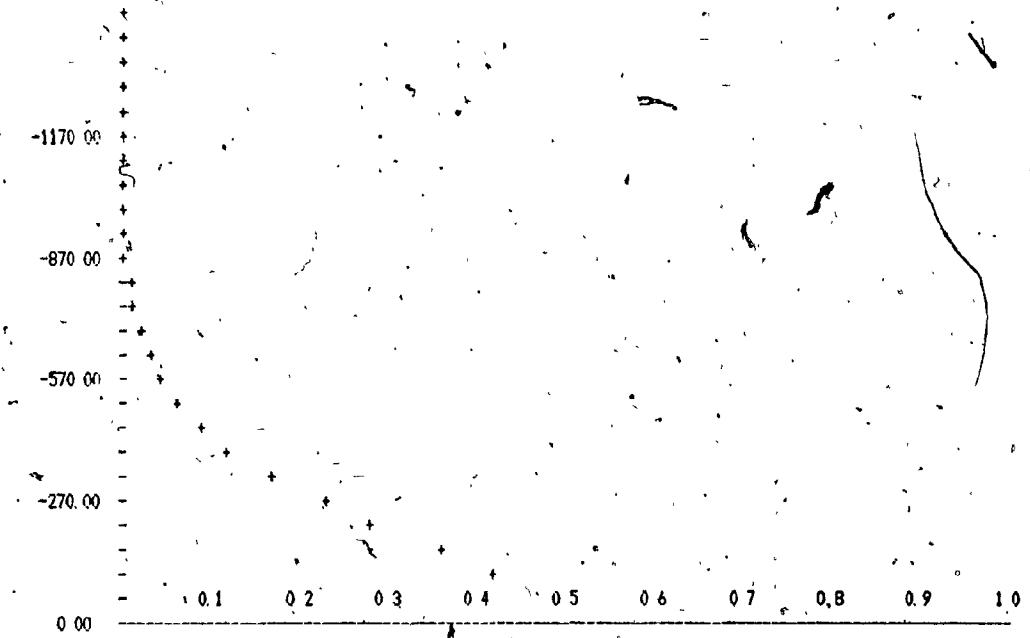
30-APR-77



283547

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RT-11 VIBFAC VIBRATION STATISTICAL ANALYSIS VO2-A
PROBABILITY DISTRIBUTION PAGE 13 30-APR-77



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RT-11 XIBPAC VIBRATION STATISTICAL ANALYSIS V02-A

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AUTOCORRELATION COEFFICIENT FUNCTION

LAG MSEC	R(T) MSEC										
0 000	1 000	0 038	0 898	0 075	0 629	0 112	0 261	0 150	-0 128	0 187	-0 452
0 225	-0 655	0 262	-0 718	0 300	-0 646	0 338	-0 473	0 375	-0 250	0 412	-0 024
0 450	0 171	0 488	0 309	0 525	0 382	0 562	0 391	0 600	0 347	0 637	0 265
0 675	0 162	0 712	0 054	0 750	-0 049	0 788	-0 137	0 825	-0 205	0 863	-0 245
0 900	-0 254	0 937	-0 228	0 975	-0 170	1 013	-0 088	1 050	0 006	1 087	0 096
1 125	0 164	1 163	0 195	1 200	0 186	1 237	-0 139	1 275	0 064	1 313	-0 021
1 350	-0 191	1 388	-0 162	1 425	-0 193	1 462	-0 192	1 500	-0 162	1 538	-0 110
1 575	-0 044	1 612	0 022	1 650	0 083	1 688	0 130	1 725	0 157	1 763	0 163
1 800	0 149	1 837	0 117	1 875	0 070						

MAXIMUM RMS ERROR 0.7 PER CENT

2837-1

RT-J1 VIBPAC VIBRATION STATISTICAL ANALYSIS V02-A PAGE 15 30-APR-77

AUTOCORRELATION COEFFICIENT FUNCTION

-1.0 -0.8 -0.6 -0.4 -0.2 0.0 0.2 0.4 0.6 0.8 1.0

00 18

00 37

00 56

00 75

00 93

01 12

01 31

01 50

01 68

B19

ST-C VIB-AN VIBRATION POWER SPECTRUM VOL-A

PAGE 1

25-JUN-77

DATA FILE NUMBER

ANALYSIS ON ACCELERATION DATA

UNITS CM/SEC/SEC

DATA SET MGT

RUNNING HOURS 2112.0

VIBRATION SIGNALS RECORDED FROM A 1 1/2 KW MOTOR GENERATOR SET LOCATED IN RM 0027

ACCELEROMETERS LOCATED ON MOTOR FREE END BEARING HOUSING, WITH MOTOR AXIS HORIZONTAL

MACHINE OPERATING CONDITIONS

MACHINE SPEED 1800 RPM

MACHINE LOAD 1500 WATTS

RECORDING SPECIFICATIONS

TAPE SPEED 15 IPS

FREQUENCY BANDWIDTH 10 HZ TO 3 KHZ

CHANNEL 1 (RCDR CH 2) RADIAL VERTICAL ACCELEROMETER B&K #344820 SENSITIVITY 10.03 PC/G & 9.12 MV/G
CHANNEL 2 (RCDR CH 3) RADIAL HORIZONTAL ACCELEROMETER B&K #344170 SENSITIVITY 10.12 PC/G & 8.83 MV/G
CHANNEL 3 (RCDR CH 4) AXIAL HORIZONTAL ACCELEROMETER B&K #344821 SENSITIVITY 10.16 PC/G & 9.16 MV/G