A Microcomputer-Based Data Acquisition System for Diagnostic Monitoring and Control of High-Speed Electric Motors

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(ABSTRACT)

A microcomputer-based data acquisition and control system was designed for the diagnostic monitoring and control of high-speed electric motors. The system was utilized in high-speed bearing life-testing, using an electric motor as a test vehicle.

Bearing vibration and outer race temperature were continuously monitored for each ball bearing in the motor. In addition, the stator winding and motor casing temperature were monitored.

The monitoring system was successful in detecting an unbalance in the rotor caused by the loss of a small piece of balancing putty. The motor was shut down before any further damage occurred. In a separate test, excessive clearance between a bearing outer race and the motor caused high vibration readings. The motor was monitored until the condition began to deteriorate and the bearing outer race began to spin significantly. Again, the monitoring system powered down the motor before any significant damage occurred.

The speed of the motor tested is controlled by a PWM (pulse width modulation) technique. The resulting voltage and current waveforms are asymmetrical and contain high frequency components. Special circuitry was designed and constructed to interface sensors for measuring the voltage and current inputs to a spectrum analyzer. Using frequency and order analysis techniques, the real and reactive power inputs to the three-phase motor were measured.

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Chapter 1

Introduction

Brushless DC motors with speed capabilities well in excess of 20,000 RPM are now being developed. Thesė new motors will find applications in the machine tool industry, the textile industry, and in research environments. Brushless motors overcome many of the problems that limit the speed of conventional electric motors. The most critical factor limiting the speed of conventional motors is the ability of their laminated rotors to withstand the centrifugal forces generated during high-speed operation. Brushless motors may be designed with solid steel rotors to overcome this limitation. In addition, there are no collaters to spark or wear out.

Along with their special capabilities, brushless motors have their own special problems. The smooth, solid steel rotors are subject to severe induction heating. The resulting high temperatures can cause premature bearing failure. As motor speed increases, centrifugal forces become significant. Excessive imbalance can cause stresses high enough to bend the rotor and result in a dangerous failure. Also, catastrophic bearing failure usually results in significant damage to the motor.

Clearly, some type of continuous monitoring system is necessary for the development and operation of high-speed brushless motors. A microcomputer-based data acquisition and control system has been developed especially for the continuous monitoring of high-speed motors. The data acquisition system monitors the motor bearing vibration level and outer race temperatures, the stator and casing temperatures, and the motor speed. The system controls motor speed and powers down the motor if any abnormal condition is detected.

Due to limitations in sampling speed, the data acquisition system can only sample the RMS value of the bearing vibration. Therefore, a spectrum analyzer is utilized periodically to gain more information about the bearing conditions.

Induction heating in the rotor can be minimized by optimizing the power factor and therefore minimizing the current flow through the motor. In order to do this, some method of measuring the active and reactive power input to the motor must be developed. Instruments are readily available for power and phase measurements of 60 Hz sinusoidal waveforms. However, the voltage and current inputs to brushless motors are not sinusoidal and contain high frequency components. This makes conventional wattmeters and phase meters unsuitable for this application. Therefore , a special system was designed for power and phase angle measurements.

The data acquisition and control system has been utilized successfully in a high-speed bearing life testing program. A brushless induction motor built by the Industrial Drives Division of Kollmorgan Corporation was used as a test vehicle. The motor is of a special inside-out design. A solid steel rotor made up of carbon steel and non-magnetic stainless steel sections is used. A separate controller uses transistor switching circuits to move a magnetic field around the stator coils causing the rotor to turn. Angular contact, 20 mm, ball bearings are used on either end of the shaft to support the rotor. Either air-oil mist or grease lubrication may be used in the bearings. With the proper bearings and air-oil mist lubrication, speeds of over 50,000 RPM may be obtained.

The outer race temperature of each bearing was continuously monitored by the data acquisition system. Although it may be preferable to monitor the inner bearing race temperature, this would require a hollow shaft and some type of slip rings or telemetry system to transmit the signal from the moving shaft out to the data acquisition system. Since the system was designed to be easily adapted to any high-speed motor, the idea was abandoned. Vibration is measured in the radial plane of each bearing. The temperature of both the stator coils and the motor casing are also measured. In the present setup, a magnetic flux sensor built into the motor provides a one pulse per revolution signal to the controller. A frequency to voltage converter in the controller provides a DC signal to the data acquisition system that is proportional to motor speed. The data acquisition system, in return, provides an output signal to control the motor speed.

The data acquisition system is built around an IBM Personal Computer. The system is totally software controlled. The data acquisition software was written in Advanced BASIC and compiled for faster execution. A low level data acquisition card was added to the microcomputer. The card was designed mainly for thermocouple inputs. Because of the relatively long settling time of the amplifier at high gains, the sample rate is limited to 6 kHz at high gain. The card includes a terminal strip with screw terminals for easy attachment of signal inputs and has a built in solid-state temperature sensor to provide cold-junction compensation for the thermocouple inputs. A multifunction card was also added to the computer. The card provides serial and parallel interface ports and a real time clock with battery backup power. This clock is used to record the time during testing and to control the sample rate of the data acquisition system. Accelerometers were mounted on the motor casing in the radial plane of each bearing to monitor the bearing vibration. The accelerometers featured integral amplifiers to produce a voltage output proportional to the casing acceleration. In order to allow the system to operate continuously, an accelerometer power supply that ran off of 60 Hz line current was chosen. Unfortunately, the power supply superimposed a 60 Hz signal on top of the vibration signal. To eliminate this undesirable component and to increase the accuracy of the measuring devices, the acceleration signals were passed through differential input operational amplifiers. The acceleration signals were then passed through true RMS to DC converters. This allowed the RMS vibration level to be monitored with the data acquisition system. In order to prevent crosstalk between the channels, each amplifier and RMS circuit combination has its own power supply. The power supplies are very well regulated to help reduce fluctuations in the amplifier output caused by an unstable supply voltage. Figure 1 on page 5 shows a schematic of the data acquisition and control system.

In addition to monitoring the RMS vibration level, a spectrum analyzer was used to perform periodic FFT (Fast Fourier Transform) analysis of the bearing vibration signals. The FFT analysis was performed when the bearings were new and periodically afterward. Typically, the FFT analysis was performed to try to explain abnormal vibration levels detected by the data acquisition system. According to Bradshaw and Randall (1983), different types of bearing failures may be identified by the characteristic vibrational frequencies that they produce. Most ball and roller bearing failures are either caused by outer race defects, inner race defects, faults on the balls or rollers, or cage faults. The equations for each characteristic frequency are:

Ball/roller-passing frequency for outer race defect

$$BPFO = \frac{N}{2} f \times (1 - \frac{B}{P} \cos \theta) \qquad [1.1]$$

Ball/roller-pass frequency for inner race defect

$$BPFI = \frac{N}{2} f \times (1 + \frac{B}{P} \cos \theta) \qquad [1.2]$$

Ball/roller double-spin frequency for a ball or roller defect impacting a raceway

$$BSF = \frac{P}{B} f \times (1 - \frac{B^2}{P^2} \cos^2 \theta) \qquad [1.3]$$

Fundamental Train frequency for a discrete defect in the cage assembly

$$FTF = \frac{f}{2} \times (1 - \frac{B}{P} \cos \theta) \qquad [1.4]$$

where:

B = ball or roller diameter (m)

$BPFO$ = ball-passing frequency for outer race (Hz)

$BPFI$ = ball-passing frequency for inner race (Hz)

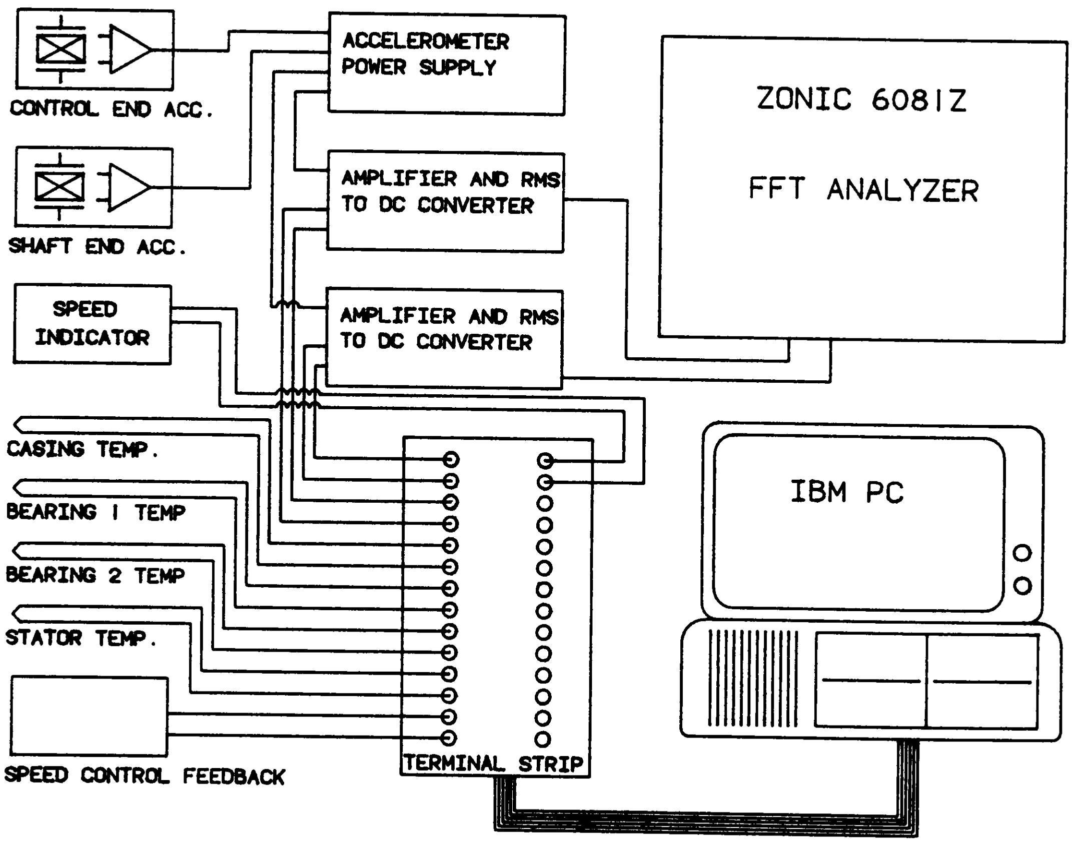

Figure 1. Schematic of the Data Acquisition and Control System

BSF = ball-spin frequency (Hz)

FTF = fundamental train frequency (Hz)

N = number of balls

P = pitch diameter of balls (m)

f = fundamental rotational frequency (Hz)

θ = contact angle (degrees)

The signal produced by an outer race fault tends to be fairly constant in amplitude and frequency. For an inner race fault, the signal will have a constant frequency, but will vary in amplitude as the defect moves in and out of the load zone. A defect on the surface of one of the balls produces the most unpredictable signal. As the ball rotates, the defect may strike the race constantly, or the ball may be oriented so that it doesn't contact the races at all.

In order to study the effects of modifications on the motor's efficiency, a system for measuring the power input was designed. The voltage input to the motor is in the form of a pulse wave. Motor speed is controlled by varying the width of the pulses. Due to imperfections in the electronics, the voltage waveform tends to overshoot at the transition points. This asymmetrical shape, along with the 5 kHz fundamental pulse frequency, makes the power measurement task too demanding for normal wattmeters. Therefore, a system for power measurement was designed and constructed.

The following constraints were imposed on the wattmeter design:

- the meter must have a wide bandwidth, at least from 0 to 10 kHz
- the meter must be accurate
- the cost must be reasonably low and existing equipment should be used as much as possible
- the meter must be able to measure the input to all three phases simultaneously
- the system must have the capability to measure real and reactive power.

General analog wattmeters operate on the principle of mechanical or thermal inertia and are calibrated for sinusoidal waveforms. Therefore, a digital sampling technique was chosen for the power measurement. Digital power measurement devices have existed since about 1975 and are usually based on a digital sampling oscilloscope or a data acquisition system. With appropriate sensors, the current and voltage are sampled simultaneously. The power value may be calculated in real time or the samples may be stored for later calculation. Most digital power measurement devices use Fourier series techniques for the power calculations.

The spectrum analyzer, already in use for vibration analysis, provided a perfect solution to the sampling problem. The 6081Z Zonic analyzer has a maximum sample rate of 126 kHz and was designed especially for simultaneous sampling with minimal phase shift difference between input channels. Eight available input channels allow the input power on all three phases to be sampled at once. In addition, multiple ensembles may be averaged for more accurate results. All of the software routines required for calculation of the real and reactive power are already present. Using the ZCALC software option, the power content of all the harmonics may be summed and multiplied by the appropriate scale factor to get a single power value.

To accurately measure the power input to the motor, appropriate sensors are required for measuring the input voltage and current. A simple voltage divider circuit was constructed to lower the input voltage to within the input limits of the analyzer. Designing the current sensor proved to be a more difficult task. To ensure greater accuracy and better reliability, it was decided to use commercially available sensors if a suitable model could be found. The most convenient current sensors available are clip-on, Hall effect sensors. Hysteresis losses in the split core limit the maximum frequency of these sensors to about 400 Hz and also limit the accuracy. The bandwidth may be extended somewhat by making the core solid. Even then, the high cost and relatively low accuracy of these sensors make them poor choices. Shunt resistors are often used for current measurement especially for large power systems. Their wide bandwidth and relatively low cost make shunt resistors very attractive. However, the low resistance of most shunts provides a very low level output signal and makes them subject to noise problems. The current sensor selected for use is based on a magnetic flux balancing principle. The sensor is similar to a current transformer. A wire-wrapped core is placed around the current carrying element. A current is generated in the secondary coil to cancel the magnetic flux created by the primary wire. A Hall-effect-type sensor is used to detect the balance. The current in the secondary coil, which is equal to the primary current divided by the turns ratio, is then measured with a shunt resistor.

The inputs to many analyzers and oscilloscopes are single ended. If a common ground between the analyzer and the motor cannot be guaranteed, some sort of isolation circuitry must be utilized to protect the analyzer as well as the user. Also, care must be taken to match the phase shift in the signal conditioning circuitry of each signal. Otherwise, significant errors will result, especially if the power factor is low. Isolation amplifiers are available that would have eliminated the need for the voltage divider circuits. This type of device was rejected because of insufficient bandwidth and because of the need for phase matching the circuitry. Differential input operational amplifiers were used to solve the isolation problem. The same amplifiers were used for both voltage and current signals. Because of its fast sampling rate and simultaneous sampling capabilities, the spectrum analyzer was used for power measurements. The cross spectrum of the voltage and current signals was taken to determine the phase angle between the two and thus obtain the power factor.

Although the original intent of the program was to do bearing life testing, severe cooling problems were encountered with the motor. Most early work was directed toward finding the causes of the cooling problems and developing suitable solutions. The motor was designed with a water jacket around the casing. A recirculating liquid cooling system was built using a submersible pump and a heat exchanger adapted from an automotive heater core. While this helped to cool the stator cools, it did little to cool the rotor surface where the induction heating was occuring.

Heating in the rotor caused a small piece of the balancing putty to become brittle, break, and fly off. The resulting imbalance was detected by the monitoring system and the motor was automatically powered down. Disassembly of the bearings revealed that the grease had overheated and begun to dry out. The bearings were replaced and a system was designed to blow compressed air over the rotor surface to help to cool it. Soon after reassembly, the outer race of one of the bearings began to spin. Although the RMS vibration level was still normal, FFT analysis of the vibration signals indicated some type of problem. The exact nature of the problem however, remained unclear. Finally, the RMS level increased enough to cause shutdown. Disassembly of the motor revealed excess clearance between the outer race and the motor casing.

Even with both cooling systems operating, the bearing temperatures remained above the acceptable level. Therefore, it was decided to try to make the motor more efficient by optimizing the power factor. This created the need for an accurate system for measuring the real and reactive power inputs to the motor.

Chapter 2

Literature Review

2.1 Overview of Vibration Testing

Perhaps the most important and most informative motor condition to monitor is the bearing vibration. High vibration levels or changing vibration amplitude patterns are often a sign of impending failure. In addition, by studying the vibrational characteristics, important clues to the cause of the motor's deterioration may be obtained.

There is no universal standard unit for classifying vibration severity of machines. Usually, for vibrations in the 10 Hz to 1,000 Hz range, vibration velocity is used. In the United States and Canada, the peak value of the velocity is commonly used to characterize machinery vibrations. In Europe, the RMS velocity is most often used (Eshleman 1976). A special quantity called the "vibration severity" has been defined by the International Standards Organization (1974). The vibration severity of a machine is defined as the maximum RMS value of the vibration velocity measured at significant points on the machine such as bearings or mounting points.

Either a continuous or a periodic monitoring scheme may be utilized. Continuous monitoring systems usually monitor only the peak or RMS vibration level. Often, a threshold vibration level is set, and provisions are made to sound a warning or stop the machine if the threshold level is exceeded. Although this type of monitoring system is effective in preventing some unexpected failures, it cannot be expected to detect all vibration problems. An alternative is to monitor the vibration only periodically. The data may then be analyzed directly, or stored on magnetic tape for later analysis. A good example of where taping the vibration signals might be advantageous is provided by Bradshaw and Randall (1983). There, the large pumps and turbines associated with the Alaska Pipeline were monitored. The remote locations of the pumping stations and adverse weather conditions made on-site analysis impractical.

Usually, some type of statistical analysis is performed on the vibration signal in a periodic monitoring program. The vibration level of the machine is compared to that of other, similar machines or to past vibrational characteristics of the same machine. The analysis may be performed in the time domain, the frequency domain, or in the cepstrum domain. A spectrum analyzer is most often utilized in the analysis task. Although the FFT algorithm may be programmed onto a personal computer, filters are necessary to prevent aliasing of high-frequency signals. These anti-aliasing filters are not included on most microcomputer-based data acquisition systems.

Different types of faults in rolling element bearings such as inner race faults or outer race faults produce specific vibrational frequencies. However, when a ball strikes a fault in one of the races, it produces a sharp impact that contains energy at all frequencies. Thus, the greatest response will be at the bearing's natural frequency.

Three different types of transducers are in common use for vibration measurements. The type of transducer used depends on the requirements of the particular system to be monitored. Proximity probes are used to measure the relative displacement between the rotor or shaft of the machine to be monitored and some point on the housing. This offers some advantages for monitoring large journal bearings where the shaft movement gives a direct indication of the bearing condition. However, these transducers are effective only over a narrow frequency range. Velocity probes are used to obtain a direct readout of an objects velocity. This type of transducer is fairly complex and is limited to low frequencies.

Because of their rugged construction and wide frequency range, accelerometers are widely used for vibration measurement. A typical accelerometer consists of a mass and spring system and a piezoelectric crystal. When the mass is accelerated, either compression or shear stress is applied to the crystal, and the crystal generates an electrical charge. A very good documentary on accelerometer design and theory of operation is provided by Bouche (1975). Piezoelectric accelerometers may be categorized into two main groups, namely, charge mode accelerometers and voltage mode accelerometers. Charge mode accelerometers contain only a piezo crystal and a mass. The charge created by the crystal is conducted to an external charge amplifier with very high input resistance. This is necessary to prevent the measuring device from overloading the crystal. The output sensed by the charge amp is dependent on the length of the connecting cable. Voltage mode transducers employ an amplifier built into the accelerometer casing. Power for the transducer is typically supplied over the signal lines. The stronger output signal provides greater noise immunity and allows the use of longer cables.

Coaxial cables are typically used to transmit the signal to the measuring instrument. Care must be taken to minimize the cable capacitance to avoid signal attenuation and induced phase shifts. Reiter, Hodgson, and Eberhardt (1975) offer an extensive explanation of transmission and processing errors.

Although there are no absolute limits for the allowable vibration in rotating machinery, some national and international standards have been developed. Some of the standards deal only with the balancing quality of rotating machinery while others cover vibrations resulting from all excitation sources. There are three major sources of standards and guidelines for vibration monitoring. National and international standards organizations such as ANSI (American National Standards Institute) and ISO (International Standards Organization) comprise the first major source. Many national standards are adopted from those of industrial organizations such as NEMA (National Electrical Manufacturers Association). Guidelines may also be obtained from experienced individuals.

A general standard for balance quality of rotating machinery is provided by the Acoustical Society of America (1975). The standard covers dynamic as well as static balancing and offers guidelines concerning which is more appropriate for a given rotor. In general, the allowable rotor imbalance increases as the mass of the rotor increases and decreases with increasing speed. The ASA standard defines different balance quality grades. For each grade, the product of the eccentricity of the center of gravity and the rotational velocity is constant. A separate standard was proposed by NEMA (1971a, 1971b) concerning the allowable rotor imbalance in electric motors. The NEMA standard specifies how the motor is to be mounted for the balance test. Residual rotor imbalance is then detected by measuring the deflection of the motor housing during operation.

The International Standards Organization has developed a general standard for acceptable vibration levels in rotating and reciprocating machinery (ISO, 1974). This standard deals only with vibrations measured on the surface of the machine. The vibration severity , as previously defined, was chosen as the unit of measurement for quantifying the vibration level of the machine. The ISO standard addresses vibrational frequencies from 10 Hz to 1,000 Hz in machines with operating speeds between 10 and 200 rev/s. Three separate methods for mounting the machine are specified. The preferred method is to mount the machine on a resilient system such that the lowest natural frequency of the machine on its test stand is less than one-fourth the lowest excitation frequency. If the machine was designed to be mounted on a rigid baseplate, it must be tested on such a plate. The baseplate may be either much lighter than the machine and used for stiffening purposes or it may be much heavier. In either case, the machine-baseplate combination should be soft-mounted so that the lowest natural frequency of the machine-base combination is less than one-fourth of the lowest excitation frequency. If the machine is to large to be easily soft-mounted, it is generally tested on a given structural foundation. For variable speed machines, the tests are to be conducted at many different speeds in order to identify resonance frequencies.

For comparison purposes, machines are divided into six different classes. The classes are as follows:

1. Individual parts of machines and engines, integrally connected to the machine during normal operation. Typical examples are electric motors of up to 15 kW output power.
2. Medium-sized machines (typically electric motors with 15 kW to 75 kW output) without special foundations, rigidly mounted engines or machines on special foundations with output power up to 300 kW.
3. Large prime movers and other large machines with rotating masses mounted on heavy, rigid foundations.
4. Large prime movers and other large machines with rotating masses whose foundations are relatively soft in the direction of vibration measurement.
5. Machines that are mounted on stiff, rigid foundations with reciprocating parts whose inertial forces cannot be balanced.
6. Machines with reciprocating masses, mounted on foundations which are relatively soft in the direction of vibration measurement.

Quality grades A through D are assigned to the machines with grade A being excellent and D being unacceptable. Each quality grade represents a 4 dB increase in vibration velocity above the previous grade. Table 1 on page 15 is taken from the ISO standard and gives some guidelines for qualifying the vibration severity of different machines.

Some additional guidelines for vibration monitoring have been provided by the Southwest Research Institute (Lifson, Simmons, and Smalley, 1987). Here, the peak-to-peak displacement is used as the unit for vibration measurement. In order to address a wider range of machines, separate guidelines are offered for measuring housing vibration, shaft-to-bearing housing differential vibration, and shaft vibration related to bearing clearance. A list of correction factors has been developed to compensate the measurement for different sized machines, vibration isolators or soft foundations, high frequency excitation sources, and other effects. The measured displacements are multiplied by the appropriate correction factors to get an effective vibration displacement.

The Southwest Research Institute has developed separate graphs of vibration displacement verses frequency for each kind of measurement. The displacement graphs are

Table 1. Vibration Severity Ranges for Class 1 Through Class 4 Machines.

Ranges of vibration severity		Examples of quality judgement for separate classes of machines			
Range	rms-velocity *v* (in mm/s) at the range limits	Class I	Class II	Class III	Class IV
0,28	0,28	A	A	A	A
0,45	0,45	A	A	A	A
0,71	0,71	A	A	A	A
1,12	1,12	B	A	A	A
1,8	1,8	B	B	A	A
2,8	2,8	C	B	B	A
4,5	4,5	C	C	B	B
7,1	7,1	D	C	C	B
11,2	11,2	D	D	C	C
18	18	D	D	D	C
28	28	D	D	D	D
45	45	D	D	D	D
71		D	D	D	D

divided into different regions which are indicative of the machines condition. Separate regions are included for:

1. No faults present; this is typical of new machines.
2. Acceptable operation; no correction is necessary.
3. Marginal operation; correction is recommended.
4. Eventual failure is probable; the machine should be monitored closely and preparations made to shut down the machine for corrective maintenance.
5. Danger of immediate failure.

2.2 Overview of Microcomputer-based Data Acquisition Systems

There are three distinctive types of microcomputer-based data acquisition systems currently in use. The original systems were simply dedicated voltmeters or other instruments that were modified to connect to the computer through its RS-232 input port. Many high quality digital voltmeters and multimeters now have this capability. Although the inherent accuracy of the measuring instrument is preserved, this type of system is the least versatile. In many cases, the computer is used simply as a data logger. Also, it is difficult to connect more than one instrument to the computer at the same time. To help alleviate some of the problems with dedicated data acquisition systems, a new breed of instruments was developed. These instruments were mounted on cards that plugged directly into the computer bus. This type of system usually includes multiple input lines with either a single, multiplexed, instrumentation amplifier and A/D converter or a separate unit for each channel. An on-board microprocessor is utilized for control of the system. Usually, D/A converters on the board allow for output capabilities as well as inputs. These systems offer high performance at a much lower cost than a series of dedicated instruments. Often, software is available to allow a limited amount of signal processing.

The latest group of data acquisition systems to be developed combines the advantages of the two previous types of systems. A separate controller houses a group of specially designed, dedicated instruments. The controller has built-in intelligence and can allow sampling of multiple instruments at a fixed sample rate or on a priority basis. This is the fastest and most versatile type of data acquisition system available. Unfortunately, these systems are also the most expensive.

2.3 Data Acquisition Systems for Diagnostic Monitoring

Data acquisition systems can take on a wide variety of shapes and levels of sophistication. One common characteristic of these systems is that remote vibration sensors are used to determine conditions that cannot be measured directly. According to Lyon and DeJong (1983), the processing of vibration signals should be elaborate enough to separate the sources, locate their position, recover their signatures, and provide enough information to decide whether a defect is present or adjustment is needed.

One of the earliest data acquisition systems for monitoring electric motors was developed by Usami et. al. (1979) in Japan. The system utilized statistical techniques and had special hardware for computing FFT algorithms. It was used for monitoring acoustic noise produced by small induction motors in an industrial plant to detect the sounds made by an abnormal motor. Variations in the peak and RMS vibration levels as well as the envelope shape were evaluated constantly to get an indication of motor conditions. Using octave analysis, different noise signatures were categorized. Each type of noise was indicative of a certain motor phenomenon such as balls rubbing, rotor imbalance, or the motor accelerating or decelerating.

This monitoring system suffered from several serious deficiencies. First, the system was susceptible to noises entirely unrelated to the motors, such as fan noise. Also, at low frequencies, the noise caused by the motors was below the threshold level in the factory.

A followup report (Usami et. al., 1980) on a revised and improved system was released a year later. The later system was designed to monitor bearings in large industrial motors and utilized accelerometers to measure vibration directly. Motor bearing defects were detected and categorized as being caused by scratched cracks, poor lubrication, or mixed rubbish. The term "scratched cracks" was used to categorize all inner and outer race faults as well as faults on the balls. Mixed rubbish was the term used to indicate foreign matter in the bearings.

Up to 256 different bearings could be monitored by the system. The accelerometer output signals were first routed to central collection points and then to a microcomputer. For displaying and storing the information, a color monitor, pen plotter, and disk drives, were included. The system also included self-diagnostic capabilities to detect broken cables or power supply failures.

Normally, only peak and RMS vibration levels were monitored. If the vibration exceeded a threshold value, a series of time-domain statistical routines were executed to identify the problem. If necessary, FFT analysis could be performed manually.

A slightly different data acquisition system was discribed by Bradshaw and Randall (1983). This system was used for periodic monitoring of machinery associated with the Alaska Pipeline. The system was required to monitor various pumps, turbines, and generators covering a wide speed range. Because of the remote locations of the pumping stations and adverse weather conditions, a very rugged and easily transportable system was necessary. To fulfill these stringent requirements, measurements were taken using a triaxial accelerometer which was bolted to various points on the machine to be monitored. The vibration signals were then stored on magnetic tape using an FM tape recorder and returned to the maintenance headquarters for detailed analysis. A comprehensive, commercial program was used for diagnosis of the vibration signals. For fault detection, the program compared the spectrum from each measurement point with previously measured spectra. Significant increases in amplitude at any frequency were taken as indicators of oncoming failure. A much more detailed procedure was used for fault diagnosis. Initially, specific frequencies such as ball-passing and blade-tip passing frequencies were studied. Cepstrum analysis was then used as an additional diagnostic tool.

The machine diagnostics program has allowed the detection of bearing faults as much as six months before the actual bearing failure occurred.

2.4 Methods of Power Measurement and Power Factor Determination

The fundamental equation for calculating the average power input to an electrical device is (Turgel 1974):

$$P = \frac{1}{T}\int_{0}^{T} e(t)i(t)dt \qquad [2.1]$$

where:

e = instantaneous voltage
i = instantaneous current
T = some time period, usually a multiple of the period of e or i

The integration of this equation may be performed either by analog or digital means.

In an analog wattmeter, the integration may be carried out by the transducer making use of some type of mechanical or thermal inertia (Turgel, 1975). Some examples of wattmeters using this principle are electrodynamometers, electrostatic wattmeters, and electrothermic type wattmeters. The oldest and most popular type is the electrodymamometer. These meters are typically calibrated for 60 Hz sinusoidal waveforms and perform very well for this purpose. However, for high-frequency signals or asymmetrical waveforms, they will not produce satisfactory results. Some analog meters use a Hall-effect or similar type transducer to sample the instantaneous current and voltage values. The integration is then performed by special analog circuits in the readout device. These devices provide the advantage of a continuous readout, but the frequency range is dictated by the speed of the analog multiplying circuits.

Recent advances in electronics have made digital power measurement more attractive. Here, the instantaneous voltage and current values are measured and the integration is carried out numerically. Equation 2.1 is, therefore, replaced by the equation:

$$P = \frac{1}{N}\sum_{j=1}^{N} e_j i_j \qquad [2.2]$$

Digital power measurement techniques offer several practical advantages. The first is that system errors following the digitization can approach zero. Also, if the data values can be stored, the multiplication in Eq. 2.2 does not have to be performed in real time. Thus, the bandwidth of the wattmeter is limited only by the digitization rate and matching of the signal conditioning equipment (Lesco, D. J., Weikle, D. H., 1980). Quantization errors may be significant, especially if the power factor is low or if the readings are substantially below full scale.

Turgel (1974, 1975) used a trapezoidal rule scheme to perform the numerical integration. The most popular mathematical tool for evaluating the power content of asymmetrical waveforms is a Fourier series analysis. This method is especially attractive if a spectrum analyzer or digital oscilloscope with built-in FFT routines is used for sampling the voltage and current.

Regardless of the mathematical evaluation technique utilized, several physical constraints must be observed. First, an adequate sample rate must be used. In order to prevent aliasing, the sample rate must be at least twice the highest frequency component of the signal to be sampled. The instantaneous power varies at twice the frequency of the voltage or current, so a sample rate of at least four times the highest voltage or current component is required. In addition, timing errors and other system errors require that a somewhat higher sample rate be used. Turgel (1975) recommends a minimum sample rate of 50 kHz and a minimum of 512 sample points for signals containing frequency components up to 10 KHz. The current and voltage must be sampled simultaneously. Any timing errors will be reflected as errors in the power measurement. In order to minimize the errors, all of the signal conditioning electronics must be phase matched (Lesco, D. J., Weikle, D. H., 1980).

Finally, many digital oscilloscopes and spectrum analyzers have single-ended inputs. If the current and voltage measurements cannot be made relative to the analyzer ground, some type of isolation devices are required.

2.5 Systems for Power and Phase Measurement

Numerous digital schemes have been proposed for electric power and phase angle measurement. The hardware and computing algorithms vary widely as do the capabilities of the various systems.

Al-Ani and Abdul-Karim (1984) developed a system where a voltage to frequency converter and a counting technique were used to determine the phase angle between the current and voltage signals. The method, however, was based on the assumption of 60 Hz sinusoidal signals and is not applicable here. Another related technique developed by Hafeth and Abdul-Karim (1984) utilized a non-linear A/D converter for digitizing the input signals and analog circuits for the multiplying operations. This system was also based on the 60 Hz input assumption.

Abdul-Niby and Fyath (1987) have proposed a scheme for measuring the phase angle between signals of frequencies up to 100 kHz. This relatively simple approach uses zero crossing detectors and binary dividers to convert the signals into square waves. Using digital logic circuits, a pulse wave is constructed with the width of the pulses being proportional to the phase difference between the two channels. Provisions for lead-lag indication are included. In addition to sine waves, the system may be used for square waves or triangular wave inputs.

A method for calibrating wattmeters using a capacitance bridge has been designed by Oldham and Petersons (1985). The system utilizes a precision voltage and current source and has an uncertainty of approximately 20 parts per million.

A novel method for measuring the real and reactive components in power systems was proposed by Kusters and Moore (1980). The method was designed for ease of use and to give a direct indication of whether the reactive power in a power system may be reduced. This was achieved by dividing the power into an active component, a reactive component, and a residual component. Voltage was treated as a constant and the current was divided. A resistive current was derived to have the same waveform and phase as a current through a resistor with the same voltage across it. Likewise the reactive current had the same waveform and phase as that in an inductor or capacitor with the same voltage across it. Whatever current was left over was defined as the residual current. With non-sinusoidal signals, the residual current will have a non-zero value. The physical current analyzer was constructed from a series of operational amplifiers.

2.6 Fourier Series Techniques

The most popular way of representing periodic signals is by a Fourier series. The one drawback of most Fourier analysis techniques is that complex and expensive data acquisition and signal processing equipment is required.

A somewhat simpler system using a standard wave analyzer was devised by Szabados and Hill (1977). The system, which is based on the principle of frequency rejection, was designed for measuring power system harmonics. The device was connected to a standard wave analyzer, used as a tuned voltmeter for null detection, and was capable of measuring steady state or slowly varying signals. The voltage and current signals were represented by Fourier series as:

$$S(t) = \sum_{n=1}^{N} S_n \sin(n\omega t + \theta_n) \qquad [2.3]$$

where:

n = the order of the harmonic
S_n = the amplitude of the harmonic
θ_n = phase angle of the harmonic
ω = fundamental frequency
t = time
N = number of harmonics

The device generated a specific harmonic frequency R precisely locked on the fundamental of the unknown signal $S(t)$. The reference wave was represented as:

$$R(t) = R_n \sin(n\omega t + \psi_n) \qquad [2.4]$$

where:

R_n = magnitude

ψ_n = absolute phase angle of the generated signal

Both signals were input into a summing amplifier and the output was sent to the waveform analyzer which was tuned to the specific harmonic frequency. The signal measured by the analyzer was:

$$A = S_n \sin(n\omega t + \theta_n) - R_n \sin(n\omega t + \psi_n) \qquad [2.5]$$

The values of R_n and ψ_n were adjusted until the unknown harmonic signal was completely cancelled. Thus, by measuring R_n and ψ_n, the magnitude and phase of the unknown harmonic were obtained.

A similar system was proposed by Lopez, Asquerino, and Rodriguez-Izquierdo (1977). Again, the voltage and current waveforms were represented by Fourier series. A frequency controlled sine/cosine oscillator was used to produce the harmonic frequencies of the voltage waveform. Analog circuits were utilized to perform algebraic manipulation of the unknown and reference signals to obtain the reactive power for each harmonic. Power components for all significant harmonics were then summed to obtain the total reactive power.

Hope, Chang, and Malik (1981) designed a microprocessor-based system for the measurement of active, reactive, and apparent power in three-phase power systems. Voltage and current signals were represented by Fourier series. The input signals were multiplied by a pair of reference functions $F_d = \sin(\omega t)$ and $F_q = \cos(\omega t)$ to resolve the active and reactive power components. Only the fundamental 60 Hz component of the power was measured by the system. A low-pass filter with the cut-off frequency set to 90 Hz was used to remove all harmonics from the voltage and current signals.

2.7 Electrical Current Measuring Devices

Digital power measuring techniques depend on separate transducers for measuring the current and voltage signals. Measuring voltage is relatively simple. In many cases, the voltage can be digitized directly by the sampling instrument. If the voltage is outside the maximum input range of the instrument, a voltage divider circuit, a voltage transformer, or an isolation amplifier may be utilized. Most instruments, however, cannot measure current directly. Some means of providing a voltage signal proportional to the current must be devised. This task is considerably more difficult if the waveform is asymmetrical or contains high-frequency components.

Rogowski coils are commonly used as current sensors for high-current, pulsed-power measurements (Krompholz, Shoenbach, and Schaefer, 1985). A Rogowski coil consists of a helical coil placed around the line carrying the current to be measured. The coil is usually terminated with a small resistor. A voltage is induced across this resistor that is related to the primary current. The output signal measured across this resistor is:

$$V(t) = \frac{R}{N}\int \frac{di}{dt}(\tau)\,\exp[\frac{R}{L}(t-\tau)]d\tau \qquad [2.6]$$

where:

N = number of turns
L = coil inductance
i = current
$\frac{di}{dt}$ = the time derivative of the current to be measured.
R = resistance value

These sensors typically have a sensitivity of 0.001 volts/ampere and thus are effective only for currents of over 100 amperes.

An improved version of the Rogowski coil has been proposed (Krompholz, Doggett, Shoenbach, et. al., 1984) that offers much higher sensitivity. This transmission line current sensor was designed with square shaped coils encased in a slotted metallic torus. A high capacitance value between the coil and the torus allows sensitivities as high as 1 volt per ampere.

An alternate current sensor proposed by Tozer (1984) utilizes a current transformer with electronic circuitry to compensate for the high-pass characteristics of the transformer. Good linearity was achieved over a bandwidth of 100 kHz to 30 megahertz. The output from the sensor was displayed using an oscilloscope. A somewhat simplified current sensor operating on the current transformer principle was discribed in the IBM Technical Disclosure Bulletin (IBM, 1985). Again, an oscilloscope was used to display the current pulses.

Shunt resistors are often used for current measurements. The voltage difference across the shunt gives a direct indication of the current magnitude and direction. These devices are available to measure impulse currents an high as 10,000 amperes with a rise time as fast as 50 nanoseconds. Shunts are relatively easy to calibrate and give a linear output over a wide frequency range. The main source of error for impulse currents is the magnetic coupling between the primary current and the output signal. Two types of shunts are in common use. Tubular shunts effectively reduce the magnetic coupling errors, but, because of their low resistance, are useful only for high currents values. For smaller currents, wirewound shunts are used. A comprehensive review of wirewound shunt designs was prepared by Malewski (1984).

Several different commercially available current sensors were considered for the present study. Fluke Inc. (Fluke, 1987) manufactures current shunts and clip-on, Hall-effect current probes. The low-cost current shunts are designed to be accurate to within 0.25 percent from DC up to 25 kilohertz. A maximum current rating of 10 amperes made this sensor unsuitable for the present study. A second clip-on sensor from Fluke was also considered. The Hall effect probe was rated for currents up to 700 amperes and frequencies up to 440 hertz. The probe is used in conjunction with an oscilloscope or voltmeter. Because of its low bandwidth and high price, this probe was also rejected. A Hall-effect current sensor built by Ohio Semetronics (1987) was also considered. This sensor was built with a solid core to extend the frequency range to five kilohertz.

A Swiss-built current sensor was chosen for the current project. The LEM current module (Liaisons Electroniques Mecaniques, 1985) operates on a zero magnetic flux principle. Magnetic flux from the current to be measured is balanced by the flux created by a current flowing through a secondary coil. A Hall-effect sensor is used to detect the flux balance. The current in the secondary coil is an exact replica of the primary current divided by the turns ratio between the primary and secondary coils. The secondary current, typically on the order of a few mA, is then measured using a small shunt resistor. The transducer has a bandwidth from DC to 100 kHz with a slew rate of 50 amperes per microsecond. Accuracy of better than 1 percent can be obtained with proper installation. The transducer also features complete electrical isolation between the primary and secondary currents and very high overload protection. The sensor was chosen mainly for its high accuracy, excellent frequency response, and low price.

Chapter 3

Bearing Test Vehicle, Instrumentation, and Data Acquisition System

3.1 Test Rig

A high-speed electric motor built by Industrial Drives Division of Kollmorgan Corporation was used as a test vehicle for the bearing-life tests. The brushless induction motor is designed with a solid steel rotor. The rotor is made up of carbon steel and non-magnetic stainless steel sections welded together. A separate controller utilizes transistor switching circuits to move a magnetic field around the stator coils in the casing causing the rotor to turn. The three-phase, 208 volt input is transformed first down to 104 volts, and then into a 5 kHz pulse wave. Motor speed is controlled by changing the width of the pulses and thus the power input into the motor. The motor was designed with a water jacket in the casing to help in cooling the stator coils. Coolant is pumped through the water jacket at a rate of approximately 0.25 liters per second. Using a submersible pump, the water is pumped through the water jacket, through a heat exchanger, and back into an open reservoir. The heat exchanger was adapted from an automobile heater core. The heater core is shrouded and a small fan is used to force air through the coils. In addition to the water cooling, compressed air is blown across each end of the rotor to help cool the bearings. The hot exhaust air is vented through a tube out of the test laboratory.

Twenty millimeter ABEC-7 grade precision ball bearings built by Barden Corporation (Barden, 1980) were used in the bearing life studies. Although the motor was designed for air-oil mist lubrication, grease lubricated bearings were used for this study.

The two bearings in the motor serve as the primary test bearings. Thus, there is no separate power unit and test bearing mounting shaft. This eliminates the coupling and alignment problems often encountered with bearing test rigs. Because alignment is not critical, there is no need to construct a special test stand for the motor. Also, since there is no external power unit, there are no bearings to be monitored other than the primary test bearings. With the limited capacity of the data acquisition system and limited computer memory, this becomes a very important factor. The rotor is extremely well balanced and eliminates the instability problems encountered with earlier test rigs (Pinckney, 1985). The solid steel rotor is very stiff and the bearings are closely spaced, so the first critical speed of the rotor is fairly high. To estimate the first critical speed, the rotor was modeled as a continuous, constant diameter elastic shaft as discribed by Reiger (1982). Bearing stiffness is dependent on the amount of bearing preload, so critical speeds were calculated for a range of bearing stiffness values between 0.5 Mpsi and 50 Mpsi. The calculated values of the first critical speed ranged between 62,000 RPM and 105,000 RPM. In addition, the air supply required for the present power unit is substantially less than what would be needed for an air-driven turbine.

Using an electric motor as a test vehicle does present several difficulties. There is no easy way to apply an external load to the test bearings without attaching another bearing to the output shaft. For high speed operation, most of the bearing stresses are caused by centrifugal forces, so this does not effect the bearing tests. However, most motors are designed to run with a load and operate very inefficiently under no-load conditions. With its solid steel design and smooth surface, the rotor is subject to severe induction heating. Some of this heat is conducted out to the bearings. The stator windings and an air gap are between the rotor and the casing containing the water jacket. Because of this, the liquid cooling system does not adequately cool the rotor at high speeds. Forced air cooling becomes necessary for continuous operation at speeds higher than 15,000 RPM. The motor is also very noisy at high speeds. Long term operation of the system is possible only in some type of acoustic isolation chamber. The electric transformer, the controller, and the motor release a significant amount of heat. Because of this, cooling the small acoustic chamber used in this study became a problem. This posed a danger to the computer and electronic instrumentation.

The motor created a very noisy electrical environment for the low output sensors used in the instrumentation system. Some of these problems were overcome by electrically isolating the accelerometers from the motor casing and using a low-pass filter on the stator thermocouple signal.

3.2 Instrumentation and Data Acquisition Hardware

A dedicated data acquisition and control system was built for the bearing testing program. The system is based on an IBM Personal Computer with dual floppy disk drives and 256 kilobytes of memory. A Data Translation DT-2805 data acquisition card and a multifunction card were added to the computer.

The DT-2805 card is designed primarily for thermocouple inputs and other low level signals. The card features a 12 bit A/D converter with integral instrumentation amplifier. Software selectable gains of 1, 10, 100, and 500 are available allowing a full scale input range of 200 mV to 10 volts. Two 12 bit D/A converters are available and may be operated together or independently. The card has its own programmable clock and has provisions for direct memory access. Maximum throughput of the A/D is 13,500 samples per second depending on the gain. As the gain is increased, the maximum sample rate decreases (Data Translation Inc., 1984).

A DT-707T terminal strip from Data Translation was connected to the DT-2805 card. The DT-707T terminal strip provides screw terminal strips for inputs and outputs. An on-board, solid-state temperature sensor provides cold junction compensation for the thermocouple inputs.

The PCTHERM software from Data Translation was used with the DT-2805 card. This group of machine language subroutines may be called from the main BASIC program. No machine language programming is required to operate the card. The PCTHERM software contains lookup tables for all standard types of thermocouples.

A MF-100 multifunction card was also added to the computer. The card provides an extra 384 kilobytes of memory as well as serial and parallel I/O ports. More importantly, the card has a real time clock with battery backup power to keep time when the PC is off. This clock is used to record the time and also to control the sample rate of the data acquisition system.

Type "K", chromel-alumel thermocouples with teflon insulation were used for all temperature measurements. The thermocouples were purchased from Omega Engineering. A special adhesive made up by Industrial Drives was used to mount the thermocouples. Copper powder was added to the adhesive to enhance its thermal conductivity. A thermocouple was held in contact with the outer race of each bearing, one was attached to the stator windings, and a fourth was attached to the motor casing. The thermocouples were hooked directly to the DT-707T terminal strip.

Model 303A02 accelerometers built by PCB Piezotronics were used to measure bearing vibration. These were mounted on the motor casing in the radial plane of each bearing. The model 303A02 accelerometer weighs only 2 grams and has a mounted resonant frequency of 100 kilohertz. If mounted properly, the transducer has an operating range from 0-10,000 Hz with a maximum error of 5% at the highest frequencies (PCB Piezotronics Inc., 1984). This allows the ball passing frequencies of the bearings to be sensed at operating speeds of over 50,000 RPM. Special insulated mounting bases were used to electrically isolate the accelerometers from the motor casing. The accelerometers have mounting studs built into the casing. These studs were screwed tightly into the coated aluminum mounting bases. The bases were attached to the motor casing using strain gauge adhesive.

A single PCB model 482A04 line power unit was used to power the accelerometers. The power unit provides power over the signal leads to the transducers. A built-in 10 microfarad coupling capacitor removes the DC bias from the transducer output signal. The power unit also includes a monitoring circuit to detect such faults as connector short circuits or transducer amplifier malfunction. The line power unit was chosen because battery powered units are impractical for long term, continuous operation. However, the line power unit imposes a 60 Hz noise signal on the output. This poses severe problems for FFT analysis of the bearing vibration signals. Also, the model 482AO4 power unit does not have a variable output gain option. For low speed operation, the vibration signals are below the accurate operating range of the RMS to DC circuits.

To solve these problems, the output from the power supplies was amplified using National Semiconductor LM318 differential input operational amplifiers. These amplifiers feature wide bandwidth and a high common mode rejection ratio (National Semiconductor, 1982b). The amplifiers are wired for a gain of ten. Sixty Hz line noise is virtually eliminated from the acceleration signals by the amplifiers. Special low noise cables are used to help prevent further contamination of the signals. For FFT analysis, the output from the amplifiers was sampled directly. Figure 2 on page 34 shows the circuit diagram of the signal conditioning circuitry for vibration signals. The trimming circuit for the RMS to DC converters is included in the calibration section.

The maximum sample rate for the data acquisition card in the PC at high gain is 6,000 samples per second. Since the output from the accelerometers contained frequency components above 10 Khz, it was impossible for the data acquisition system to accurately sample the waveform. The problem was solved by constructing a true RMS rectifier circuit for each acceleration signal. Each rectifier circuit consists of a National Semiconductor LM0091 true RMS to DC converter and the appropriate trimming circuitry. The RMS to DC converter generates a DC output equal to the RMS value of an arbitrary input via the transfer function:

$$V_{out} = \sqrt{\frac{1}{T}\int_0^T E_{in}^2(t)dt} \qquad [3.1]$$

The RMS to DC converter can be trimmed for maximum accuracy over a one decade input voltage range (National Semiconductor, 1982a). The minimum input voltage is about 50 millivolts. With the normal vibration level in the area of 1-3 g, the amplifiers are essential for the RMS circuits to be accurate. The RMS circuits were trimmed to operate in the 100 mV to 1.0 V range.

In order to prevent crosstalk between the channels, a separate power supply was used for each RMS circuit and amplifier combination. The two power supplies provide bipolar 12 V output and are extremely well regulated. This helps to eliminate 60 Hz ripple from the output of the amplifiers.

A magnetic-inductance-type sensor in the motor provides a 1 pulse/rev signal to the motor controller. A frequency to voltage converter in the controller then provides a DC output signal proportional to the motor speed. This DC signal is monitored by the data acquisition system. The frequency to voltage converter was found to be highly sensitive to temperature changes. This was overcome somewhat by allowing the motor to run until reaching equilibrium before calibrating the system.

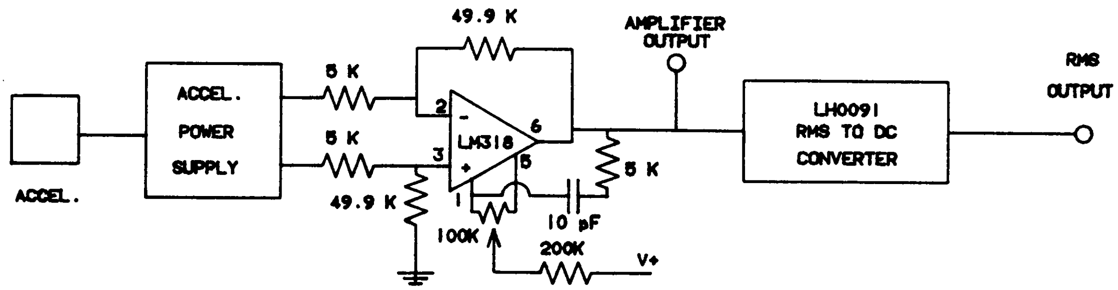

Figure 2. Circuit Diagram of Vibration Amplifiers and RMS to DC Converters.

3.3 Hardware for Power Measurement

Power input to the motor was measured by sampling the instantaneous current and voltage inputs and using Fourier series analysis to calculate the power.

The LEM Module (Liaisons Electroniques Mecaniques, 1985) current sensor was used for current measurement. It operates on a zero magnetic flux principle. The module is capable of measuring any type of arbitrary waveform over a wide frequency and amplitude range. In addition, complete electrical isolation between the primary and secondary currents is provided. The operating principle of the sensor is simple. The magnetic flux created by the current to be measured is balanced by the flux from a current generated in a secondary coil. A power supply with positive and negative 12 V outputs is required to generate the secondary current. The secondary coil has an air gap, in which a Hall-effect sensor is located. The Hall-effect sensor detects the product of the magnetic flux created by the two currents and controls an electronic circuit that, in turn, controls the current in the secondary coil. Thus, the current is related to the primary current by the equation by the equation:

$$N_p i_p = N_s i_s \qquad [3.2]$$

where:

N_p = number of turns in the primary coil

i_p = current in the primary coil

N_s = number of turns in the secondary coil

i_s = current in the secondary coil

The LEM Module has a slew rate of 50 amps per microsecond and a response time of less than 1 microsecond. Bandwidth is up to 100 kHz with accuracy of better than 1 percent. In addition, because the secondary current is electrically isolated from the primary current, the sensor can withstand extreme overloads without any damage.

The voltage of each input line was measured relative to the controller ground. A voltage divider circuit was constructed to reduce the voltage to within the input limits of the Zonic 6081Z spectrum analyzer.

Because the analyzer inputs are single ended, and the analyzer and controller did not have common electrical grounds, differential input operational amplifiers were used to isolate the input signals. National Semiconductor LM318 amplifiers were chosen for their wide bandwidth and flat gain characteristics. The amplifiers were all configured exactly alike to assure phase matching and wired for unity gain. Because the spectrum analyzer was located a considerable distance from the controller, special compensation was required to drive the long coaxial cables. Figure 3 on page 37 shows the setup of the current and voltage measuring circuits.

A Zonic 6081Z spectrum analyzer and modal analysis system was used for the spectrum analysis of the bearing signals and for power measurements. The 6081Z analyzer is a stand-alone unit with its own microprocessor. The system has eight single-ended input channels. The maximum sample rate for all the channels is 50 kHz. All setup and data acquisition procedures are software controlled. The RTL (real-time language) software from Zonic makes data acquisition and processing easy. The ZCALC software option allows data obtained in RTL to be manipulated and displayed in alternate formats. Thus, the harmonic components of the cross spectrums of the voltage and frequency signals can be summed and multiplied by the appropriate scale factor to get the true power value. The built-in auto-ranging capability allows a wide range of input voltages. Autospectra and cross spectra for each channel pair may be stored either on the 15 megabyte hard disk or on 3 1/2 in floppy disks. Up to four frequency response functions may be overlaid on the color monitor for easy comparison.

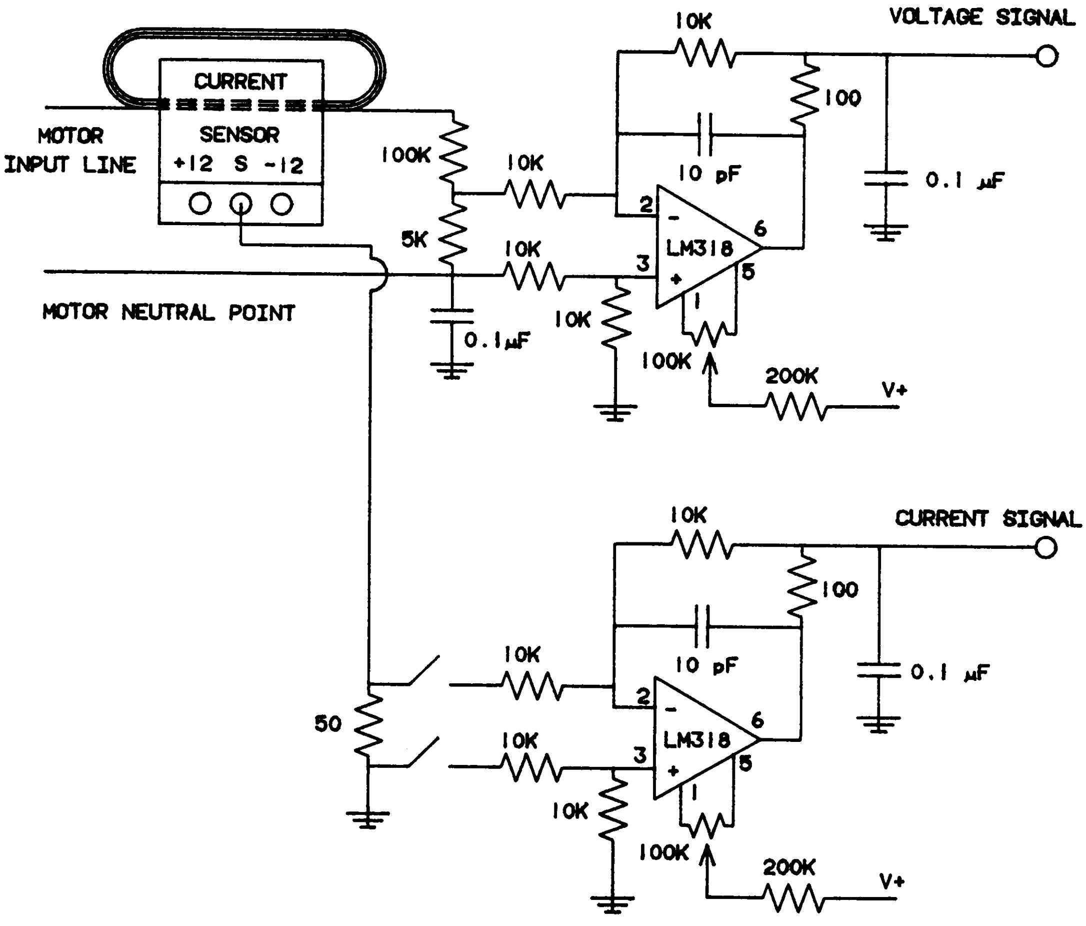

Figure 3. Hardware for Power Measurement: Voltage and current transducers and amplifiers for common mode voltage isolation.

3.4 Data Acquisition Software

Two separate software packages were written to control the PC-based data acquisition system and to obtain plots of the data on a Versatec electrostatic plotter. A third BASIC program was utilized to produce plots on a PC dot matrix printer.

The main data acquisition program was written in BASIC. The program was developed interactively, then compiled for faster execution. The program was written as a series of separate modules with different subroutines for sampling each input. This made the program easier to develop and also to understand. A flowchart of the program logic is included in Appendix A, and the actual code is in Appendix B.

Writing the program in BASIC allowed the PCTHERM (Data Translation Inc., 1984) software to be used to interface the PC to the data acquisition card. The PCTHERM software consists of a library of machine language subroutines to control the DT2805 data acquisition card. These routines may be accessed by issuing calls in the main BASIC program. Three separate routines were utilized. The "Measure Thermocouple" routine was used to sample the thermocouple inputs. A channel number and thermocouple type must be input to the routine, which then sets the amplifier for the correct gain and takes 16 readings of the thermocouple input voltage. The output of the solid state temperature sensor on the terminal strip is likewise sampled and, using the built-in thermocouple tables, the correct temperature is calculated. The "Measure Volts" routine takes 16 readings of the input voltage on the specified channel and returns the average voltage value. A third PCTHERM routine is used to control the output of the D/A converter to control the motor speed.

The data acquisition software allows the user to independently specify the data sampling and storage rate. Motor speed may be varied on command, and the data may be stored on either disk drive. Two separate output displays are available. The first displays the data in digital form. In addition to the data values being sampled, the amount of data on the disk and the sample and storage rates are displayed. A menu is also displayed to list the function key that is used to specify each software option. Figure 4 on page 40 shows the digital output format. In order to allow the operator to quickly see the operating condition of the motor, a graphical display was developed. This displays the operating parameters of the test vehicle in the form of bar graphs. Figure 5 on page 41 shows an example of the bar graph output.

DATE/TIME (mn-dy-hr-min-s)	T.CAS (C)	T.B1 (C)	T.B2 (C)	T.STAT (C)	M.SPEED (rpm)	V.ACC1 (g)	V.ACC2 (g)
11 6 13 15 9	28	38.9	39.1	38	16,313	2.38	2.90

AMOUNT OF DISK SPACE USED = 0 KILOBYTES
SAMPLING ON DRIVE B
SAMPLE RATE = 30 SAMPLES/MIN
STORAGE RATE = 1.0 SAMPLES/MIN
PRESS F1 TO STORE DATA ON DISK DRIVE A
PRESS F2 TO STORE DATA ON DISK DRIVE B
PRESS F3 TO RETURN TO SCREEN #1
PRESS F4 TO DISPLAY BAR GRAPHS
PRESS F5 TO CHOOSE OPERATING SPEED
PRESS F6 TO POWER DOWN MOTOR
PRESS F7 TO RETURN TO NORMAL STORAGE RATE
PRESS F8 TO GO TO FAILURE STORAGE RATE
PRESS F9 TO GO TO OPERATING SPEED
PRESS F10 TO GO TO WARMUP SPEED

Figure 4. Digital Output Display From Data Acquisition System

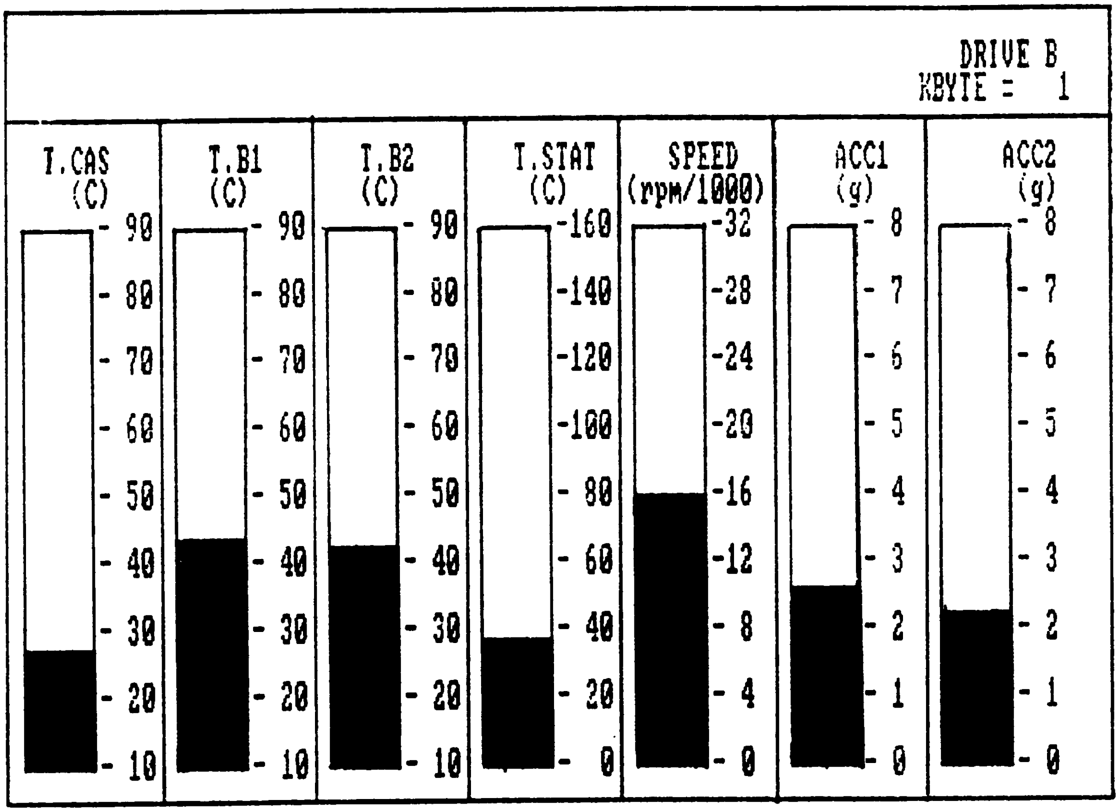

Figure 5. Graphical Display for Data Acquisition System

Chapter 4

Calibration and Testing Procedures

4.1 Test Conditions

Because of the noise generated by the motor at high speeds, all testing was conducted in an acoustic isolation chamber. The chamber is well insulated thermally as well as acoustically. A small amount of air circulation was provided by specially ducted fans in the ceiling of the room. The temperature in the chamber varied, but was usually between 24 and 30 degrees Celcius. The liquid cooling system was operated continuously while the motor was in operation. A cooling fluid flow rate of approximately 0.25 liters/second was used and coolant temperatures ranged between 27 C and 46 C depending on the motor speed. Various cooling air flowrates were used for different tests.

After some initial runs to determine the normal operating characteristics of the motor, the maximum normal casing temperature was set to 50 degrees Celcius. The maximum normal bearing temperature value was set to 65 C and the stator temperature value was set to 140 degrees Celcius. The average RMS vibration level for normal bearings at 20,000 RPM was found to be around 4 g. A maximum normal RMS bearing vibration level of 8 g was chosen. Above these maximum normal levels, the data acquisition system sampled at an increased rate until shutdown levels were reached. These maximum allowable values were set at 80 C, 70 C, and 160 C for the casing temperature, bearing temperature, and stator temperature respectively, and 10 g RMS for the bearing vibration.

4.2 Calibration Procedure

The data acquisition card and accelerometers were calibrated at the factory and no further calibration was attempted. Calibration curves were included with each accelerometer that included the nominal average sensitivity of the transducer.

The vibration amplifiers and RMS to DC converters were calibrated before each major test. A Fluke model 8050A, 4 1/2 digit multimeter was used for the calibration. The RMS circuits and operational amplifiers were designed with a mechanical switch between them. This switch was opened to allow the amplifier and RMS circuit to be calibrated independently. The data acquisition system was operated for several hours before calibration to allow all circuits to reach their equilibrium temperature. Because a suitable AC calibration method was not available, the RMS circuits were calibrated for DC inputs only. The frequency response characteristics of the amplifiers were documented using the spectrum analyzer.

In order to adjust the zero offset of the amplifiers, a shorting plug was placed in the input connectors and the balance trim potentiometer was adjusted to get a zero output. The amplifiers do not have a provision to adjust the gain. In order to compensate for the gain errors, the output was measured for inputs from 0.01 V to 0.1 V in steps of 10 mV. The average gain value was calculated, and the value was programed into the data acquisition software.

The RMS to DC converters were trimmed for DC inputs from 0.1 volt to 1.0 volt. Figure 6 on page 45 shows the trimming circuitry used for the RMS converters. The trim procedure is taken from the National Semiconductor Hybrid Products Databook (1982a) and is as follows:

1. Apply 0.1 V DC to the input. Read and record the output.
2. Apply -0.1 V DC to the input. Use R2 to adjust for an output of the same magnitude as in step number 1.
3. Apply 0.1 V to the input. Use R3 to adjust the output to 0.1 volt.
4. Apply -0.1 V to the input. Use R2 to adjust the output for 0.1 volt.
5. Apply plus and minus 1 V alternately to the input . Adjust R1 until the output for both polarities are equal (not necessarily that they be equal to 1.0 V).
6. Apply 1.0 volt to the input. Use R4 to adjust for 1.0 V at the output.
7. Repeat the procedure to obtain the desired accuracy.

The motor speed was calibrated using a strobe light. Because the output from the motor speed sensor was not linear and varied widely with temperature, a highly accurate calibration was not possible. As the motor speed was not considered a critical variable, no attempt was made to correct the sensor error. However, in order to compensate for the temperature dependence, the motor was allowed to run for several hours to reach an equilibrium temperature before calibrating the speed sensor. The output voltage was measured for speeds from 500 RPM to 20,000 RPM in 500 RPM increments. A straight line was then fit to the data points to estimate the sensor output.

4.3 Calibration of Power Measurement Circuits

The calibration procedure for all of the amplifiers in the power measurement circuitry was the same. The circuits were powered up and allowed to operate for several hours to reach

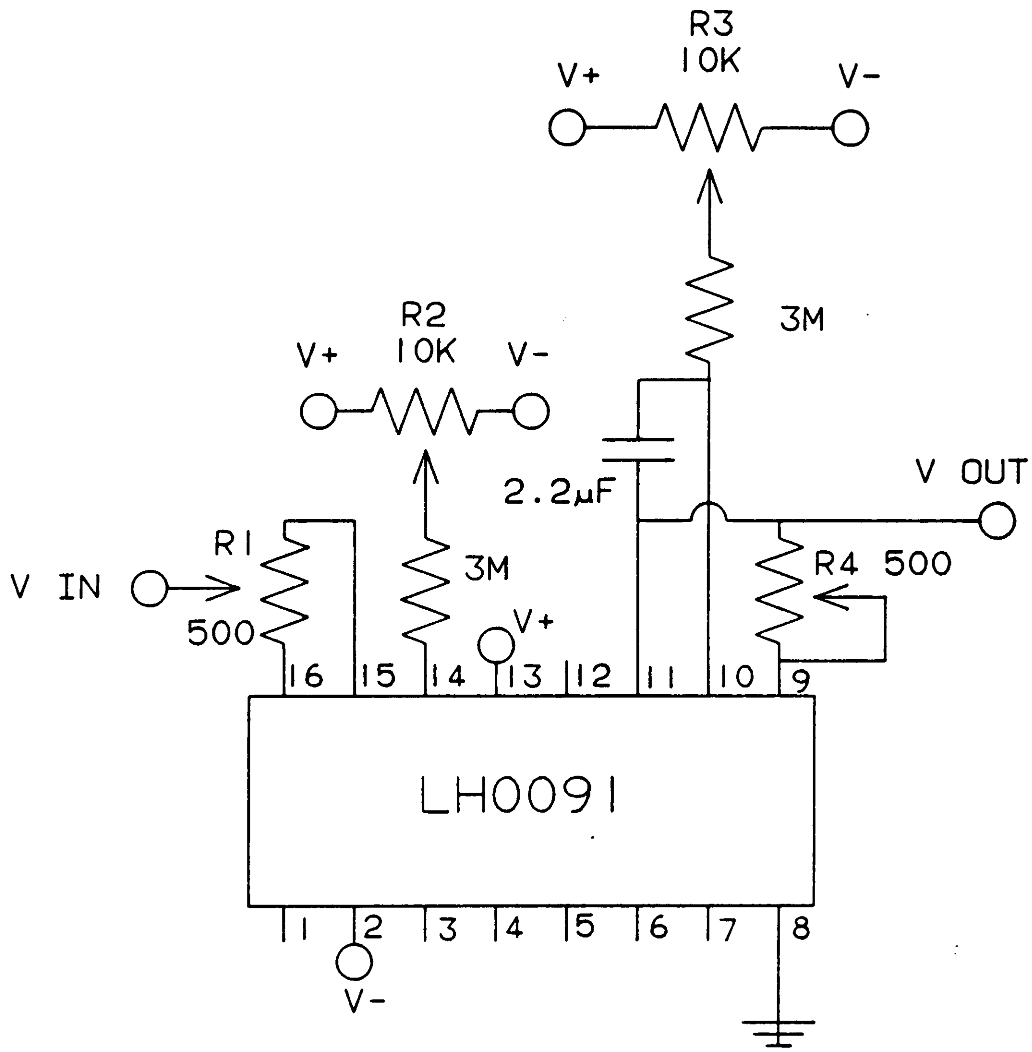

Figure 6. Trimming Circuitry for RMS to DC Converters

an equilibrium temperature. A shorting wire was then connected across the inputs of the amplifier to provide a zero input voltage. The associated trimpot was then adjusted to get a zero output voltage. Special connectors were included on the circuit board to allow direct access to the amplifier inputs.

A precise current source was not available for calibrating the current shunt resistors. After the circuits had reached equilibrium temperature, the resistance of the shunts was measured with the circuits operating. The current was then calculated using Ohm's law.

The AC characteristics of each amplifier were evaluated by imposing wideband random noise on the inputs of the amplifier and taking the frequency response function using the Zonic 6081Z analyzer. The input signal to the voltage amplifier was applied across the voltage divider circuit. This allowed the gain of the amplifier and the voltage divider circuit to be calibrated simultaneously. The same long cables that were hooked to the amplifiers during measurement were also attached for the calibration. The frequency response function for each amplifier was stored. The FRF's were then plotted using the ZCALC software package for better resolution. The real and imaginary components of each amplifier were summed and an average gain factor was calculated. When the power was measured, the amplifier output was divided by its gain factor to get the true input signal. Figure 7 on page 47 through Figure 12 on page 52 show the frequency response functions of the power measurement amplifiers and voltage divider circuits.

4.4 Test Procedure

Before starting the motor, the PC should be booted up and the accelerometer power supplies and power supplies for all the electronic circuitry turned on. It is important to make sure that the power measurement circuits are powered up before the motor is started to pre-

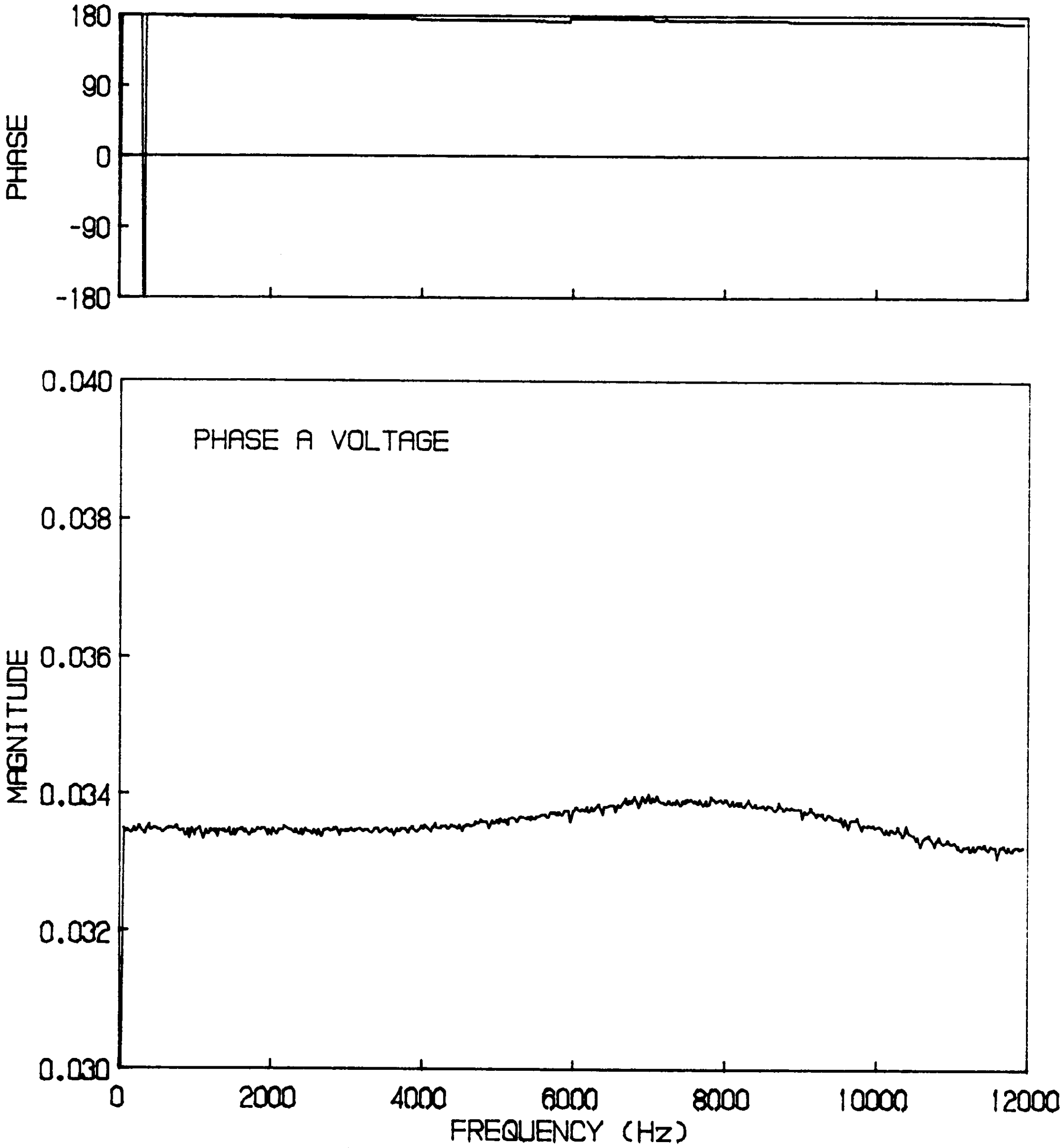

Figure 7. FRF for Phase A Voltage Amplifier and Voltage Divider Circuit

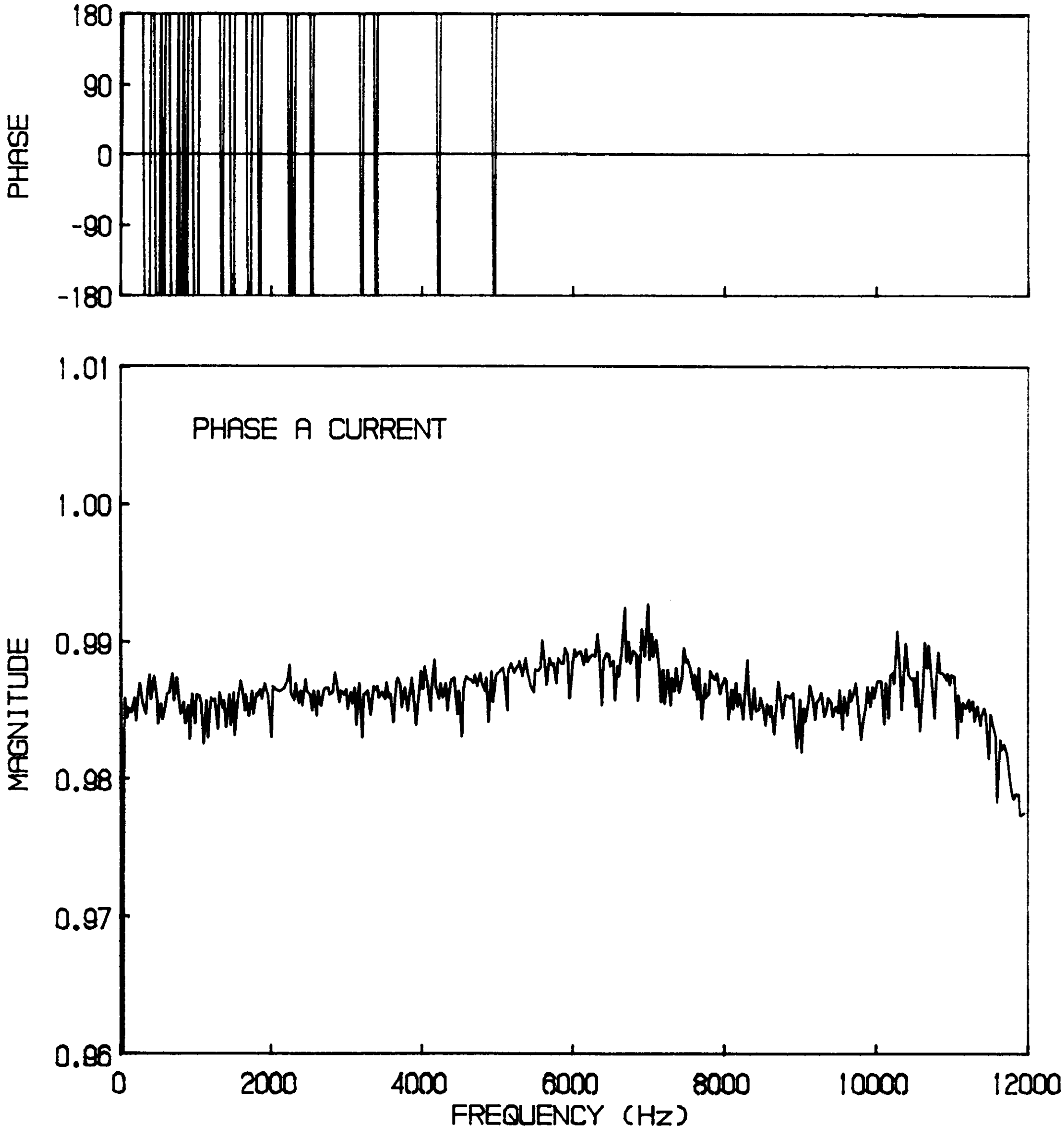

Figure 8. Frequency Response Function for Phase A Current Amplifier

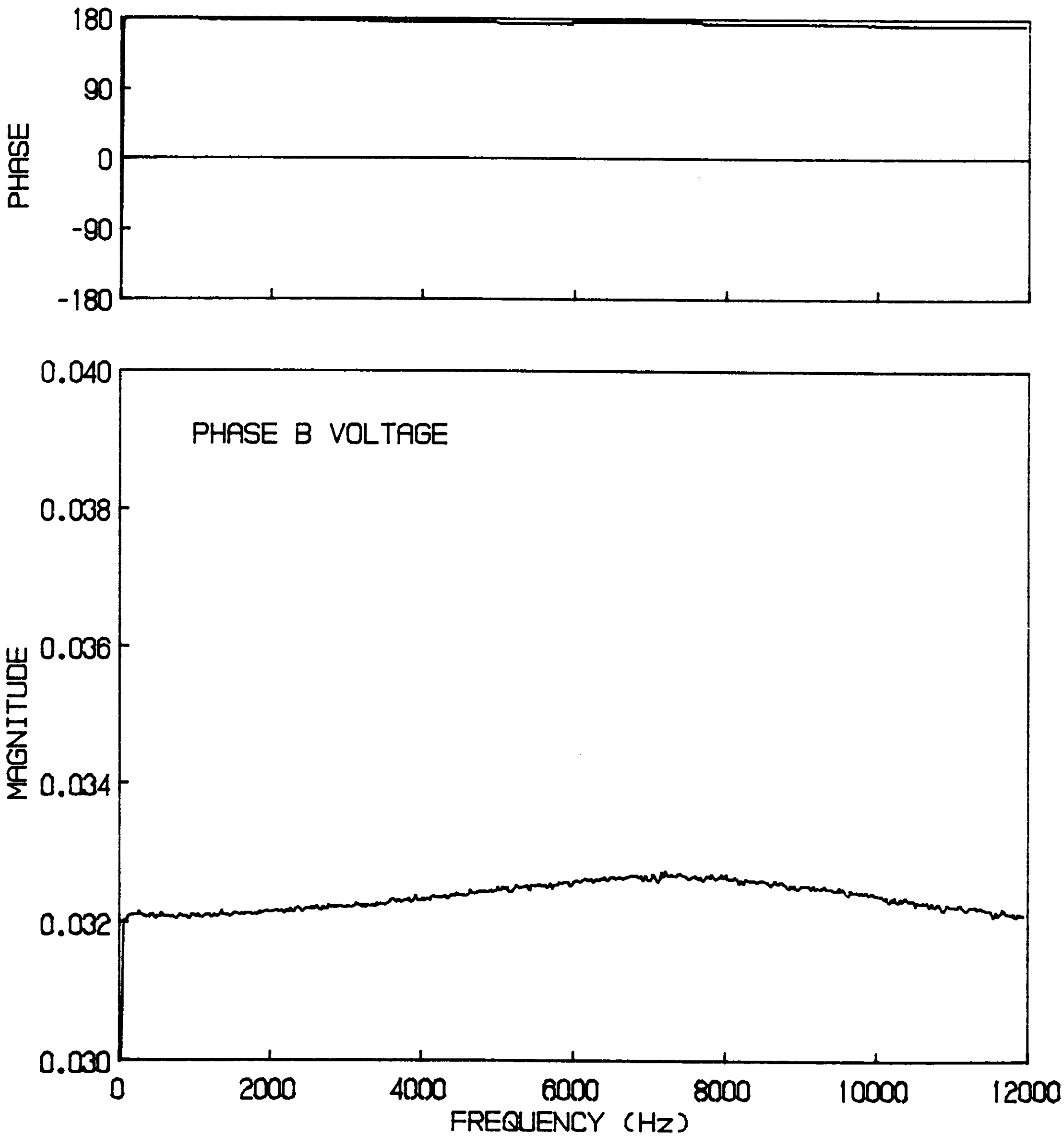

Figure 9. FRF for Phase B Voltage Amplifier and Voltage Divider Circuit

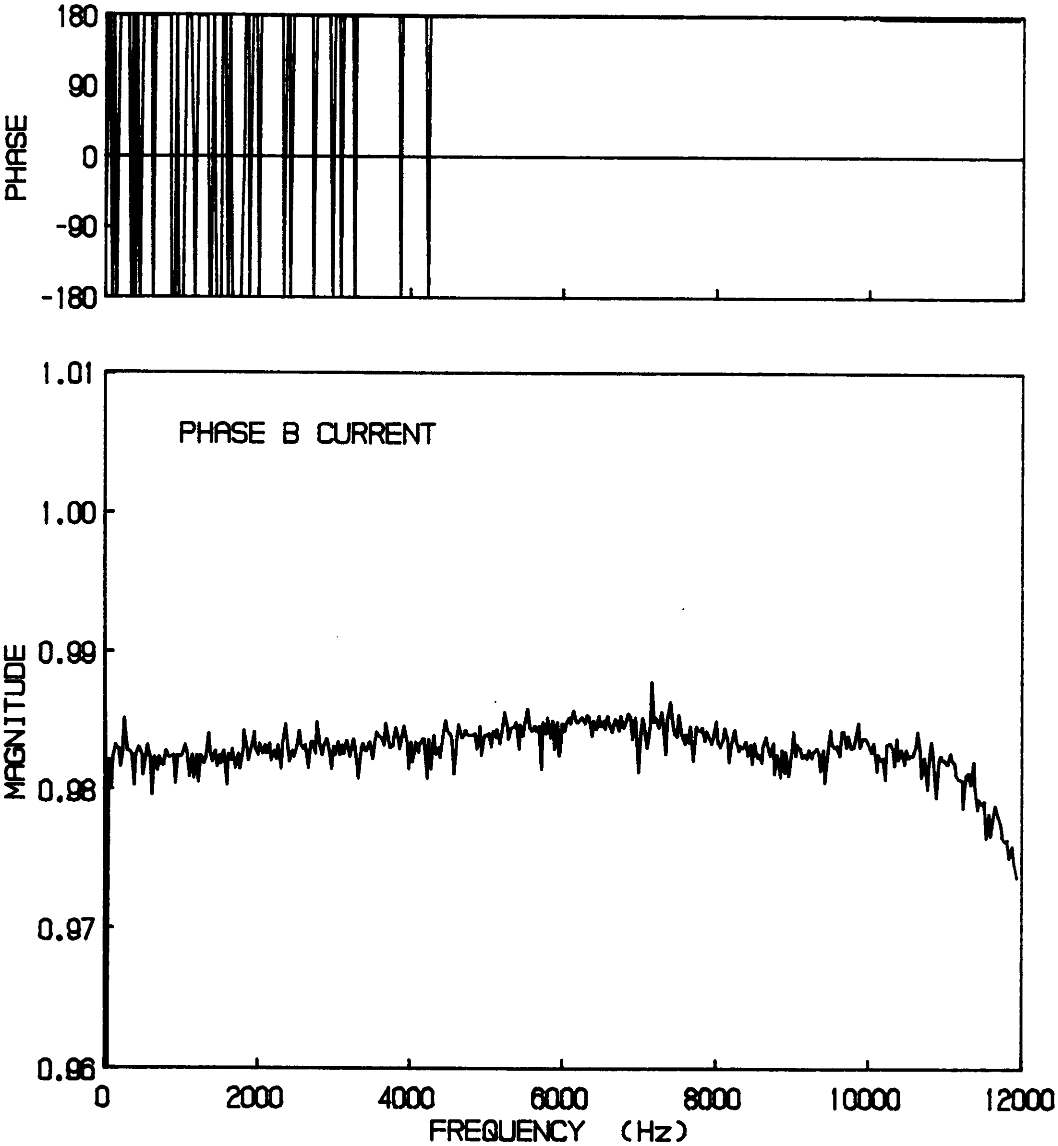

Figure 10. Frequency Response Function for Phase B Current Amplifier

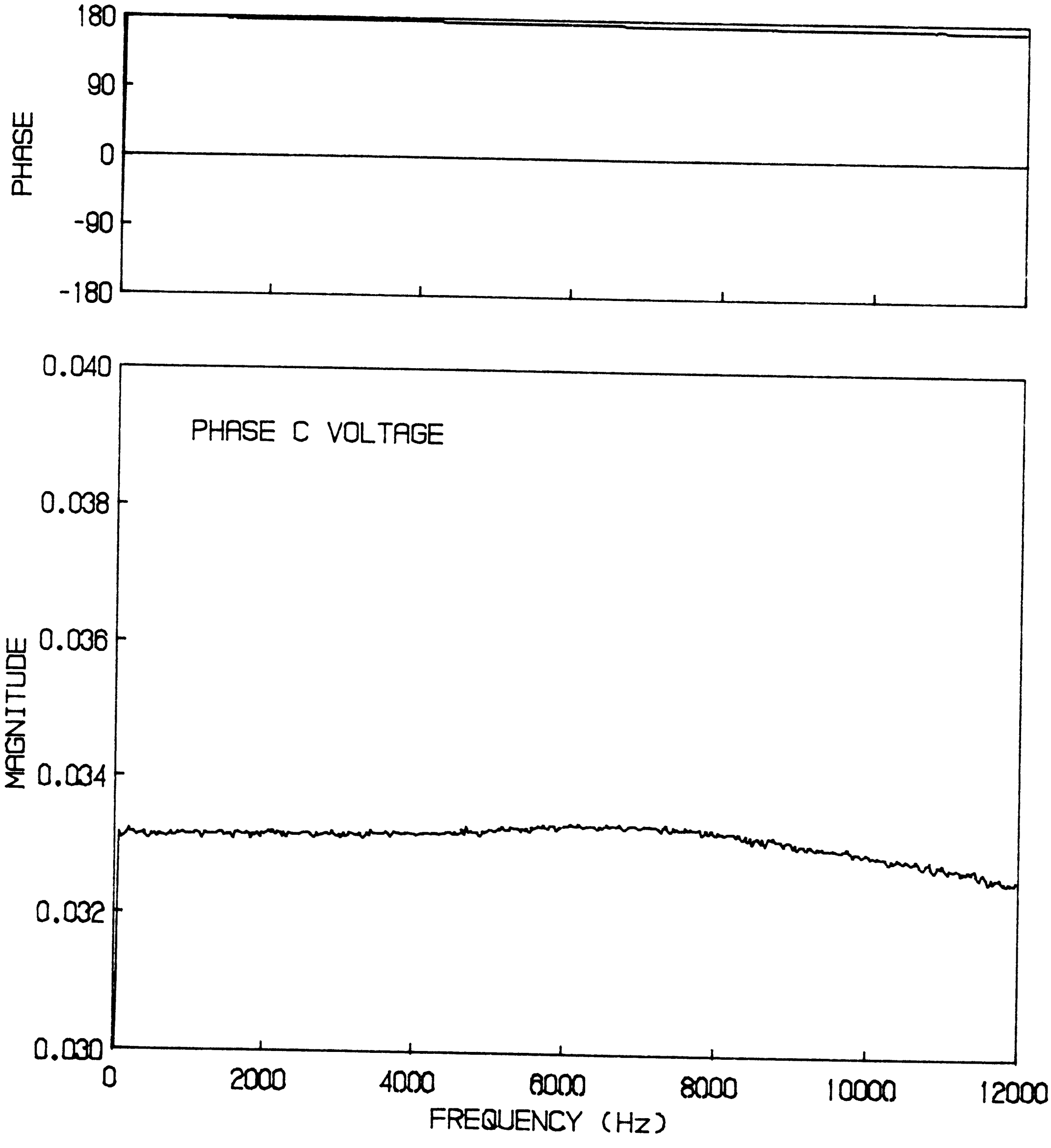

Figure 11. FRF for Phase C Voltage Amplifier and Voltage Divider Circuit

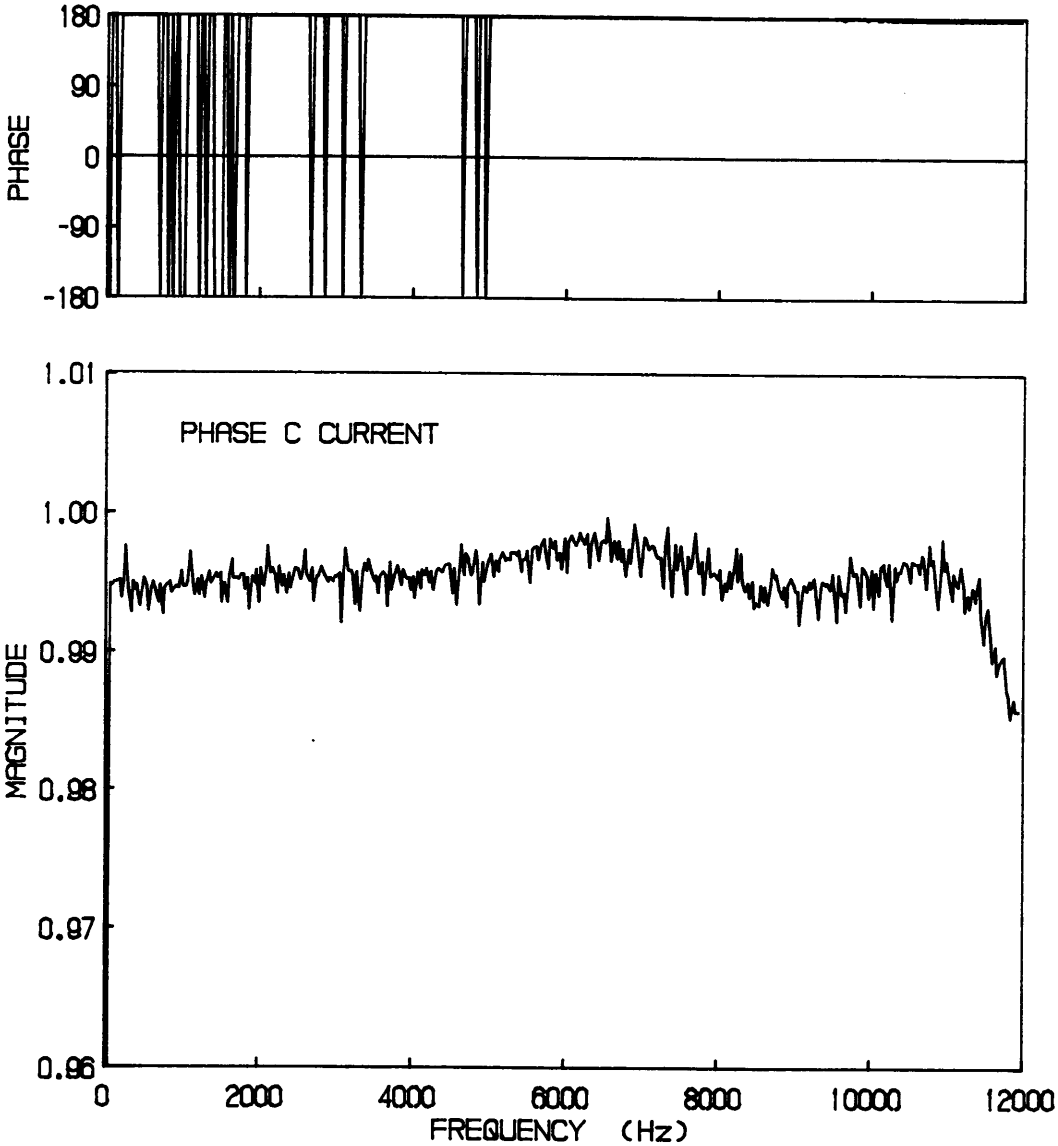

Figure 12. Frequency Response Function for Phase C Current Amplifier

vent damage to the amplifiers and current sensors. The accelerometer power supplies produce a high output voltage when first turned on and will cause the motor to shut down if it is operating. Both power cords for the controller should then be plugged in and the main breaker in the controller turned on. A small toggle switch inside the controller that enables the power transistors should then be turned on. The data acquisition program should then be started and the operating parameters input. Once the program is taking data, the toggle switch on the top of the controller should be flipped to start the motor. The D/A output from the data acquisition system goes high when the PCTHERM routines are initialized. Although there is a statement in the program to send it low as soon as possible, a surge of power will be sent to the motor if the toggle switch on top of the controller is closed.

Each time the motor was powered up, it was run at some slow speed, typically between 1,000 and 2,000 RPM for 20 to 30 minutes before going to full speed in order to allow the grease to heat up gradually. A special routine in the data acquisition software was written to change the motor speed in small steps to prevent excessive accelerations.

The life of high speed, grease lubricated bearings depends greatly on the run-in procedure used for new bearings. Running the bearings to full speed before the run-in can cause premature bearing failure. When new grease lubricated bearings are installed, the following run-in procedure should be used. The motor should initially be operated at a low speed for about 1/2 hour and should then be powered down and allowed to cool to equilibrium temperature. It should then be restarted and warmed up at a low speed before taking it to the next higher run-in speed. The complete bearing run-in schedule is shown in Table Two. If any indication of roughness is detected, the cycle should be extended until the roughness disappears.

Table 2. New Bearing Run-in Speeds and Times

Speed (rpm)	Run Time (min)
2,000	30
4,000	30
8,000	30
12,000	30
16,000	30
20,000	30

4.5 FFT Analysis Procedure

In order to detect and identify impending bearing failures, spectrum analysis of the bearing vibration signals was performed periodically. The bearings were analyzed when they were installed and the resulting spectra were stored. Each time the FFT analysis was performed, the spectrum from each bearing signal was visually compared with earlier results to identify any significant changes that might indicate problems.

Spectrum analysis was performed at motor speeds of 5,000, 10,000 and 20,000 rpm each time. For FFT analysis, the output of the acceleration amplifiers was passed through differential input operational amplifiers. This eliminated the 60 hertz signal superimposed on the vibration signals by the accelerometer power supplies. The analyzer was set up for continuous processing and periodic input. A Hanning window was used to reduce leakage. The frequency setting depended on the running speed. Maximum frequencies were set to 1,000 Hz for 5,000 RPM operation, 1,500 Hz for 10,000 RPM operation, and 2,500 Hz for a 20,000 RPM motor speed. The input amplifiers were always auto-ranged to use the maximum dynamic range of the analyzer's A/D converters.

The spectrum of each bearing vibration signal was displayed and stored for later comparison. In order to improve the accuracy, 50 averages were taken. Plots were then made on the Zonic dot matrix plotter and compared with earlier results to detect any trends in the vibration. Special attention was paid to the magnitude of the once per revolution vibration component to detect imbalance. The plots were also scrutinized to detect any peaks that were close to the ball-pass frequencies.

4.6 Power Measurement Procedure

The power measurement circuit is connected directly to the motor power input cables. Therefore, it is necessary to leave the circuits in-line at all times. To prevent damage to the power circuit amplifiers and current sensors, it is necessary to have power to the circuits whenever the motor is in operation. The same cables were used to connect the amplifiers to the analyzer for power measurement and calibration. Using the eight-channel analyzer allows all three phases to be measured simultaneously. However, since the power input to each phase is stationary for constant speed operation, the phases may be measured separately without any loss of accuracy. This would allow a two-channel analyzer to be used for the measurement.

The analyzer was set up for continuous processing and the frequency range was set from 0 to 12,000 hertz. The input signals for voltage and current were divided by the gain factor for the respective circuit to get the true voltage or current value. No window was used in the power measurements. If the motor speed varies or if the input signal does not fit perfectly in the sample time window, leakage and errors in the power measurement will result. Using a window such as a Hanning window would reduce the error in the amplitude but not eliminate it. If a window is used, it is difficult to tell if a leakage problem is present and to determine the correct amplitude. If the motor is operated at high speeds, most of the power input is at the fundamental rotational frequency. The frequency range of the analyzer can be adjusted to force the fundamental frequency to fall on a spectral line. This greatly reduces the leakage problem.

Two separate approaches were used for the power measurement. The first involved analyzing the input signals in the frequency domain. The frequency range was set from 0 to 12,000 hertz. With the appropriate gain factors applied, the cross spectra of the voltage and current signals give the peak power at each frequency directly in units of volt-amperes or watts. Thirty averages of the cross spectra for each phase were computed and stored for later analysis. The peaks of the cross spectra were inspected visually for signs of leakage. If leakage is present, the base of the peak will be spread out over several spectral lines.

The power input was also measured using order analysis. Here, the data is sampled relative to the motor speed rather than relative to time. A tachometer pulse must be supplied to the analyzer. Resolution is determined by the number of orders or multiples of the fundamental frequency that are analyzed. The order analysis may be performed in RTL using the same setup as for frequency analysis. The only adjustment necessary is to determine the number of orders to analyze. Using order analysis eliminates the leakage in the power components whose frequencies are dependent on motor speed that is encountered using frequency analysis. At high speeds, where most of the power is at the fundamental frequency and its harmonics, order analysis should be superior. At lower speeds, a significant amount of the power input is at the PWM (pulse width modulation) frequency and frequency analysis is more effective. A sufficient number of orders must be analyzed to include the PWM frequency. For power measurement at 5,000 RPM, 70 orders are necessary while at 20,000 RPM, only 20 orders are required.

Chapter 5

Analysis and Data Reduction

During normal operation, the motor condition was sampled by the PC-based data acquisition system every minute. This data was stored in tabular form on floppy disks. Figure 13 on page 59 shows a short data file. Under normal conditions, a disk full of data was collected every few days. During the course of a 1,000 hour bearing test, as many as 20 disks may be filled. Clearly, it is impossible to study this much data manually. In addition, while the data values at any given time provide an indication of the motor condition at that time, it is often more valuable for diagnostic purposes to study trends in the variables. This is extremely difficult to do using the tabular data.

To reduce the analysis to a feasible chore, several graphics programs were developed. A software package for producing plots on a PC-based dot matrix printer was obtained from the combustion research group and adapted for use in the high-speed bearing research. The plotting package consists of two separate programs, one to set the printer up for graphics output, and a second program to do the actual plotting. The plotting program was written in BASIC and compiled for faster execution. The program reads a data file produced by the data

TEST NAME = air16h3

INITIAL DATE = 06-20-1987

LUBRICANT USED = grease

APPROXIMATE MOTOR SPEED = 20000

SAMPLING RATE = 30 SAMPLES/MIN

DATE/TIME (mn-dy-hr-min-s)	T.CAS (C)	T.B1 CONTR (C)	T.B2 SHAFT (C)	T.STAT STATOR (C)	M.SPEED (rpm)	V.ACC1 CONTR (g)	V.ACC2 SHAFT (g)
6 20 14 48 1	33.5	32.5	31.3	29.4	2616	1.52	1.04
6 20 14 50 1	33.0	31.5	30.9	29.3	2653	1.42	1.02
6 20 14 52 1	32.3	32.4	30.8	30.4	2624	1.55	1.14
6 20 14 54 1	31.6	31.4	30.4	30.2	2759	1.55	1.07
6 20 14 56 1	31.3	31.1	32.3	29.7	2795	1.49	1.03
6 20 14 58 1	31.7	32.3	27.6	29.6	2699	1.62	0.97
6 20 15 0 1	30.5	31.0	30.6	29.1	2714	1.57	1.25
6 20 15 2 1	30.8	30.2	32.6	29.7	2706	1.55	1.10
6 20 15 4 1	30.7	29.6	30.0	27.9	2698	1.59	1.06
6 20 15 6 1	31.1	30.0	27.8	29.2	2732	1.55	0.98
6 20 15 8 1	30.5	30.5	28.9	28.2	2730	1.56	1.03
6 20 15 10 1	30.6	29.6	25.1	28.0	2760	1.49	1.01
6 20 15 12 1	30.7	30.4	25.6	27.9	2652	1.65	1.08
6 20 15 14 1	30.1	28.8	29.6	28.8	2621	1.62	1.13
6 20 15 16 1	29.8	29.1	28.1	28.7	2777	1.31	1.00
6 20 15 18 1	29.7	30.1	26.4	29.3	2681	1.65	0.97
6 20 15 21 38	29.0	29.7	30.5	31.3	19684	4.77	3.67
6 20 15 23 38	30.5	32.3	30.8	38.3	19684	4.45	3.39
6 20 15 25 38	30.3	35.7	37.5	46.8	19739	4.27	3.30
6 20 15 27 38	31.2	38.2	36.8	48.3	19670	3.28	3.50
6 20 15 29 38	32.2	40.4	43.8	47.7	19739	3.71	3.26
6 20 15 31 38	33.8	42.7	47.9	53.1	19684	3.57	3.64
6 20 15 33 38	34.5	47.2	44.0	55.0	19739	3.76	3.60
6 20 15 35 38	34.8	46.1	38.9	55.0	19698	3.55	3.31
6 20 15 37 38	35.2	48.6	40.4	57.4	19767	3.71	3.44
6 20 15 39 38	36.7	50.9	44.3	55.8	19767	3.91	3.44
6 20 15 41 38	35.3	50.5	48.8	56.2	19739	3.90	3.46
6 20 15 43 38	36.4	51.0	52.4	57.7	19753	3.73	3.44
6 20 15 45 38	38.3	53.4	49.3	59.9	19781	3.87	3.76
6 20 15 47 38	39.1	54.5	50.6	61.2	19712	3.86	3.64
6 20 15 49 38	40.1	55.0	51.2	61.7	19795	3.88	3.51
6 20 15 51 38	40.2	55.5	51.2	61.5	19781	3.61	3.58
6 20 15 53 38	40.4	55.6	51.5	62.5	19795	4.07	3.54
6 20 15 55 38	40.9	56.3	51.7	62.5	19739	3.73	3.32
6 20 15 57 38	41.0	56.5	52.0	61.6	19739	3.77	3.10
6 20 15 59 38	41.0	56.4	52.1	62.8	19781	3.80	3.39
6 20 16 1 38	41.1	56.6	52.1	62.6	19795	3.79	3.16
6 20 16 3 38	41.5	57.1	52.1	62.4	19753	3.67	3.54
6 20 16 5 38	41.4	57.0	52.4	62.4	19739	3.93	3.48
6 20 16 7 38	41.6	57.0	52.2	62.8	19795	3.87	3.55
6 20 16 9 38	41.6	57.5	52.5	63.0	20419	4.15	3.43
6 20 16 11 38	41.6	57.3	52.2	63.0	19809	3.93	3.57

Figure 13. Sample Data File

acquisition program and converts the real time values into an elapsed time of minutes. The user then select any measured variable to be plotted on the vertical axis with time on the horizontal axis. Minimum and maximum values must be supplied for the vertical axis along with a maximum time value for the horizontal axis. Axes are automatically proportioned and numerical values printed next to the tic marks. A square grid may be displayed or suppressed. Points may be plotted independently or joined by line segments. Labels for the axes as well as for the graph may be provided. Figure 14 on page 61 shows a sample dot matrix plot.

The PC plotting program was normally used to produce a few plots for quick review without the necessity of transferring files to the mainframe computer. However, the printer was very slow and, as the number of plots desired increased, that option became less desirable. In order to produce high quality plots more efficiently, a FORTRAN program was written to read the data files and produce plots on the Versatec electrostatic plotter. Data files were initially transferred to the mainframe computer and edited to remove all non-numerical characters. To conserve mainframe memory, the data files were down-loaded to the PC after plotting and stored on floppy disks. The plotting program first read the data values into arrays and converted the time values from a hour-minutes-seconds format into a standard runtime variable in units of hours. All temperature, speed, and acceleration values were then plotted on separate graphs. The PLOT 10 PREVIEW routines were utilized to allow the program to be run interactively. A copy of the plotting program in included in Appendix C.

5.1 Spectral Analysis Results

Complex commercial software packages for bearing signature analysis are available. One notable package is the Application Package BZ 7006 software developed by Bruel and

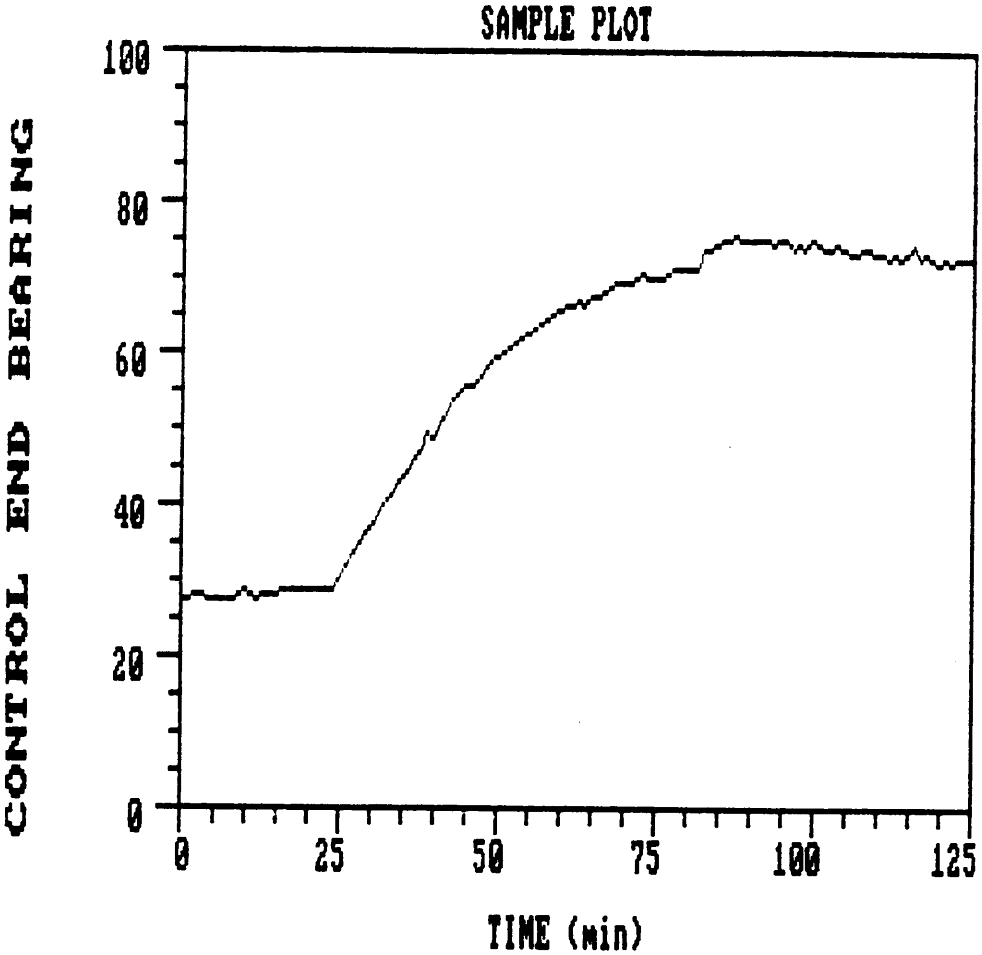

Figure 14. Sample Dot Matrix Plot

Kjaer Company. This analysis package was used by Bradshaw and Randall (1983) for vibration analysis on the Alaska pipeline machinery. A much simpler method was used in this study. The vibration spectrum from each bearing was plotted and compared visually to previous results. With the small amount of data to consider, this procedure worked well. The vibration signal peaks at the fundamental rotational frequency were studied closely to detect any increased rotor imbalance. Ball-pass frequencies were examined for indications of developing fatigue faults.

5.2 Analysis of Power Measurement Data

Two separate options were used for analysis of the power measurement data. As the data was taken, the cross spectra of the voltage and current signals were displayed. The peaks were visually inspected for signs of leakage. If the spectral lines adjacent to the peaks were two orders of magnitude or more lower than the peak, then leakage was neglected. Using the cursor, all peaks of significant amplitude with good coherence were marked. The marked values were then printed out and summed manually. The sum for each phase represents the peak power for that phase. Since the voltage and current components are sinusoidal, this value may be divided by two to get the true RMS power input. This method is valid for either frequency or order analysis. If only a few peaks are considered, it provides quick and easy answers.

If there is considerable leakage around the peaks or if many peaks are to be considered, summing the peaks manually becomes very tedious. In this case, the RTL data files were copied into the ZCALC software package. All of the real and imaginary components were then summed to get the total power input. An added advantage of using the ZCALC software is that better, higher resolution plots may be obtained than the plots using the RTL format.

Chapter 6

Test Results and Discussion

6.1 Data Acquisition System

Most early test runs with the data acquisition system were conducted to discover the equilibrium operating conditions of the motor at various operating speeds. The initial runs indicated that the desired operating speeds could not be sustained without some type of cooling system. After that point, a long series of tests were conducted to evaluate different cooling schemes. Figure 15 on page 65, Figure 16 on page 66 , and Figure 17 on page 67 show the results of one of the early high-speed runs.

Neither liquid nor air cooling was utilized in this test. The data acquisition system powered down the motor because of an excessive stator temperature after only five minutes of operation. Although it is feasible to run with higher stator temperatures, the high bearing temperatures clearly indicate the need for some kind of cooling system. At the time that this test was conducted, the vibration amplifiers had not been constructed and the output from the accelerometer power supplies was sampled directly by the RMS to DC converters. The ac-

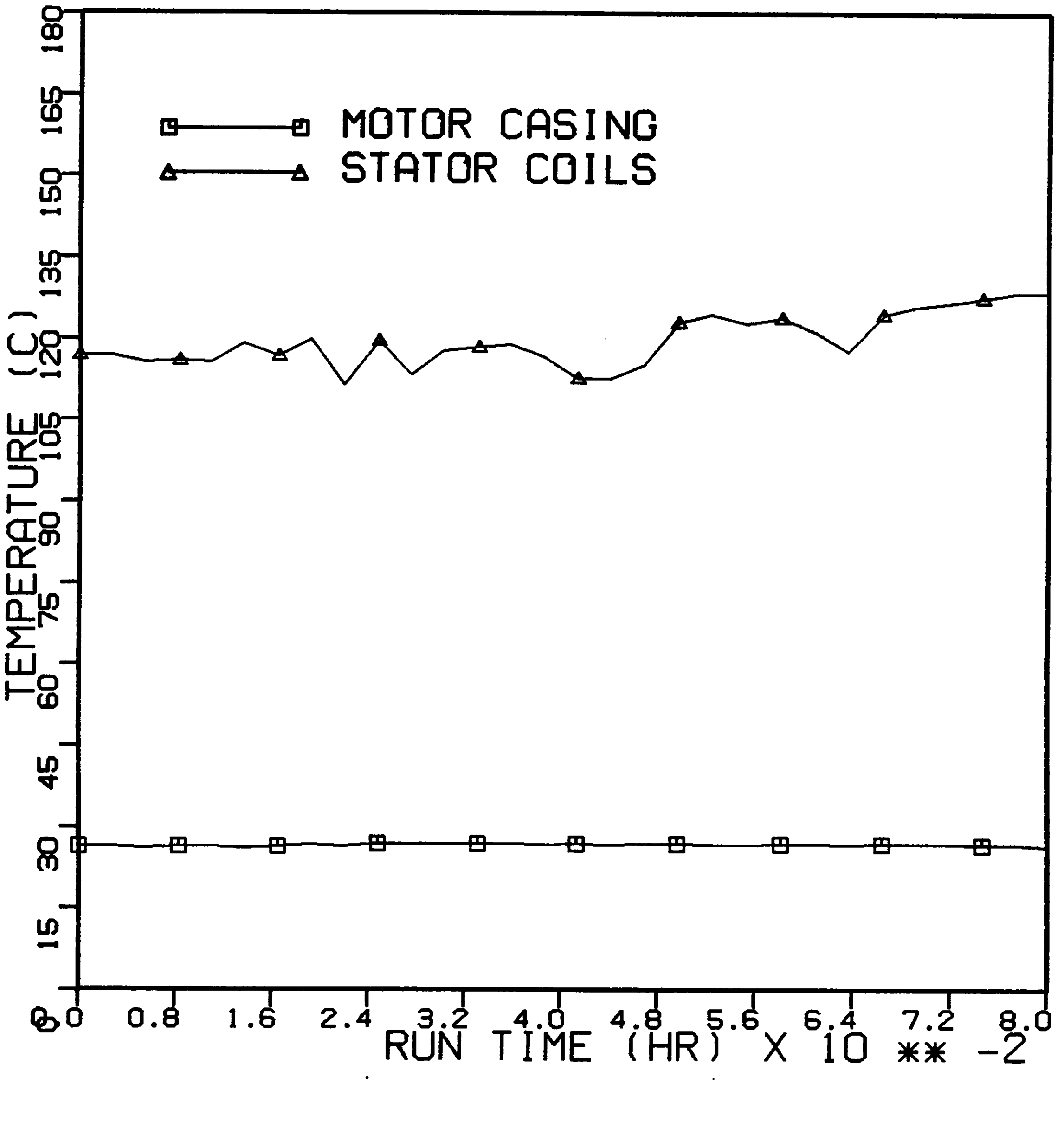

Figure 15. Motor Casing and Stator Coil Temperature for Early Run

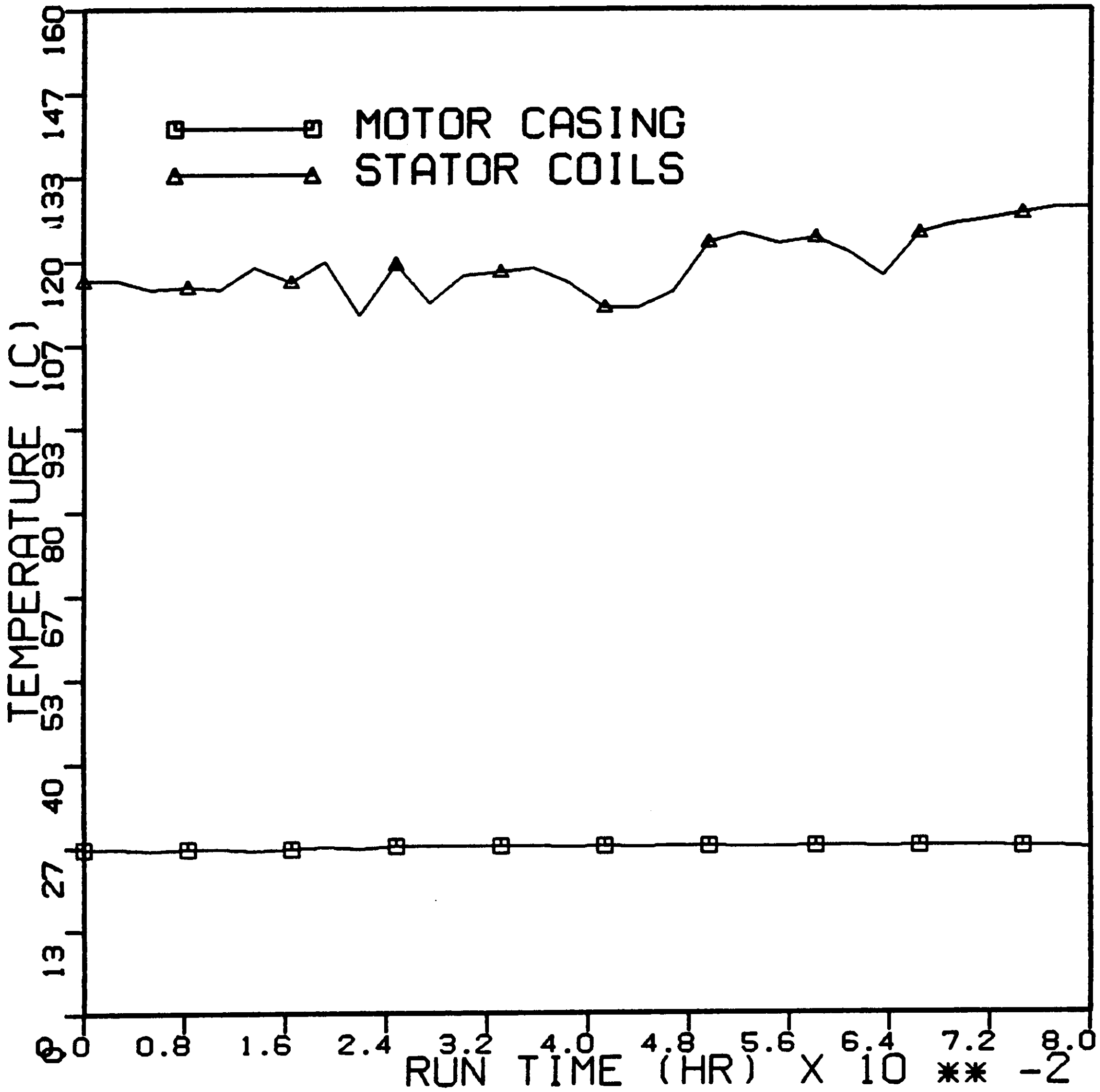

Figure 16. Bearing Temperatures for Early Test

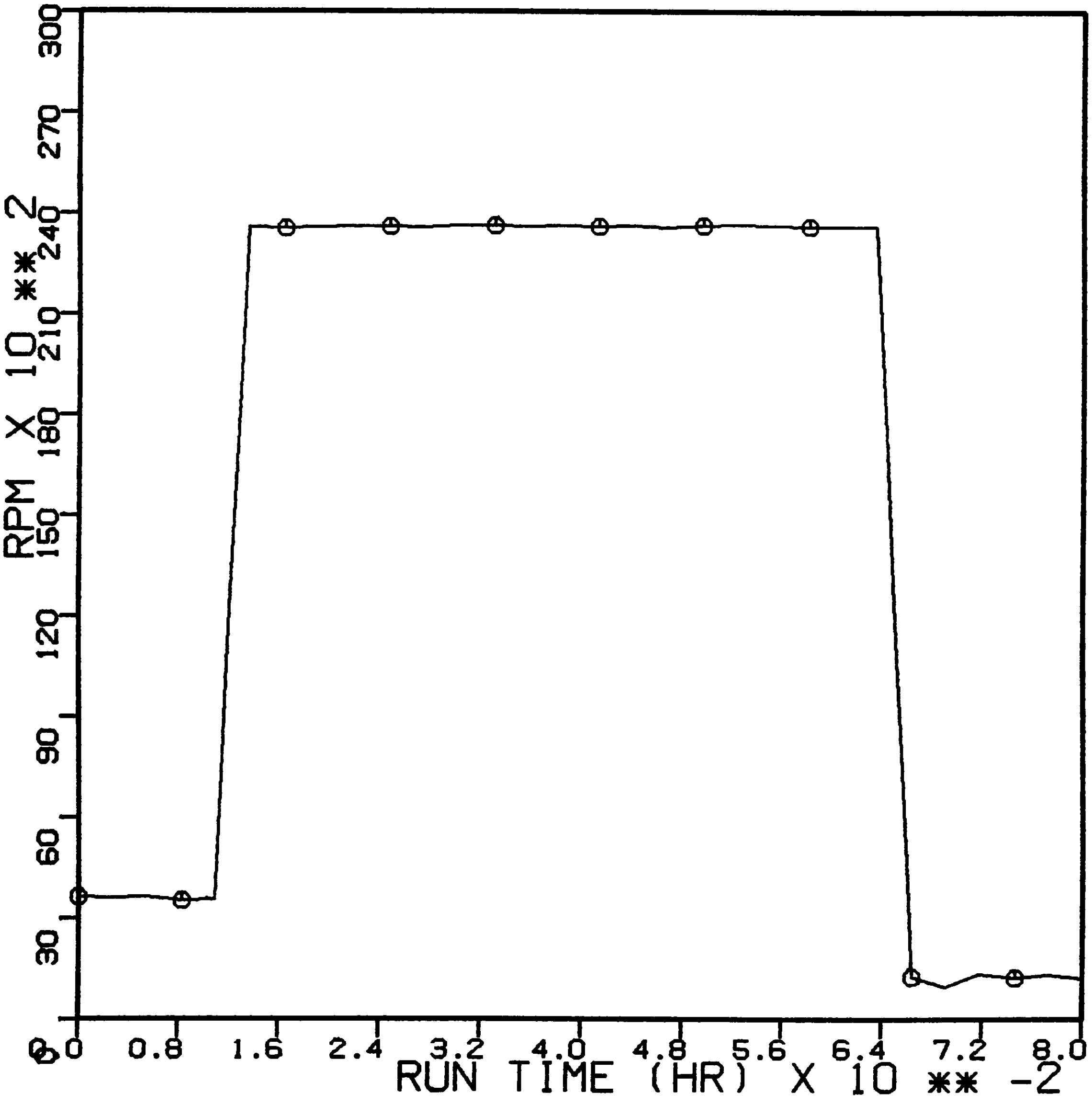

Figure 17. Motor Speed For Early Test

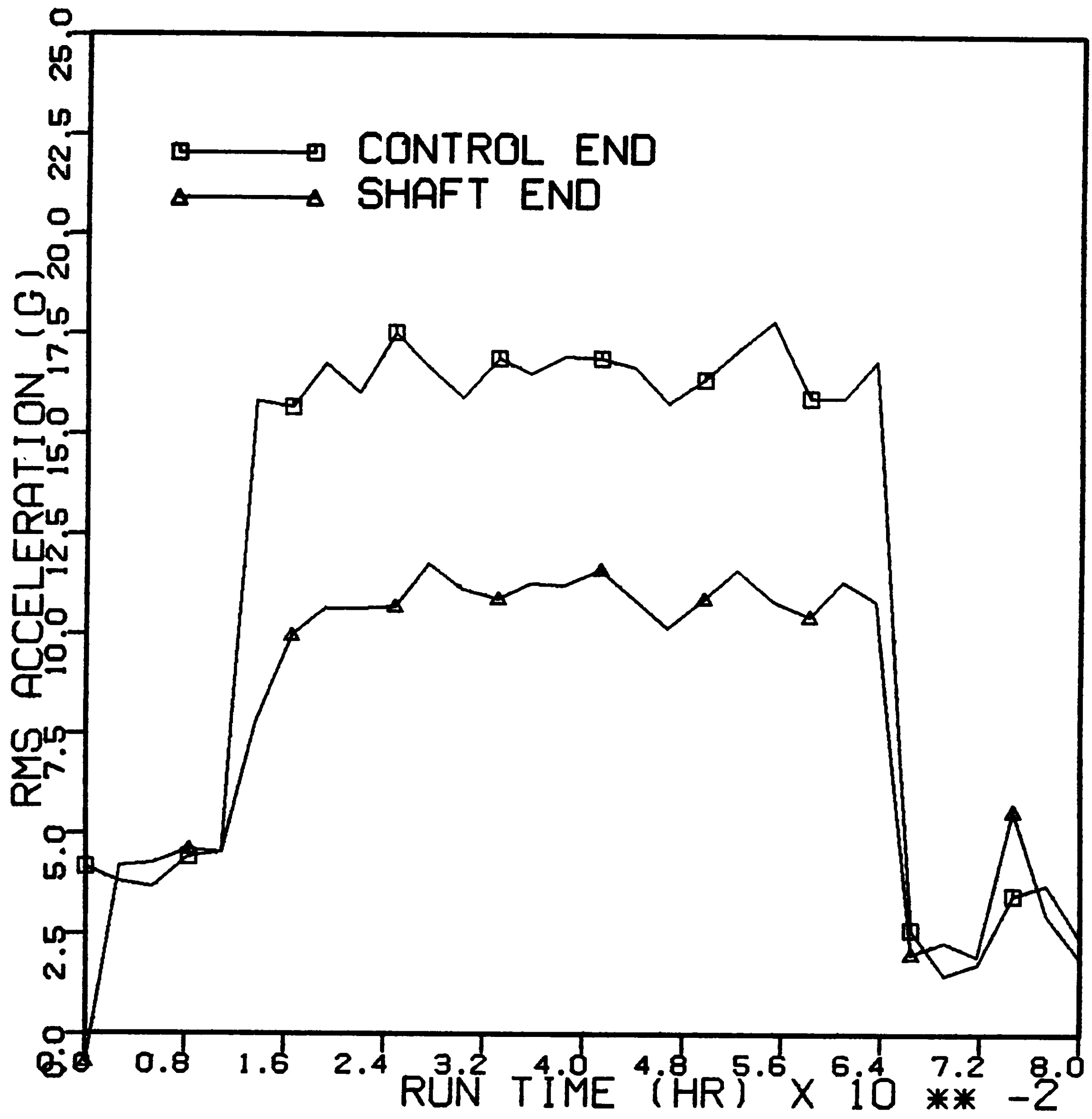

Figure 18. RMS Bearing Accelerations for Early Test

celerations were also sampled using a digital multimeter. Considerable error was discovered in the RMS vibration readings. This was because the output of the accelerometers was below the accurate input range of the RMS circuits.

After the initial runs, the liquid cooling system was developed in an attempt to bring the bearing temperatures down. Although some improvement was achieved, it was still not possible to run at 20,000 revolutions per minute. To determine the maximum benefit that could be obtained from liquid cooling, a series of tests were conducted where tap water was pumped through the water jacket as fast as possible. During one of the tap water tests, high RMS accelerations were detected by the data acquisition system. The system immediately powered the motor down before any further damage occurred. It was later discovered that a small piece of balancing putty had flown off of the rotor. Figure 19 on page 70, Figure 20 on page 71, and Figure 21 on page 72 show the operating conditions prior to shutdown.

Following this failure, the allowable vibration level was increased to allow operation of the motor, and FFT analysis of the bearing signals was performed. The spectra of the vibration signals showed high peaks at the fundamental frequency and its harmonics. The loss of the balancing putty was attributed to excessive rotor temperatures. The motor was taken apart and the rotor rebalanced. Before reassembly, the bearings were replaced.

Unusual behavior was observed from the time the second set of bearings were installed. The motor sounded rough when operated at certain speeds between 8,000 and 12,000 revolutions per minute. When the spectra of the bearing vibration were analyzed, an energy band centered around 900 Hz appeared in the noise level of the shaft end signal. Figure 22 on page 73 shows the vibration velocity of the shaft end of the motor casing. The readings were taken at 10,000 RPM shortly after the bearings were run in. Smaller peaks appeared between the between the peaks caused by the fundamental frequency harmonics, especially on the control end of the motor. As shown in Figure 23 on page 74, the 900 Hz energy band was not as evident in the velocity readings on the control end.

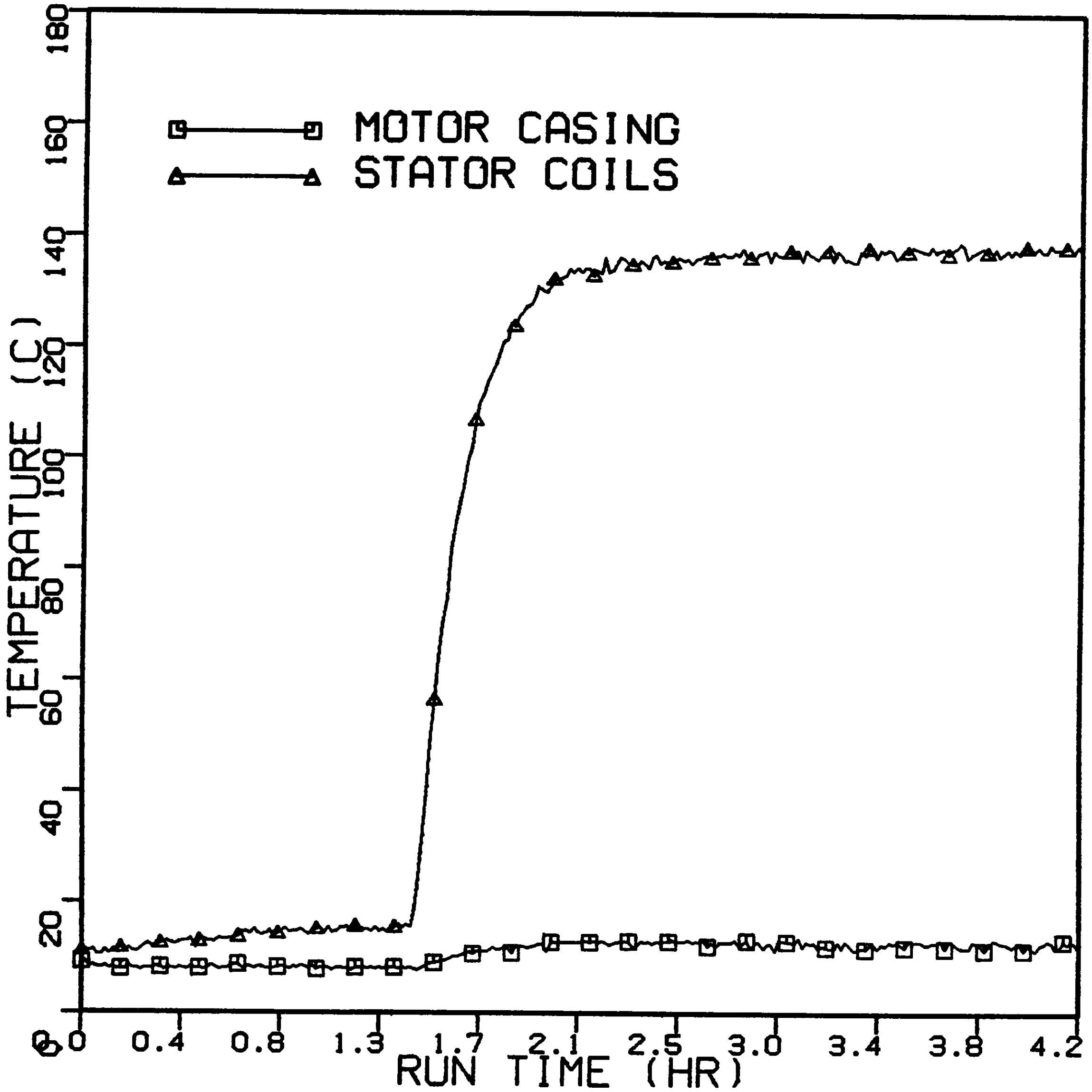

Figure 19. Motor Casing and Stator Coil Temperature for Tap-Water Cooling

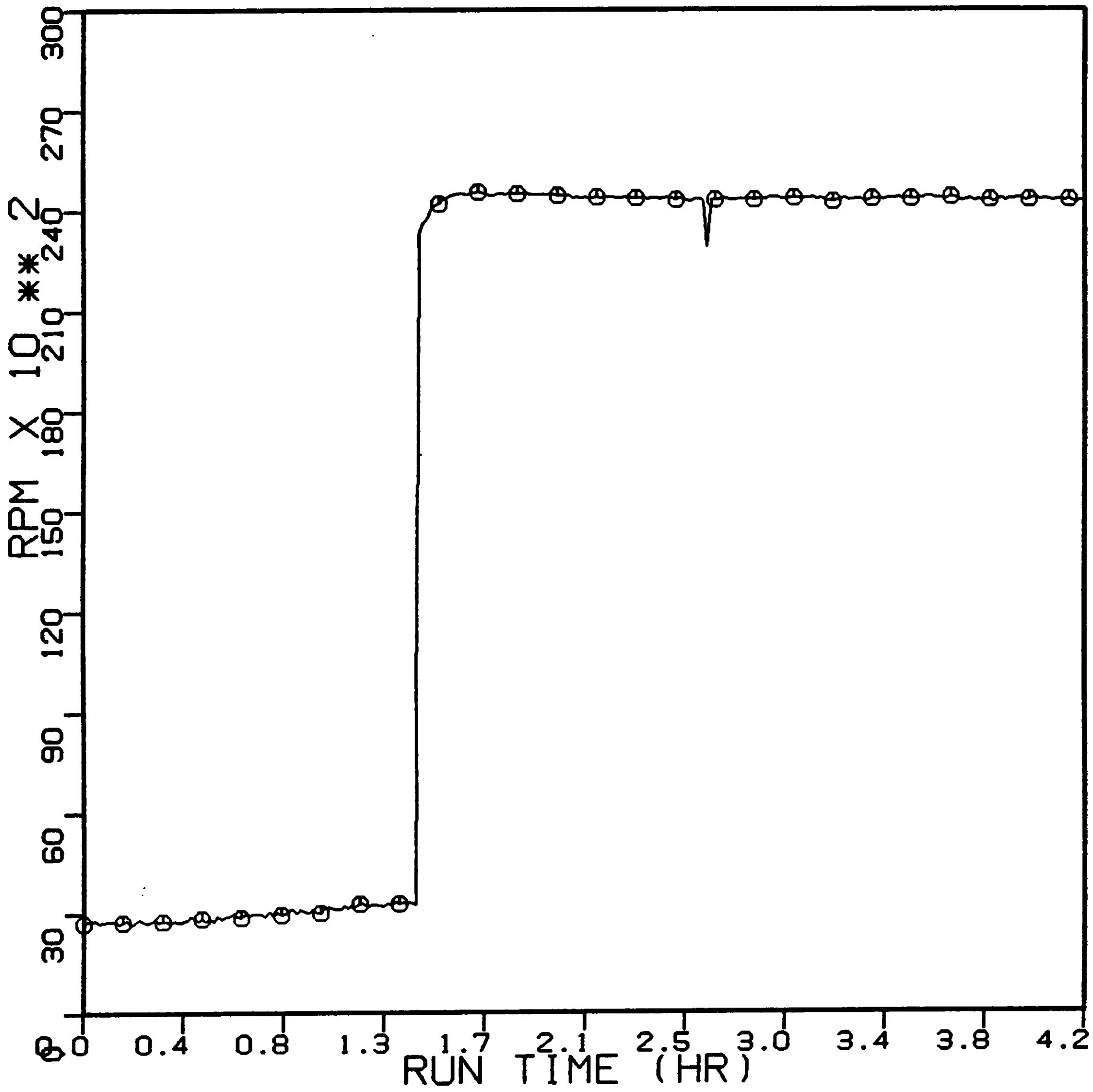

Figure 20. Motor Speed for Tap-Water Cooling

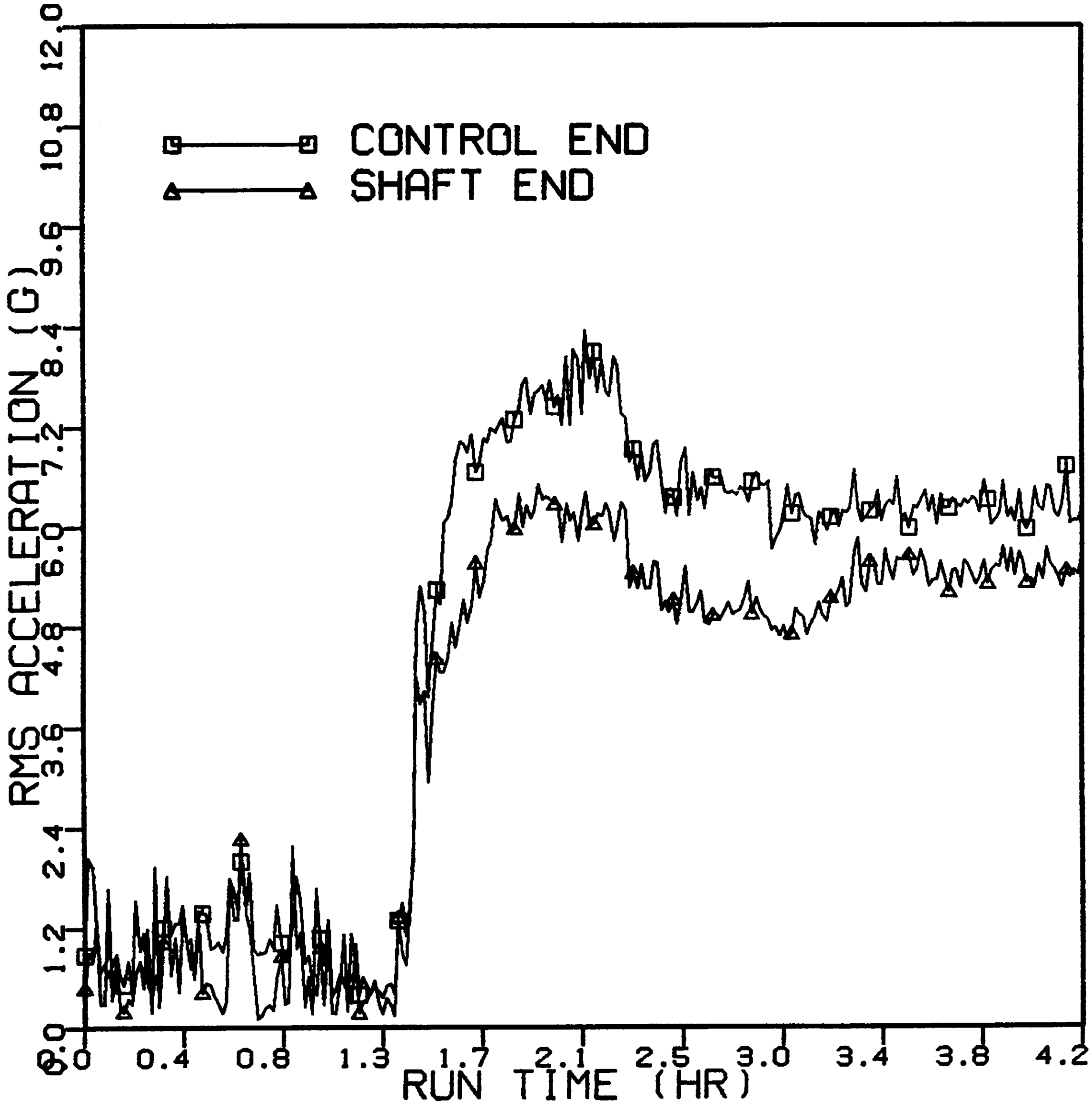

Figure 21. Bearing Accelerations for Tap-Water Cooling

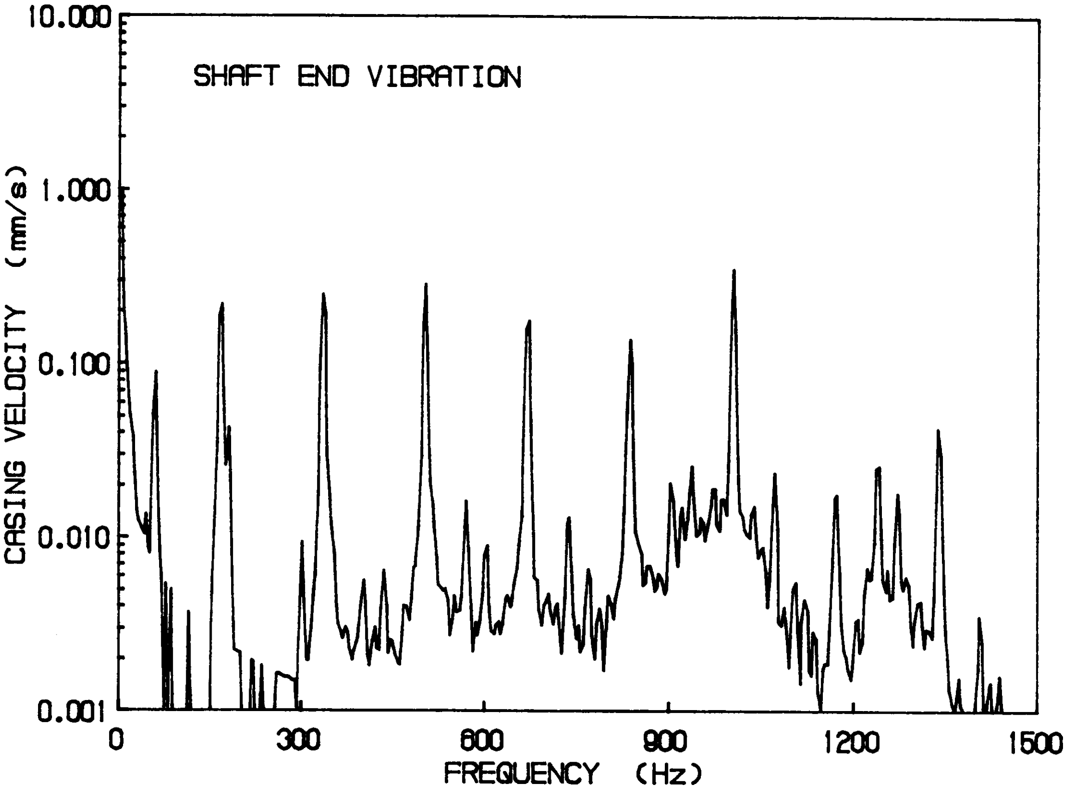

Figure 22. Shaft End Bearing Vibration at 10,000 RPM: Taken shortly after installing second set of bearings.

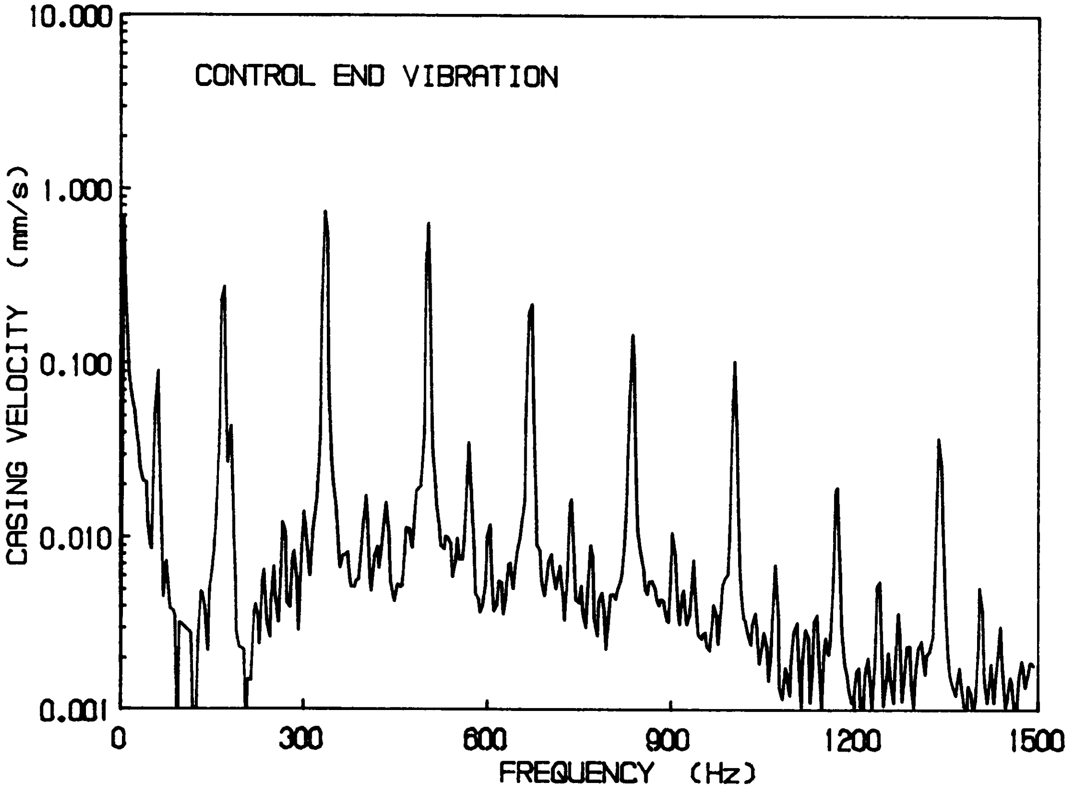

Figure 23. Control End Bearing Vibration at 10,000 RPM: Taken shortly after installing second set of bearings.

All of the motor temperatures and RMS vibration levels were normal, so the tests were continued. Provisions were made to blow compressed air over the rotor to improve cooling. After running several short air cooling tests to measure rotor temperature, a 100 hour test at 20,000 RPM was started. Figure 24 on page 76 and Figure 25 on page 77 show the bearing temperatures and RMS vibration level for the 100 hour test.

A gradual increase in the vibration level was noted along with excessive scatter in the shaft end bearing temperature readings. The vibration level continued to climb slowly for almost 10 hours before rising suddenly and causing shutdown. The motor was powered up and operated at 10,000 RPM for long enough to perform FFT analysis of the bearing vibrations.

Figure 26 on page 78 shows the velocity of the shaft end of the casing when the motor was powered back up. The amplitudes of the low frequency harmonics of the 1/rev frequency are slightly higher than when the bearings were installed. In addition, the noise level has risen by more than an order of magnitude. Figure 27 on page 79 shows the same effect on the control end of the motor. The near normal amplitude of the once per rev peaks and the absence of any peaks at the ball-passing frequencies indicated that no balancing or bearing problems were present. Upon disassembly of the motor, excessive clearance and signs of slippage between the shaft end bearing outer race and the motor housing were detected. The relative motion between the outer race and the motor housing was responsible for the high noise level that was measured.

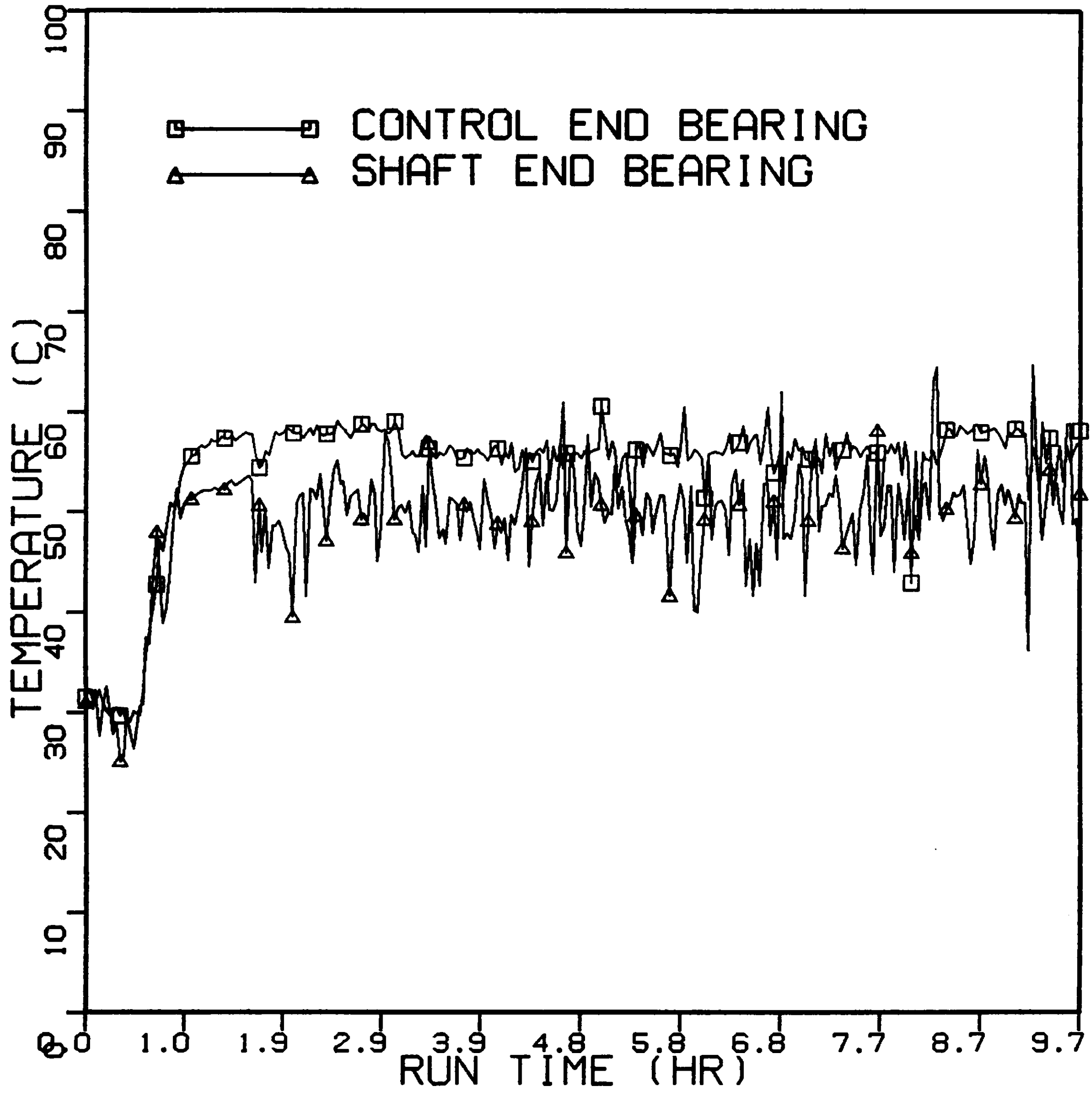

Figure 24. Bearing Temperatures for Air Cooling at 20,000 RPM

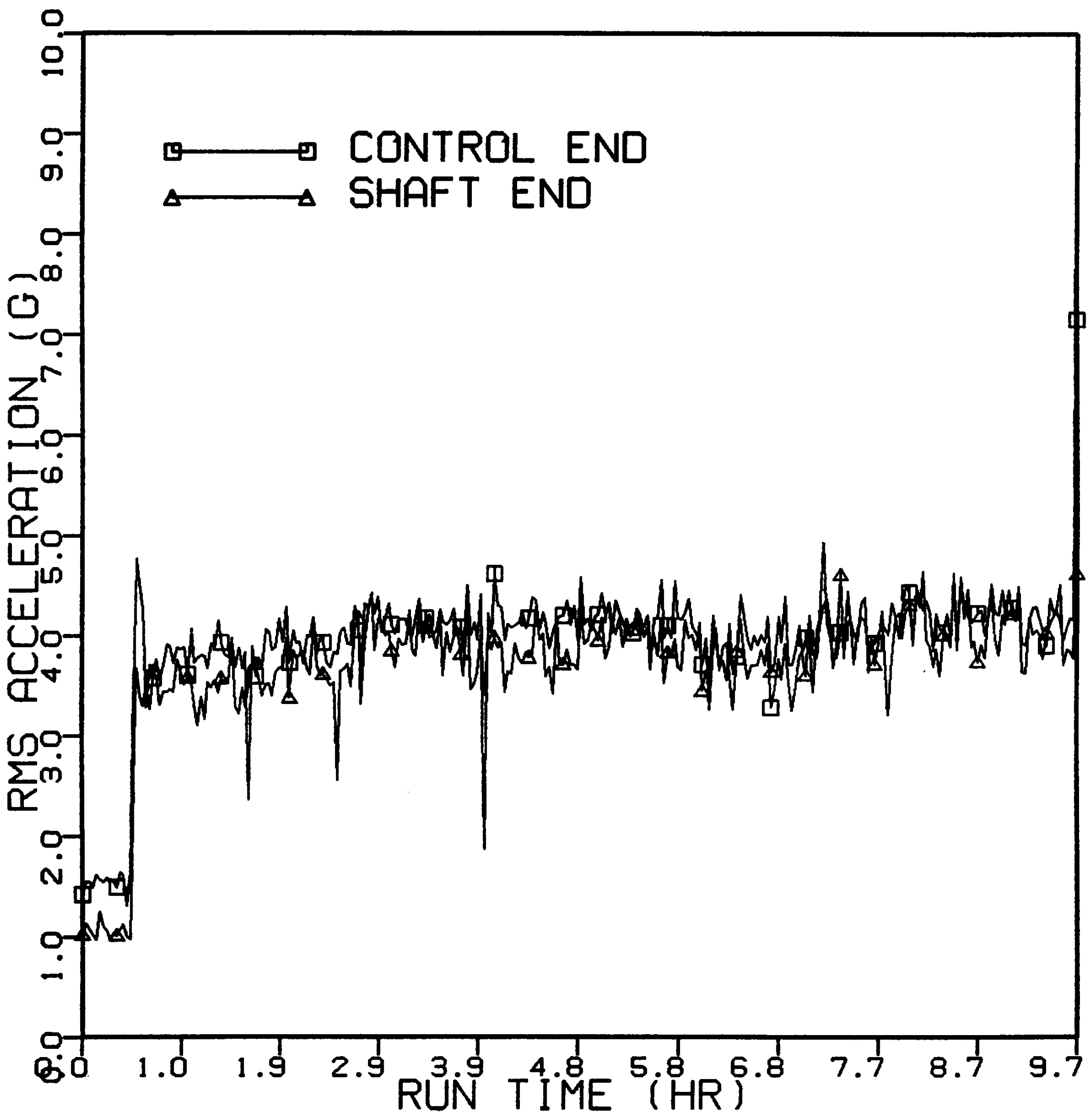

Figure 25. RMS Bearing Vibration Levels for Air Cooling Test

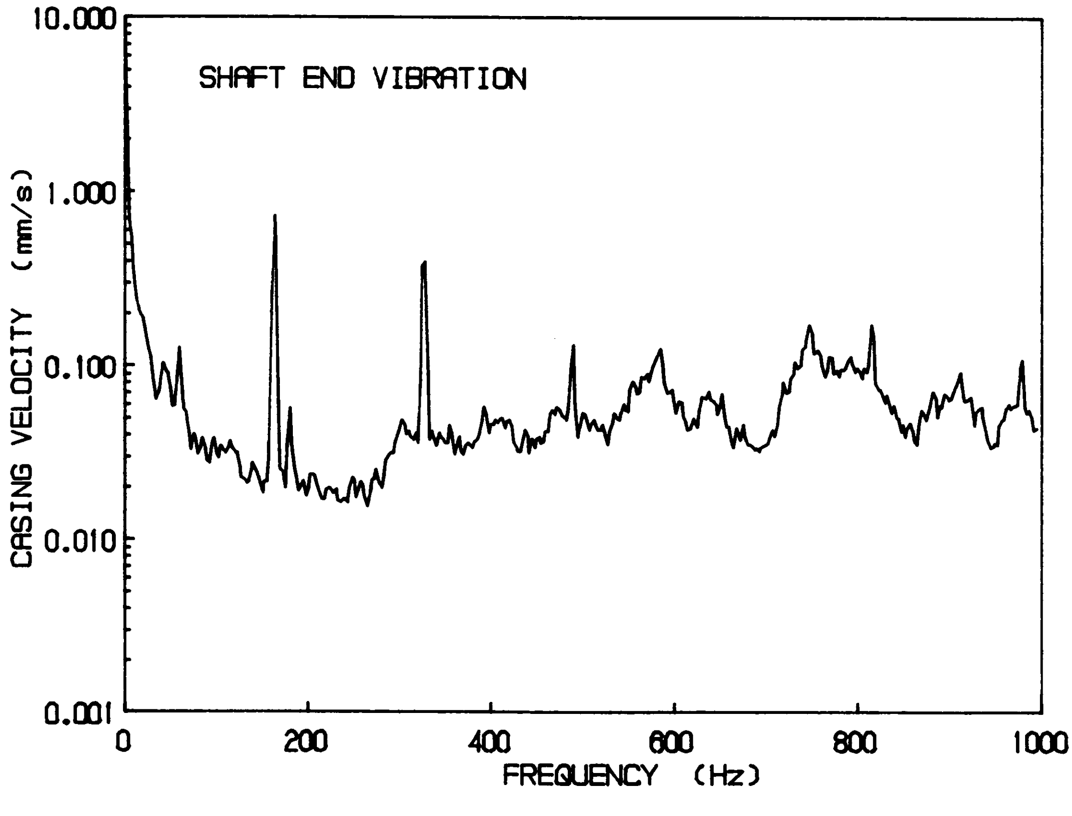

Figure 26. Shaft End Bearing Vibration at 10,000 RPM: taken after shutdown with second set of bearings.

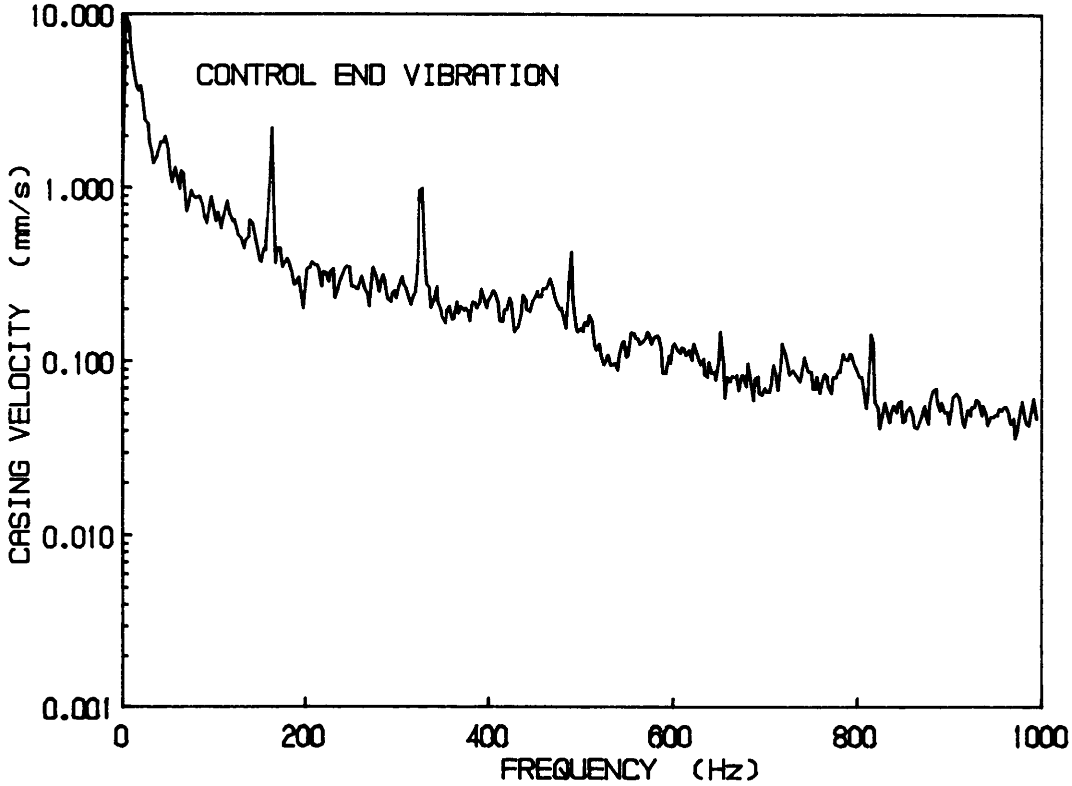

Figure 27. Control End Bearing Vibration at 10,000 RPM: taken after shutdown with second set of bearings.

6.2 Power Measurement Results

The power input to the motor was initially measured at 5,000 RPM and at 20,000 RPM. To simplify the measurements, only one phase was measured at a time. The first power measurements were taken immediately after running in a new set of bearings, and the motor had not yet been tuned. Since no signs of leakage were present, order analysis was not performed. Figure 28 on page 81 shows the cross spectrum of the voltage and current signals for phase A with the motor running at 20,000 RPM. Figure 29 on page 82 and Figure 30 on page 83 show the power input for phase B and phase C respectively.

The sharp clean peaks of the cross spectrums for all three phases indicate the absence of leakage. The power for each phase was calculated by transferring the data into ZCALC and summing all of the real and reactive components. The real RMS power input to the motor was 991 watts with 565 volt amperes of reactive power. The average phase angle between the voltage and current signals was 29.7 degrees. This corresponds to a power factor of 0.868 for the motor. All the harmonic components represent sinusoidal waveforms, so the true RMS power may be obtained by dividing the peak values of the cross spectrum by two. As the plots indicate, most of the power input at high-speeds is at the fundamental rotational frequency. This makes order analysis very attractive to use when fluctuations in the motor speed cause leakage for frequency analysis.

Power measurements were also performed at low speeds. Figure 31 on page 84 shows the power input to phase A at 5,000 RPM. A total real RMS power input of 147 watts was measured with 65 watts of reactive power. The power factor for operation at 5,000 RPM was 0.915, slightly better than that for high speed operation. The peaks at the PWM frequency are almost as high as the fundamental frequency component. This indicates that there is a significant amount of power at the PWM (pulse width modulation) frequency.

Using the spectrum analyzer, the motor was tuned at 20,000 RPM so that the power factor of the fundamental frequency component was unity. Figure 32 on page 86, Figure 33

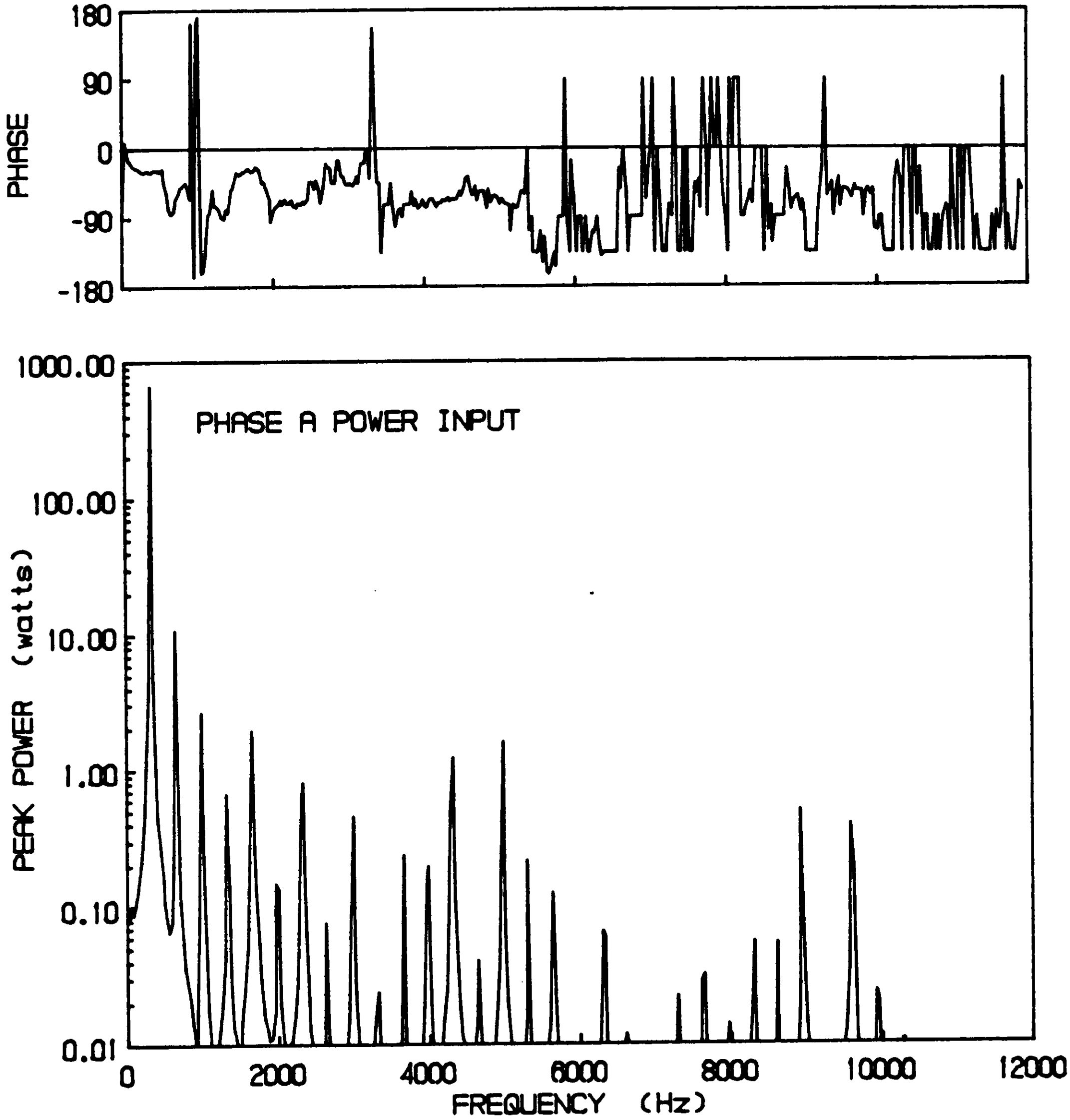

Figure 28. Power Measurement of Phase A at 20,000 RPM Before Tuning

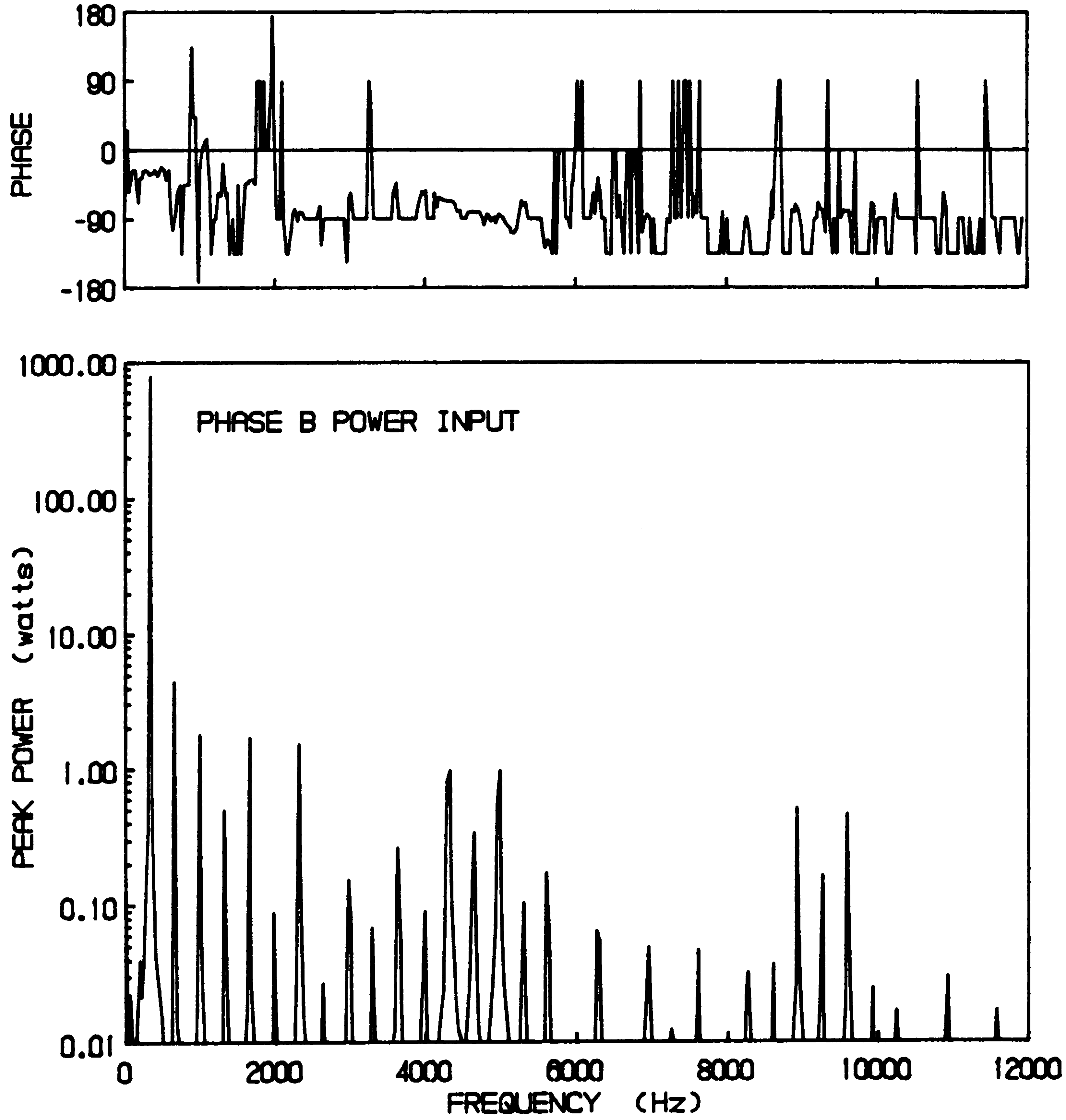

Figure 29. Power Measurement of Phase B at 20,000 RPM Before Tuning

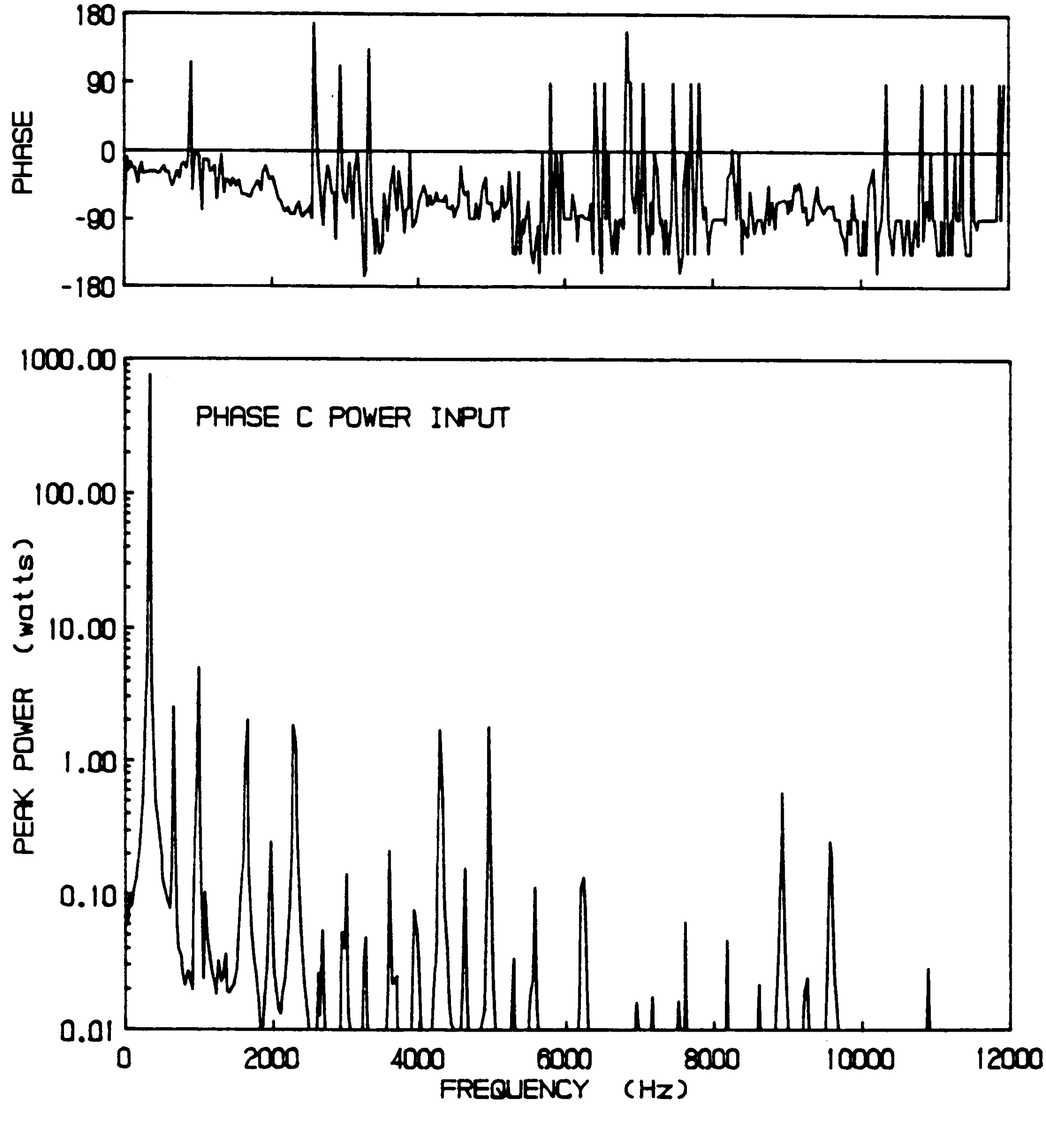

Figure 30. Power Measurement of Phase C at 20,000 RPM Before Tuning

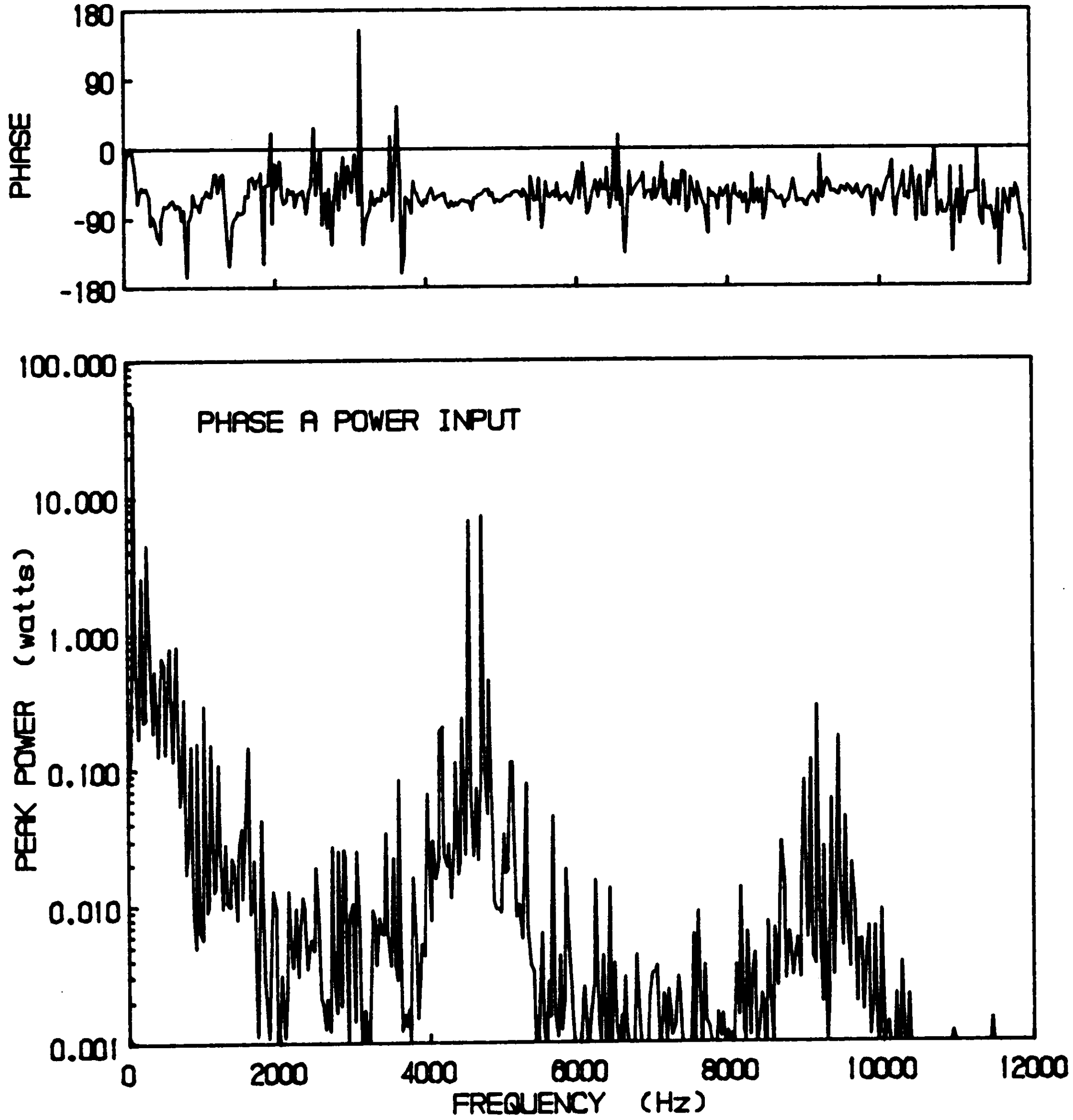

Figure 31. Power Measurement of Phase A at 5,000 RPM Before Tuning

on page 87 and Figure 34 on page 88 show the input power to the motor at 20,000 RPM after it was tuned. The total RMS real power input after tuning was 894 watts with 61 watts of reactive power input. The average phase angle between the voltage and current waveforms was 3.9 degrees. Not only was the reactive power input reduced by an order of magnitude, but the real power input was reduced by 9.5 percent.

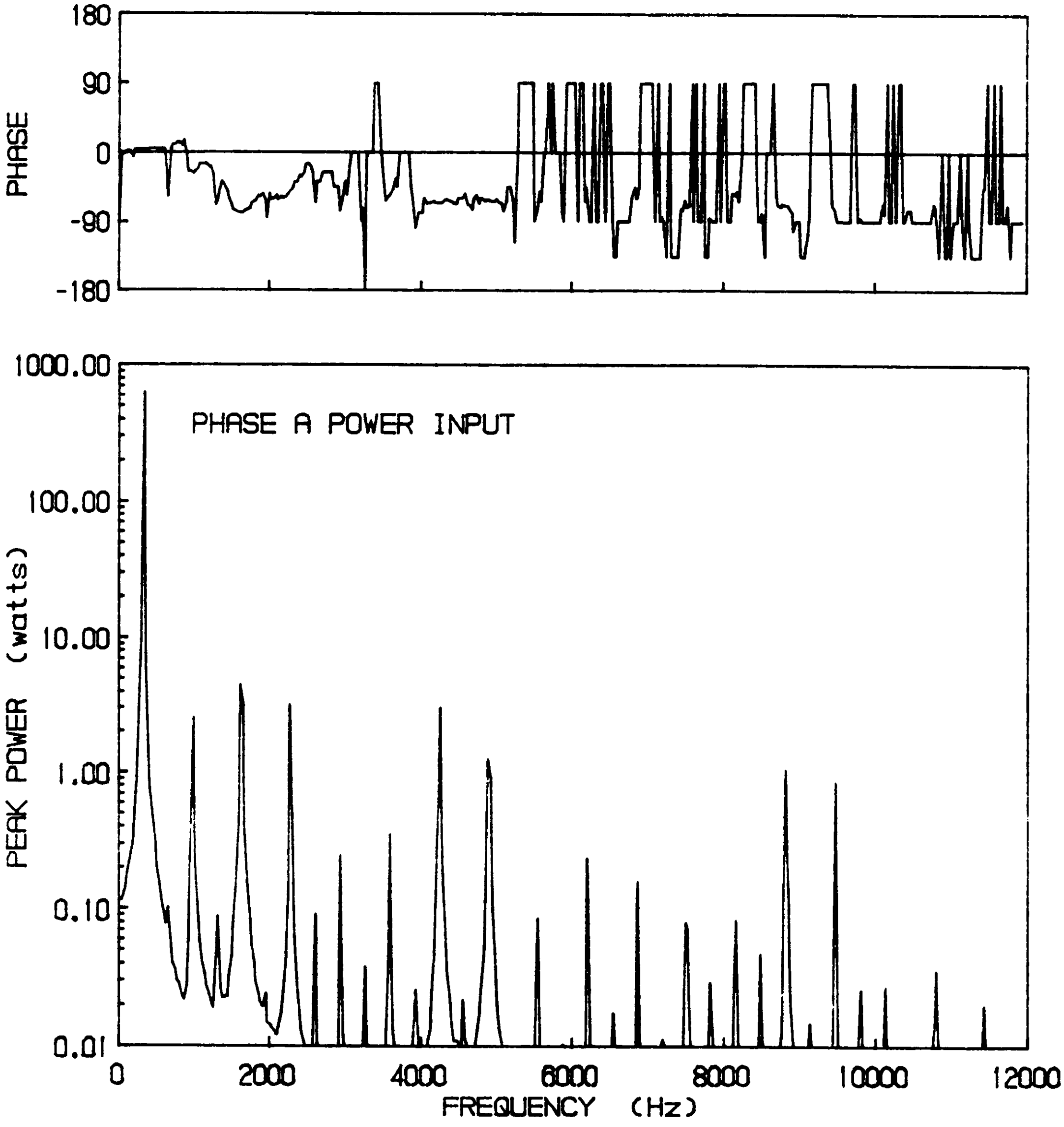

Figure 32. Power Measurement of Phase A at 20,000 RPM After Tuning

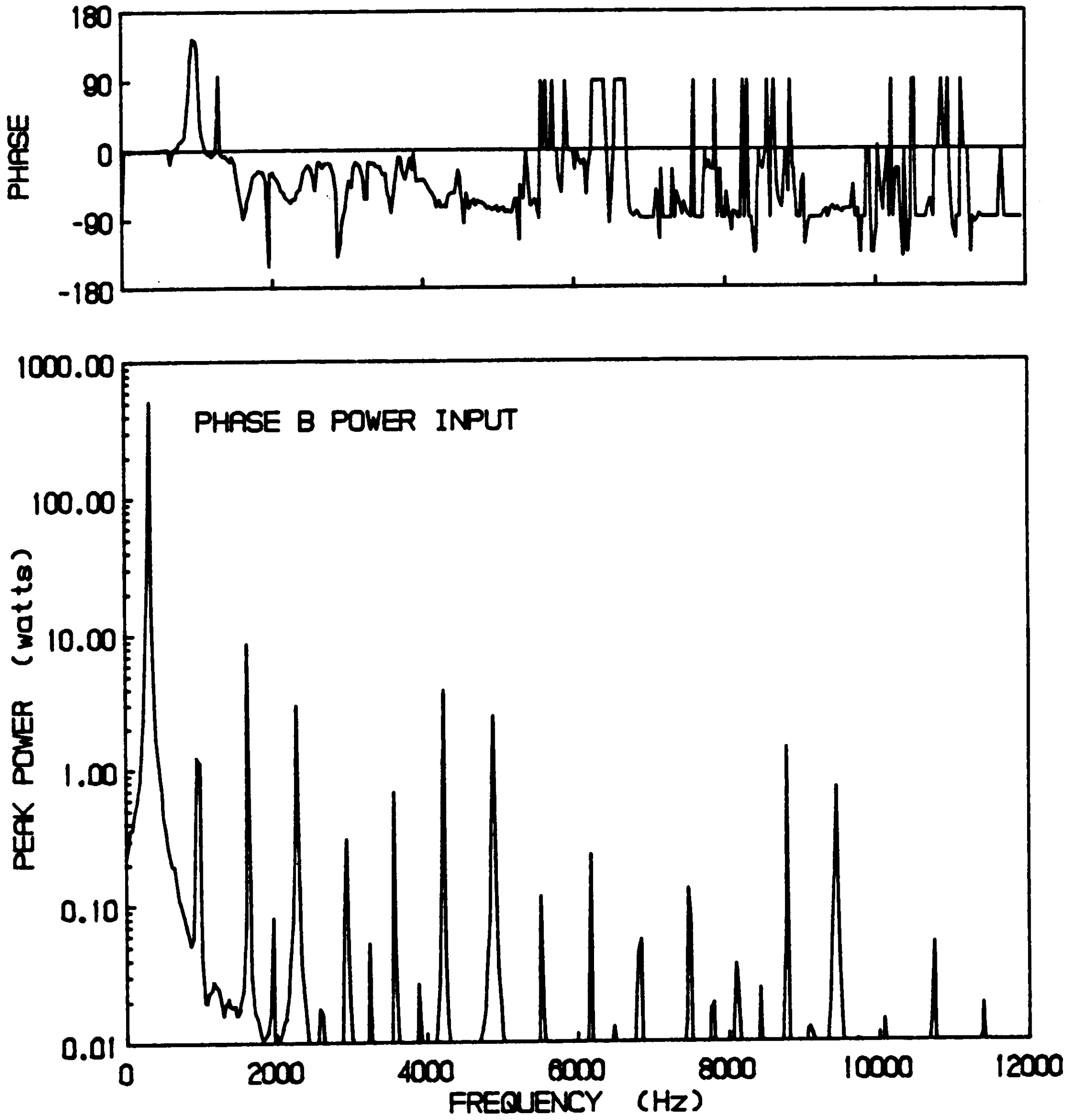

Figure 33. Power Measurement of Phase B at 20,000 RPM After Tuning

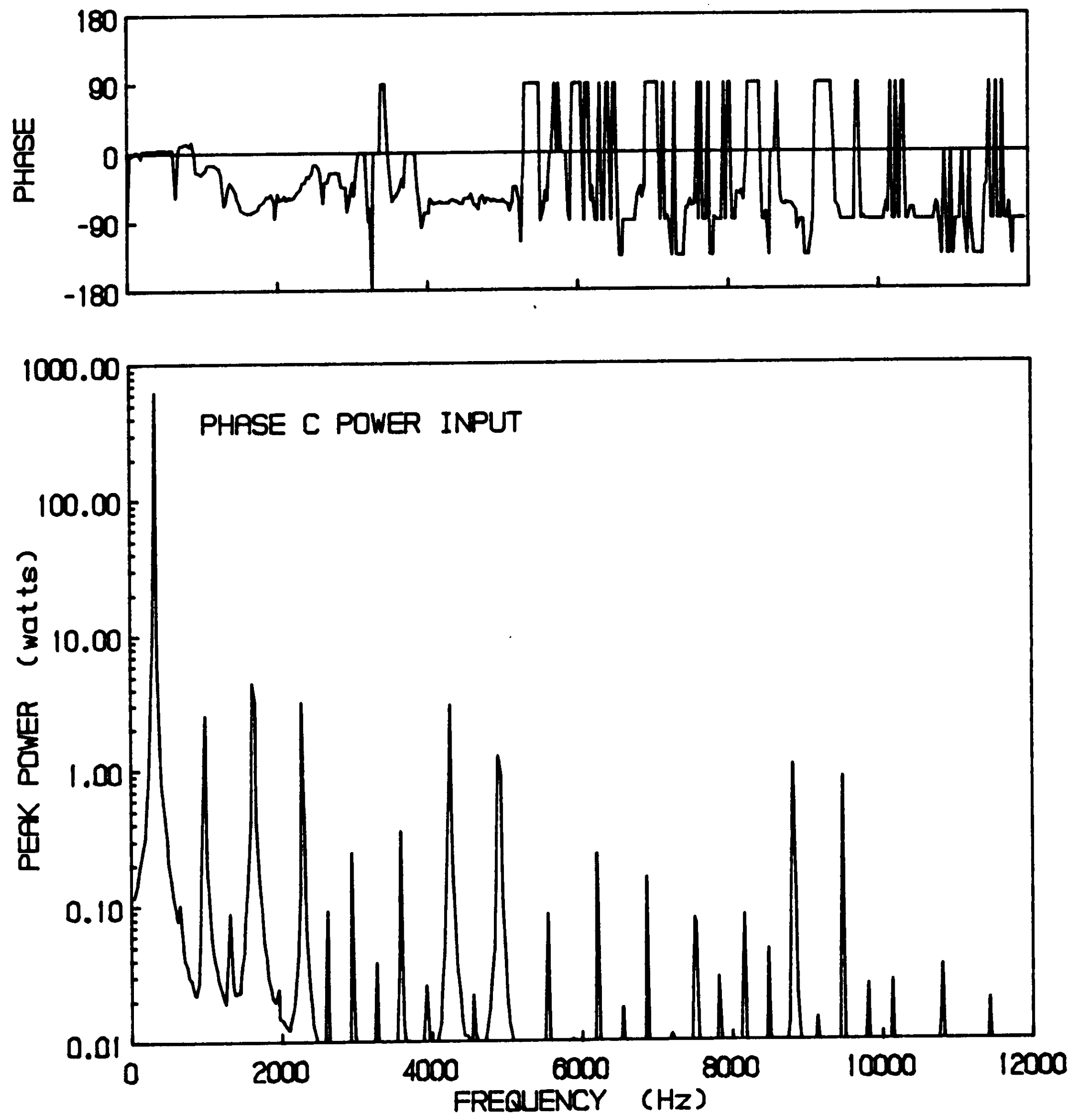

Figure 34. Power Measurement of Phase C at 20,000 RPM After Tuning

Chapter 7

Conclusions and Recommendations

Several conclusions can be drawn from the experience gained in this testing program. They are:

1. The data acquisition system described herein has been proven to be accurate and dependable for monitoring and controlling high-speed electric motors.

2. Because the zero offset of the amplifiers and RMS circuits are temperature dependent, it is necessary to allow the circuits to operate until they reach equilibrium temperature before calibration.

3. Special care must be taken to ground the motor and properly shield all transducers and cables to reduce noise on the signals.

4. The microcomputer must be protected from excessive heat and vibration. This is especially important if the computer is used for controlling the motor.

5. Even slight increases in imbalance or bearing faults will increase the RMS vibration level in the motor housing by a factor of two or more. The RMS vibration level can thus be used reliably for fault detection in continuous monitoring systems.

6. Spectral analysis of the bearing vibration signals can be used very effectively for identifying vibration caused by excessive imbalance or fatigue faults in bearings. However, as demonstrated by the spinning outer bearing race encountered, considerable skill is required to interpret the results of complex problems.

7. If appropriate current and voltage sensors are available, accurate measurements of real and reactive power for asymmetrical waveforms may be obtained using a spectrum analyzer. Again, special care must be exercised to ensure accurate results.

8. Leakage must be identified and removed from the voltage and current spectrums. This may be accomplished by keeping the motor speed constant and adjusting the frequency range so that the major peaks in the cross spectrum coincide with spectral lines on the analyzer.

9. Order analysis can be used effectively to reduce leakage in the motor speed dependent frequency components. A trade-off is involved as increased leakage will occur in the constant frequency power components if the motor speed varies.

10. With a pulse width modulation controller like the one used in the present study, as the motor speed increases, the voltage and current inputs approach a sinusoidal waveform at the fundamental rotational frequency. Thus, with the appropriate sensors, power measurements of reasonable accuracy may be obtained with a true RMS voltmeter. Even at high speeds, Fourier analysis techniques are required to extract phase information to compute the power factor.

Several recommendations are in order for future testing efforts.

1. The computer and electronics need to be located in a temperature controlled environment. This is necessary to prevent computer failures that might allow the motor to continue operating unattended.

2. The cooling air pressure has proven to be a critical factor for successful operation. Monitoring the air pressure would provide more useful information than the motor casing temperature presently being measured.

3. For the vortex coolers to be used effectively, a dependable high-pressure air supply must be obtained.

4. Future efforts to cool the motor should include improving its efficiency by correcting the power factor.

5. Considerable work needs to be done in the area of bearing fault diagnosis using spectrum analysis.

6. The speed monitoring circuitry should be improved to allow the motor speed to be recorded accurately.

7. A load should be applied to the motor to determine the effect on efficiency.

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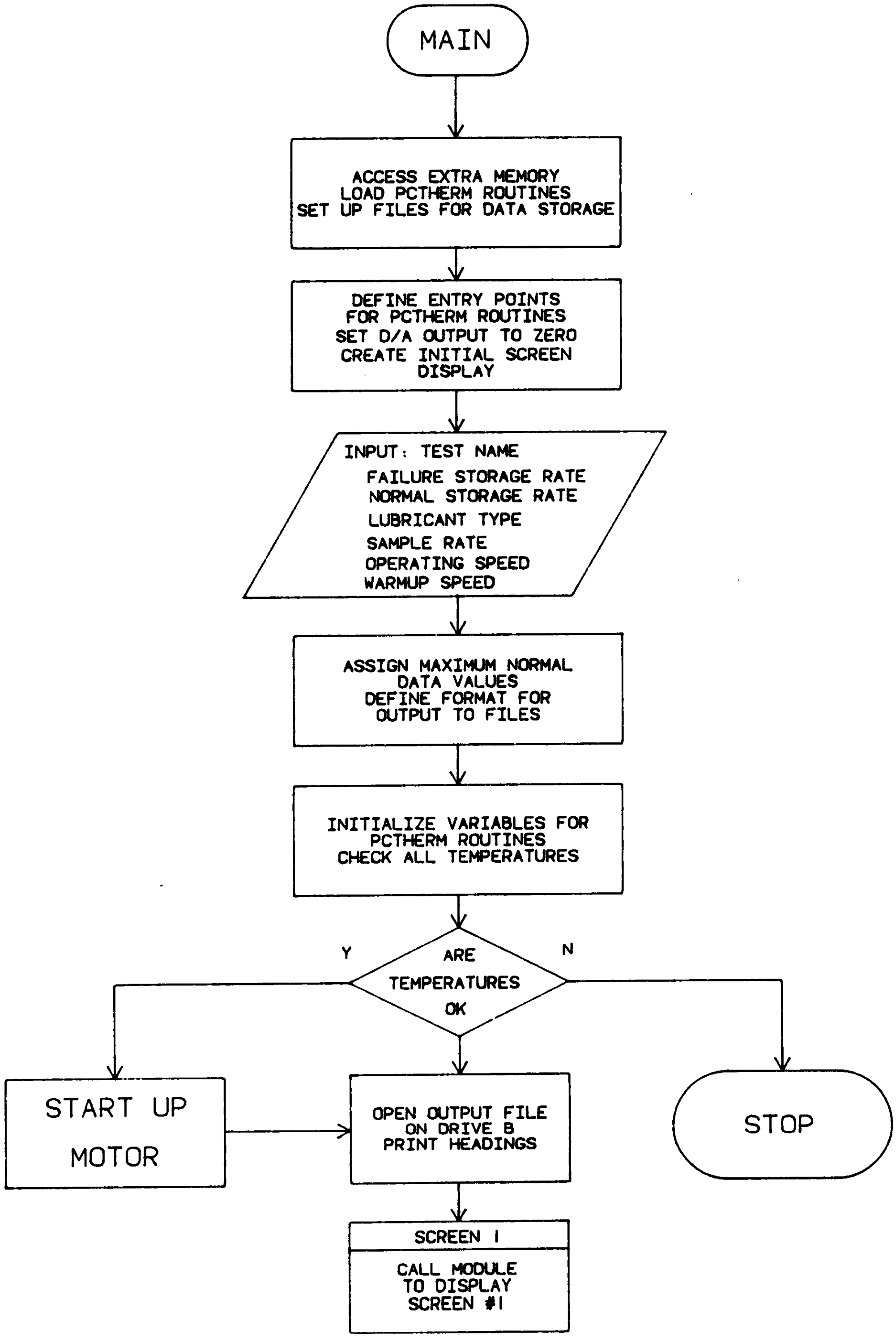
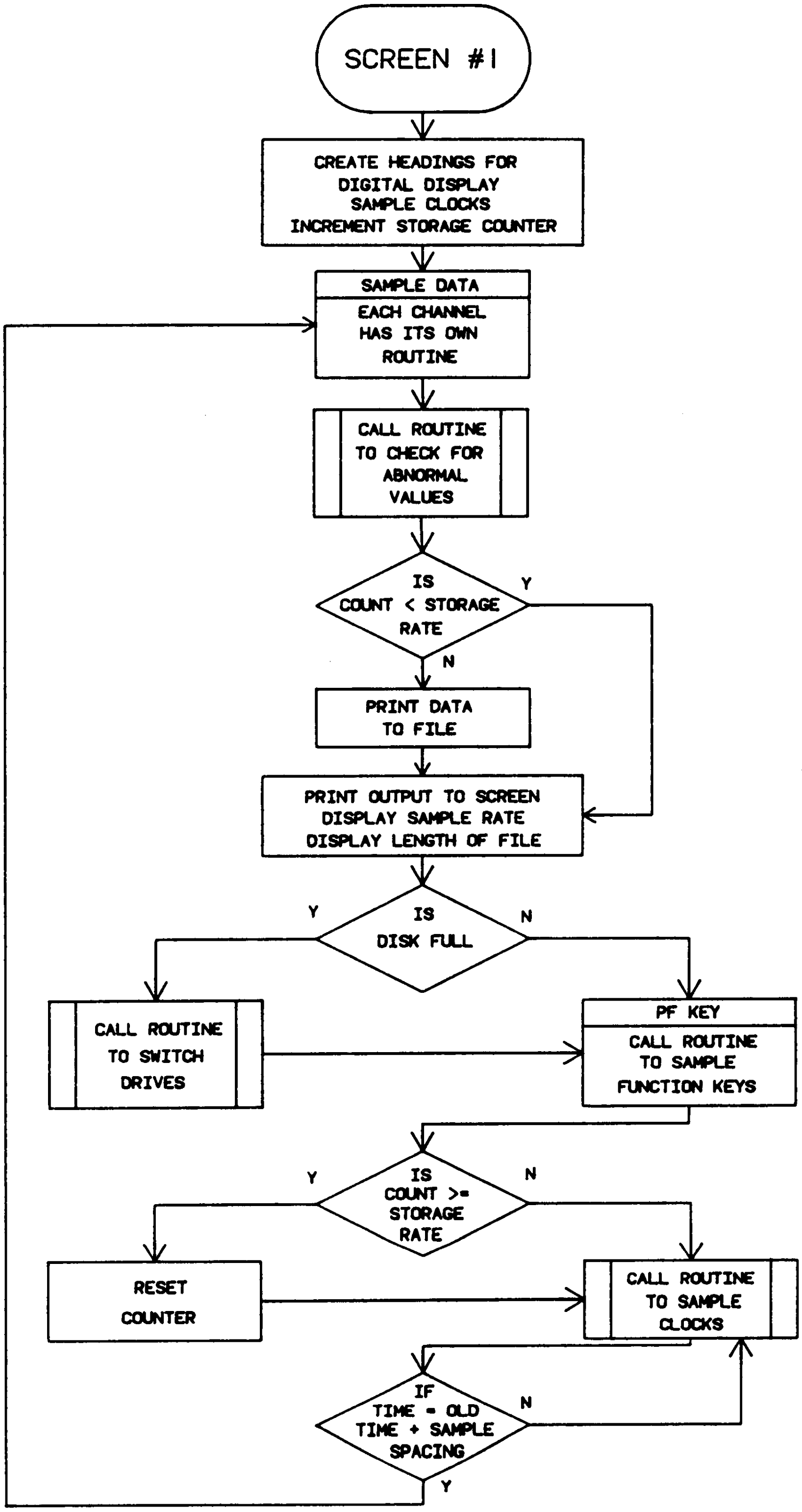
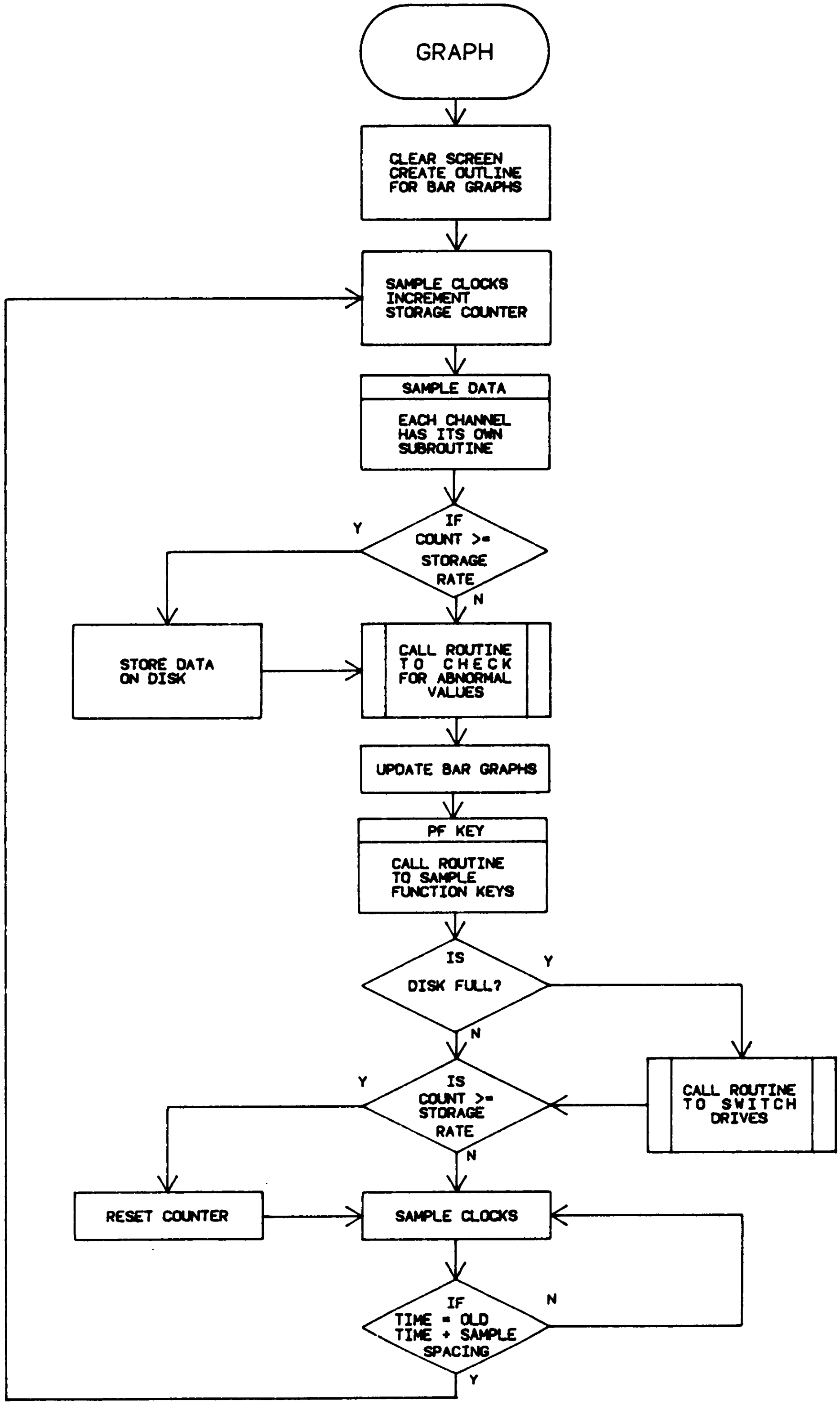
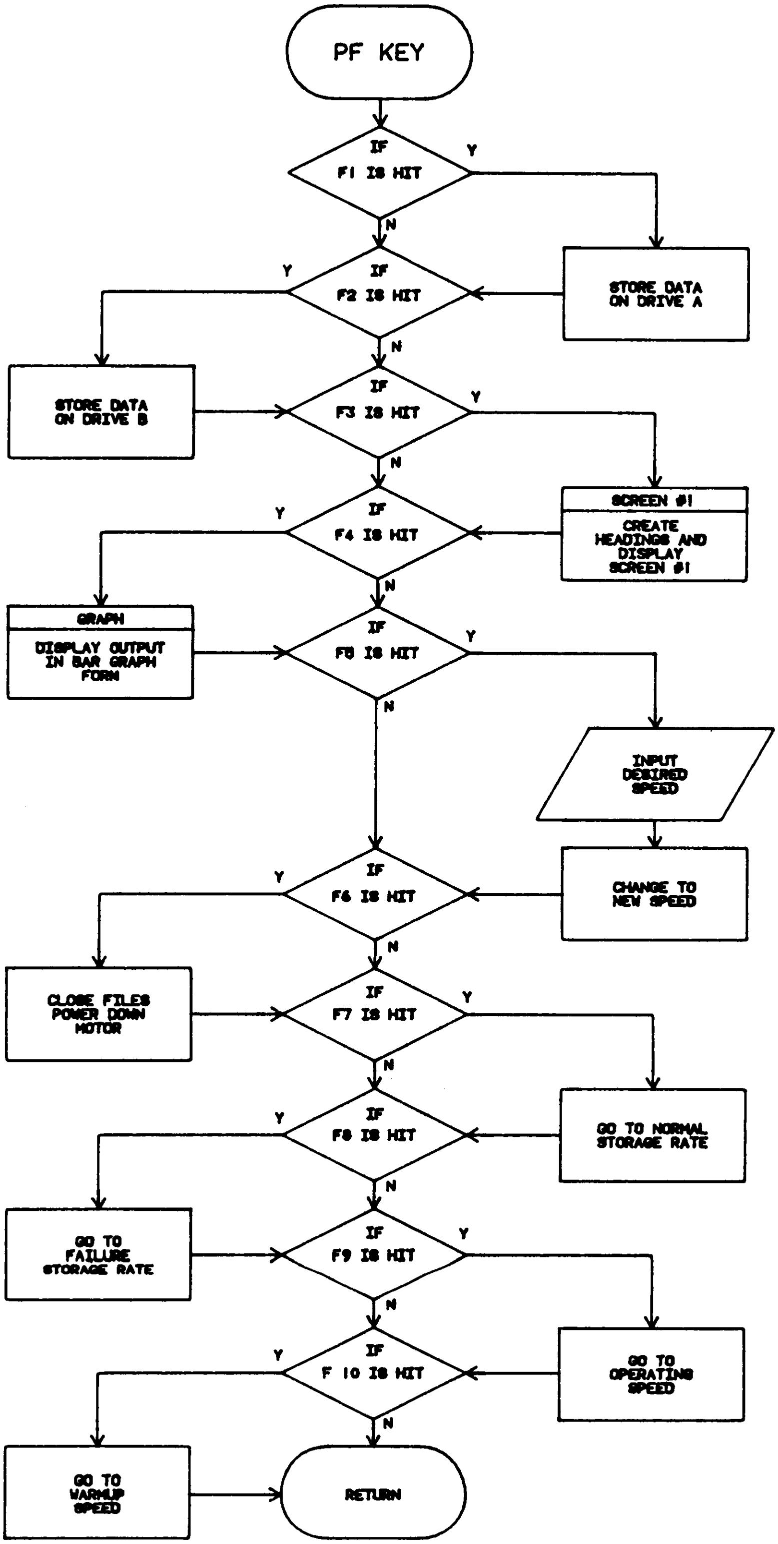
Appendix A

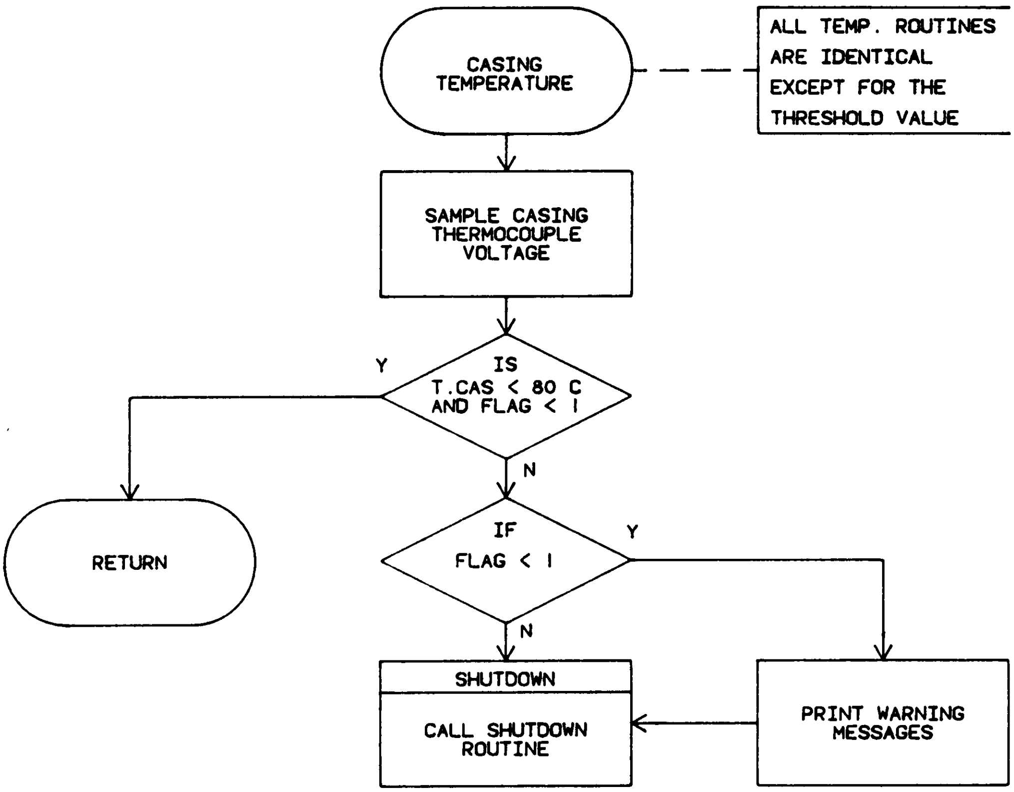
Flowcharts of Data Acquisition Program

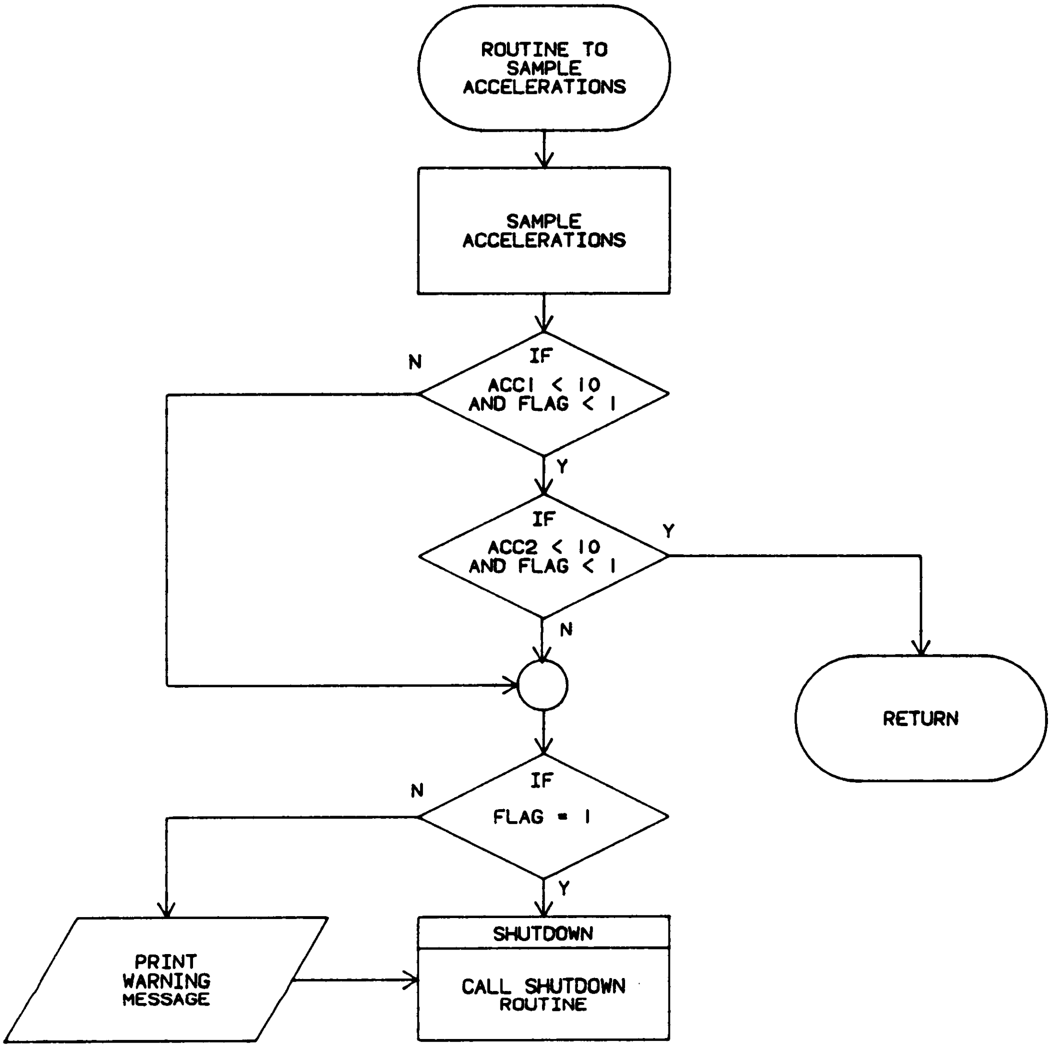

MAIN
ACCESS EXTRA MEMORY
LOAD PCTHERM ROUTINES
SET UP FILES FOR DATA STORAGE
DEFINE ENTRY POINTS
FOR PCTHERM ROUTINES
SET D/A OUTPUT TO ZERO
CREATE INITIAL SCREEN
DISPLAY
INPUT: TEST NAME
FAILURE STORAGE RATE
NORMAL STORAGE RATE
LUBRICANT TYPE
SAMPLE RATE
OPERATING SPEED
WARMUP SPEED
ASSIGN MAXIMUM NORMAL
DATA VALUES
DEFINE FORMAT FOR
OUTPUT TO FILES
INITIALIZE VARIABLES FOR
PCTHERM ROUTINES
CHECK ALL TEMPERATURES
Y
ARE
TEMPERATURES
OK
N
START UP
MOTOR
OPEN OUTPUT FILE
ON DRIVE B
PRINT HEADINGS
STOP
SCREEN 1
CALL MODULE
TO DISPLAY
SCREEN #1

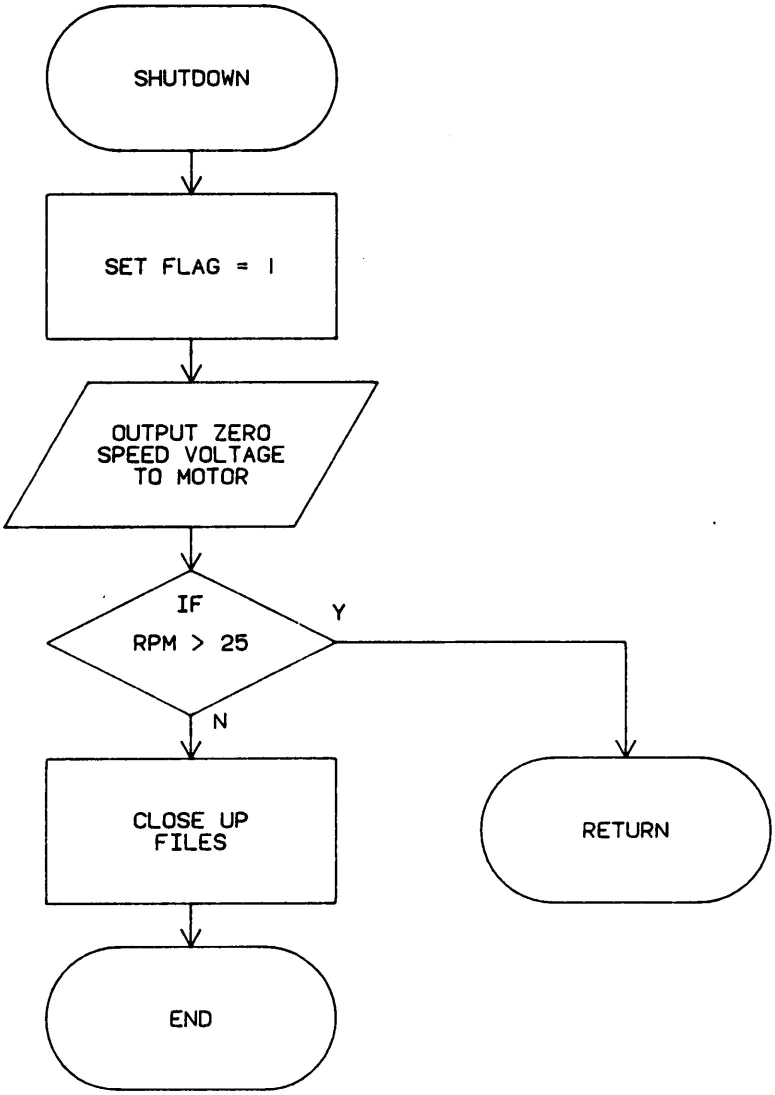

SCREEN #1
CREATE HEADINGS FOR
DIGITAL DISPLAY
SAMPLE CLOCKS
INCREMENT STORAGE COUNTER
SAMPLE DATA
EACH CHANNEL
HAS ITS OWN
ROUTINE
CALL ROUTINE
TO CHECK FOR
ABNORMAL
VALUES
IS
COUNT < STORAGE
RATE
Y
N
PRINT DATA
TO FILE
PRINT OUTPUT TO SCREEN
DISPLAY SAMPLE RATE
DISPLAY LENGTH OF FILE
IS
DISK FULL
Y
N
CALL ROUTINE
TO SWITCH
DRIVES
PF KEY
CALL ROUTINE
TO SAMPLE
FUNCTION KEYS
IS
COUNT >=
STORAGE
RATE
Y
N
RESET
COUNTER
CALL ROUTINE
TO SAMPLE
CLOCKS
IF
TIME = OLD
TIME + SAMPLE
SPACING
N
Y


GRAPH
CLEAR SCREEN
CREATE OUTLINE
FOR BAR GRAPHS
SAMPLE CLOCKS
INCREMENT
STORAGE COUNTER
SAMPLE DATA
EACH CHANNEL
HAS ITS OWN
SUBROUTINE
IF
COUNT >=
STORAGE
RATE
Y
N
STORE DATA
ON DISK
CALL ROUTINE
TO CHECK
FOR ABNORMAL
VALUES
UPDATE BAR GRAPHS
PF KEY
CALL ROUTINE
TO SAMPLE
FUNCTION KEYS
IS
DISK FULL?
Y
N
CALL ROUTINE
TO SWITCH
DRIVES
IS
COUNT >=
STORAGE
RATE
Y
N
RESET COUNTER
SAMPLE CLOCKS
IF
TIME = OLD
TIME + SAMPLE
SPACING
N
Y


PF KEY
IF F1 IS HIT
Y
N
STORE DATA ON DRIVE A
IF F2 IS HIT
STORE DATA ON DRIVE B
IF F3 IS HIT
SCREEN #1
CREATE HEADINGS AND DISPLAY SCREEN #1
IF F4 IS HIT
GRAPH
DISPLAY OUTPUT IN BAR GRAPH FORM
IF F5 IS HIT
INPUT DESIRED SPEED
CHANGE TO NEW SPEED
IF F6 IS HIT
CLOSE FILES POWER DOWN MOTOR
IF F7 IS HIT
GO TO NORMAL STORAGE RATE
IF F8 IS HIT
GO TO FAILURE STORAGE RATE
IF F9 IS HIT
GO TO OPERATING SPEED
IF F 10 IS HIT
GO TO WARMUP SPEED
RETURN


CASING TEMPERATURE
ALL TEMP. ROUTINES ARE IDENTICAL EXCEPT FOR THE THRESHOLD VALUE
SAMPLE CASING THERMOCOUPLE VOLTAGE
IS T.CAS < 80 C AND FLAG < 1
Y
N
RETURN
IF FLAG < 1
Y
N
SHUTDOWN
CALL SHUTDOWN ROUTINE
PRINT WARNING MESSAGES


ROUTINE TO SAMPLE ACCELERATIONS
SAMPLE ACCELERATIONS
IF ACC1 < 10 AND FLAG < 1
N
Y
IF ACC2 < 10 AND FLAG < 1
Y
N
RETURN
IF FLAG = 1
N
Y
PRINT WARNING MESSAGE
SHUTDOWN
CALL SHUTDOWN ROUTINE


SHUTDOWN
SET FLAG = 1
OUTPUT ZERO
SPEED VOLTAGE
TO MOTOR
IF
RPM > 25
Y
N
CLOSE UP
FILES
RETURN
END

Appendix B

Data Acquisition Code

```
10 ' INLAND11        10-24-87
20 '
25 ' DATA ACQUISITION AND CONTROL SOFTWARE FOR HIGH SPEED
26 '                 ELECTRIC MOTORS
27 '
28 ' SOFTWARE WRITTEN BY KEVIN K. MOYERS
29 '
30 CLEAR ,,2000
40 DEF SEG=8192:BLOAD "pctherm",0
50 DEF FNCLK(Q) = VAL(HEX$(INP(Q)))
60 DIM E1$(6) : DIM OLD.Y%(7)
70 D$ = "B:"
80 A$ ="A:"
90 FOR I = 1 TO 6 ' this changes the file name each time the drives are
100 '            switched to prevent overwriting files a after dt6
110 '            the file resets to dt1
120 READ E1$(I)  : NEXT
130 DATA ".DT1",".DT2",".DT3",".DT4",".DT5",".DT6"
140 KEY OFF
150 ' define entry points for PCLAB and PCTHERM routines
160 ADC.VALUE = 3: GENERATE.VOLTS = 165: MEASURE.THERMOCOUPLE = 141
170 SET.CLOCK.DIVIDER = 45: SETUP.ADC = 9: ADC.SERIES = 12
: MEASURE.VOLTS = 138
180 GET.ERROR.CODE = 78
190 SET.ADC.RANGE = 90 : CLS
195 ' set D/A output to zero
200 VVOLTS! = -.1 : DAC.SELECT% = 0
210 CALL GENERATE.VOLTS (DAC.SELECT%,VVOLTS!)
215 ' create initial screen display
220 PRINT:PRINT:PRINT:PRINT
```

```
230 PRINT "           ELECTRIC MOTOR MONITORING SOFTWARE          "
240 PRINT:PRINT
250 PRINT "     THIS SOFTWARE DESIGNED TO AUTOMATICALLY MONITOR THE "
260 PRINT "     OPERATION OF A HIGH SPEED ELECTRIC MOTOR AND TO STOP"
270 PRINT "           THE MOTOR IF ANY TYPE OF FAILURE OCCURS "
280 PRINT
290 PRINT:PRINT: PRINT
300 PRINT "     KEVIN K. MOYERS "
310 PRINT "   MECHANICAL ENGINEERING DEPARTMENT  "
320 PRINT "      V.P.I. and S.U.  "
330 PRINT:PRINT:PRINT:PRINT:PRINT
340 INPUT " PRESS ENTER TO CONTINUE ",CONTINUE$:CLS
345 ' input test parameters
350 INPUT " ENTER TEST NAME ",TN$
360 INPUT " ENTER DESIRED OPERATING SPEED IN RPM ",O.RPM
370 INPUT " ENTER DESIRED WARMUP SPEED IN RPM ",W.RPM
380 IF W.RPM > 4000 THEN GOTO 370
390 INPUT " ENTER TYPE OF LUBRICANT TO BE USED ",LUB$
400 INPUT " ENTER SAMPLING RATE IN SAMPLES PER MINUTE ",SAMPLE.RATE%
410 INPUT " ENTER NORMAL STORAGE RATE AS SAMPLES TAKEN PER
SAMPLE STORED";STRN%
420 INPUT " ENTER STORAGE RATE FOR FAILURE MODE ";FAIL.RATE
430 T.CAS.NORM! = 80 ' assigned maximum normal temperature for motor casing
440 T.B1.NORM! = 70 ' assigned maximum normal temp. for bearing #1
450 T.B2.NORM! = 70 ' assigned maximum normal temp. for bearing #2
460 T.STAT.NORM! = 140' assigned maximum normal stator temperature
470 ACC1.NORM! = 8 'assigned maximum normal vibration for accelerometer #1
480 ACC2.NORM! = 8 ' assigned maximum normal vibration for accelerometer #2
490 RACC = 500  ' angular acceleration rate in rpm/sec
500 Q1$="  DATE/TIME      T.CAS  T.B1   T.B2  T.STAT  M.SPEED  V.ACC1  V.ACC2"
510 Q3$="                 CONTR  SHAFT  STATOR         CONTR   SHAFT  "
520 Q2$="(mn-dy-hr-min-s) (C)    (C)    (C)    (C)    (rpm)    (g)     (g)"
530 R$ =" ## ## ## ## ##  ##.#  ###.#  ###.#  ###.#  ##.####  ###.##  ###.##"
540 S$="---------------------------------------------------------------"
550 ' initialize variables to be used in PCLAB routines
560 TEST.VALUE% = 0 : RPM.TEST% = 0
570 SAMPLE.SPACING% = INT(60/SAMPLE.RATE%)
580 'DIM ANALOG.DATA.ARRAY%(2)
590 'UMBER.OF.TICKS% = 400
600 'CALL SET.CLOCK.DIVIDER(NUMBER.OF.TICKS%)
610 'IMING.SOURCE% = 0: GAIN% = 1
620 'START.CHAN = 6: END.CHAN% = 7
630 'ALL SETUP.ADC(TIMING.SOURCE%,START.CHAN%,END.CHAN%,GAIN%)
640 ' check all temperatures and start up motor
650 GOSUB 2410 ' call subroutine to sample temperature of motor casing
660 GOSUB 2540 ' call subroutine to sample bearing #1 temperature
670 GOSUB 2660 ' call subroutine to sample bearing #2 temperature
680 GOSUB 2780 ' call subroutine to sample stator temperature
690 GOSUB 3130 ' call subroutine to power up motor
700 TEST.VALUE% = 1
710 COUNT% = 0 : STORAGE.RATE% = STRN% : K  = 0
720 GOSUB 3970
730 '              screen 1, numerical values
740 CLS : KEY(3) OFF
750 LOCATE 4,1 : PRINT Q1$
760 LOCATE 5,1 : PRINT Q2$
```

```
770 LOCATE 6,1 : PRINT S$
780 LOCATE 10,1 : PRINT "AMOUNT OF DISK SPACE USED ="
790 LOCATE 10,34 : PRINT "KILOBYTES"
800 LOCATE 12,1 : PRINT " SAMPLE RATE =    SAMPLES/MIN "
810 LOCATE 13,1 : PRINT " STORAGE RATE = 00.0 SAMPLES/MIN "
820 LOCATE 14,1 : PRINT " PRESS F1 TO STORE DATA ON DISK DRIVE A "
830 LOCATE 15,1 : PRINT " PRESS F2 TO STORE DATA ON DISK DRIVE B "
840 LOCATE 16,1 : PRINT " PRESS F3 TO RETURN TO SCREEN #1  "
850 LOCATE 17,1 : PRINT " PRESS F4 TO DISPLAY BAR GRAPHS "
860 LOCATE 18,1 : PRINT " PRESS F5 TO CHOOSE OPERATING SPEED "
870 LOCATE 19,1 : PRINT " PRESS F6 TO POWER DOWN MOTOR "
880 LOCATE 20,1 : PRINT " PRESS F7 TO RETURN TO NORMAL STORAGE RATE "
890 LOCATE 21,1 : PRINT " PRESS F8 TO GO TO FAILURE STORAGE RATE "
900 LOCATE 22,1 : PRINT " PRESS F9 TO GO TO OPERATING SPEED "
910 LOCATE 23,1 : PRINT " PRESS F10 TO GO TO WARMUP SPEED "
920 LOCATE 11,1 : PRINT " SAMPLING ON "
930 ' portion to sample data
940 COUNT% = COUNT% + 1
950 GOSUB 3540   ' call subroutine to sample clocks
960 OLD.MIN = MIN% : OLD.SEC = SEC%
970 GOSUB 2410 ' call subroutine to sample temp. of motor casing
980 GOSUB 2540 ' call subroutine to sample bearing #1 temp.
990 GOSUB 2660 ' call subroutine to sample bearing #2 temp.
1000 GOSUB 2780' call subroutine to sample stator temp.
1010 GOSUB 2890 ' call subroutine to sample motor speed
1020 GOSUB 2940 ' sample accelerometers
1021 'check error code in pctherm
1022 IF ERROR.CODE% = 0 GOTO 1100
1023 GOSUB 3180
1100 IF COUNT% < STORAGE.RATE% GOTO 1111
1110 PRINT #1,USING R$;MON%,DY%,HR%,MIN%,SEC%,T.CAS!,T.B1!,T.B2!,
T.STA!,RPM%,ACC1!,ACC2!
1111 GOSUB 3440  ' call subroutine to check for abnormal values
1115 ' print out data values
1120 LOCATE 7,1 : PRINT USING "##"; MON%
1130 LOCATE 7,4 : PRINT USING "##";DY%
1140 LOCATE 7,7 : PRINT USING "##";HR%
1150 LOCATE 7,10 : PRINT USING "##";MIN%
1160 LOCATE 7,13 : PRINT USING "##";SEC%
1170 LOCATE 7,19 : PRINT USING "###.";T.CAS!
1180 LOCATE 7,25 : PRINT USING "###.#";T.B1!
1190 LOCATE 7,32 : PRINT USING "###.#";T.B2!
1200 LOCATE 7,39 : PRINT USING "###";T.STA!
1210 LOCATE 7,49 : PRINT USING "##,###";RPM%
1220 LOCATE 7,57 : PRINT USING "###.##";ACC1!
1230 LOCATE 7,65 : PRINT USING "###.##";ACC2!
1240 KBYTE% = LOF(1)/1000 ' kilobytes of memory stored on disk
1250 LOCATE 10,28 : PRINT USING "###";KBYTE%
1260 LOCATE 11,14: PRINT SCR$
1270 LOCATE 12,16 : PRINT USING "##"; SAMPLE.RATE%
1280 LOCATE 13,17 : PRINT USING "##.#"; SAMPLE.RATE%/STORAGE.RATE%
1290 IF KBYTE% > 328 THEN GOSUB 4040
1295 ' sample function keys
1300 KEY(1) ON : ON KEY(1) GOSUB 3900 ' if F1 is hit, sample on drive A
1310 KEY(2) ON : ON KEY(2) GOSUB 3970 ' if F2 is hit sample on drive B
1320 KEY(4) ON : ON KEY(4) GOSUB 1490 ' if F4 is hit go to screen 2
```

```
1330 KEY(6) ON : ON KEY(6) GOSUB 3180 'manual shutdown
1340 KEY(5) ON : ON KEY(5) GOSUB 4280 ' if F5 is hit choose new speed
1350 KEY(7) ON : ON KEY(7) GOSUB 4080 ' if F7 is hit go to normal storage rate
1360 KEY(8) ON : ON KEY(8) GOSUB 4110 ' if F8 is hit go to failure storage rate
1370 KEY(9) ON : ON KEY(9) GOSUB 4140 ' if F9 is hit go to operating speed
1380 KEY(10) ON : ON KEY(10) GOSUB 4240 ' if F10 is hit go to warmup speed
1390 IF COUNT% > = STORAGE.RATE% THEN COUNT% = 0
1400 'CLOCK ROUTINE TO CONTROL SAMPLE RATE
1410 GOSUB 3540
1420 IF (MIN% = OLD.MIN) THEN GOTO 1450
1430 IF((60 - INT(OLD.SEC)) + SEC%) = SAMPLE.SPACING% THEN GOTO 940
1440 GOTO 1410
1450 IF INT(SEC% - OLD.SEC) = SAMPLE.SPACING% THEN GOTO 940
1460 GOTO 1410
1470 RETURN
1480 '
1490 '  second screen
1500 CLS : KEY(4) OFF
1510 SCREEN 2,,0,0  'high resolution, no color
1520 '                create outline for bar graphs
1530 LINE (2,0)-(638,0) : LINE (2,26)-(638,26) : LINE (2,188)-(638,188)
1540 LINE (2,0)-(2,188) : LINE(638,0)-(638,188)
1550 LINE (92,26)-(92,188) : LINE (180,26)-(180,188) :
LINE (268,26)-(268,188)
1560 LINE (356,26)-(356,188) : LINE (444,26)-(444,188) :
LINE (532,26)-(532,188)
1570 LOCATE 5,4 : PRINT "T.CAS" : LOCATE 6,6 : PRINT "(C)"
1580 LOCATE 5,16 : PRINT "T.B1" : LOCATE 6,16 : PRINT "(C)"
1590 LOCATE 5,27 : PRINT "T.B2" : LOCATE 6,27 : PRINT "(C)"
1600 LOCATE 5,38 : PRINT "T.STAT" : LOCATE 6,39 : PRINT "(C)"
1610 LOCATE 5,49 : PRINT "SPEED" : LOCATE 6,46 : PRINT "(rpm/1000)"
1620 LOCATE 5,61 : PRINT "ACC1" : LOCATE 6,61 : PRINT "(g)"
1630 LOCATE 5,73 : PRINT "ACC2" : LOCATE 6,74 : PRINT "(g)"
1640 LINE (12,52)-(52,180),,B
1650 FOR I = 8 TO 30 STEP 11
1660  LOCATE 7,I : PRINT "- 90" : LOCATE 9,I : PRINT "- 80"
1670 LOCATE 11,I : PRINT "- 70" : LOCATE 13,I : PRINT "- 60"
1680 LOCATE 15,I : PRINT "- 50" : LOCATE 17,I : PRINT "- 40"
1690 LOCATE 19,I : PRINT "- 30" : LOCATE 21,I : PRINT "- 20"
1700 LOCATE 23,I : PRINT "- 10" : NEXT
1710 LOCATE 7,41 : PRINT "-160" : LOCATE 9,41 : PRINT "-140"
1720 LOCATE 11,41 : PRINT "-120" : LOCATE 13,41 : PRINT "-100"
1730 LOCATE 15,41 : PRINT "- 80" : LOCATE 17,41 : PRINT "- 60"
1740 LOCATE 19,41 : PRINT "- 40" : LOCATE 21,41 : PRINT "- 20"
1750 LOCATE 23,41 : PRINT "-  0"
1760 LINE (100,52)-(140,180),,B  : LINE (188,52)-(228,180),,B
1770 LINE (276,52)-(316,180),,B
1780 LOCATE 7,52 : PRINT "-32" : LOCATE 9,52 : PRINT "-28"
1790 LOCATE 11,52 : PRINT "-24" : LOCATE 13,52 : PRINT "-20"
1800 LOCATE 15,52 : PRINT "-16" : LOCATE 17,52 : PRINT "-12"
1810 LOCATE 19,52 : PRINT "- 8" : LOCATE 21,52 : PRINT "- 4"
1820 LOCATE 23,52 : PRINT "- 0" : LINE (364,52)-(404,180),,B
1830 FOR I = 63 TO 74 STEP 11
1840 LOCATE 7,I : PRINT "- 8" : LOCATE 9,I : PRINT "- 7"
1850 LOCATE 11,I : PRINT "- 6" : LOCATE 13,I : PRINT "- 5"
1860 LOCATE 15,I : PRINT "- 4" : LOCATE 17,I : PRINT "- 3"
```

```
1870 LOCATE 19,I : PRINT "- 2" : LOCATE 21,I : PRINT "- 1"
1880 LOCATE 23,I : PRINT "- 0"
1890 NEXT
1900 LINE (452,52)-(492,180),,B  : LINE (540,52)-(580,180),,B
1910 LOCATE 3,67 : PRINT  "KBYTE ="
1920 FOR I = 1 TO 7 : OLD.Y%(I) = 180 : NEXT
1930 '    portion to sample data
1940 COUNT% = COUNT% + 1
1950 GOSUB 3550  'call subroutine to sample clocks
1960 OLD.MIN = MIN% : OLD.SEC = SEC%
1970 GOSUB 2410 ' call subroutine sample temperature of motor casing
1980 GOSUB 2540 ' call subroutine to sample bearing #1 temp.
1990 GOSUB 2660 ' call subroutine to sample bearing #2 temp.
2000 GOSUB 2780 ' call subroutine to sample stator temp.
2010 GOSUB 2890 ' call subroutine to sample motor speed
2020 GOSUB 2940 ' sample accelerometers
2021 'check error code in pctherm
2022 IF ERROR.CODE% = 0 GOTO 2030
2023 GOSUB 3180
2030 IF COUNT% < STORAGE.RATE% THEN GOTO 2050
2040 PRINT #1, USING R$;MON%,DY%,HR%,MIN%,SEC%,T.AMB!,T.B1!,T.B2!,
T.STA!,RPM%,ACC1!,ACC2!
2050 GOSUB 3450 ' call subroutine to check for abnormal values
2060 L.SIDE% = 13 : R.SIDE% = 51
2065 ' compute values for bar graphs
2070 FOR CHANNEL% = 1 TO 7 STEP 1
2080  IF CHANNEL% = 1 THEN GOSUB 3620
2090  IF CHANNEL% = 2 THEN GOSUB 3660
2100  IF CHANNEL% = 3 THEN GOSUB 3700
2110  IF CHANNEL% = 4 THEN GOSUB 3740
2120  IF CHANNEL% = 5 THEN GOSUB 3780
2130  IF CHANNEL% = 6 THEN GOSUB 3820
2140  IF CHANNEL% = 7 THEN GOSUB 3860
2145 ' update bar graphs
2150 IF Y% < OLD.Y%(CHANNEL%) THEN BC% = 1 ELSE BC% = 0
2160 LINE (L.SIDE%,Y%)-(R.SIDE%,OLD.Y%(CHANNEL%)),BC%,BF
2170 L.SIDE% = L.SIDE% + 88 : R.SIDE% = R.SIDE% + 88
2180 OLD.Y%(CHANNEL%) = Y%
2190 NEXT CHANNEL%
2195 ' sample function keys
2200 KEY(3) ON : ON KEY(3) GOSUB 740   ' if F3 is hit, make screen 1 active
2210 KEY(2) ON : ON KEY(2) GOSUB 3970  ' if F2 is hit, sample on drive B
2220 KEY(1) ON : ON KEY(1) GOSUB 3900  ' if F1 is hit, sample on drive A
2230 KEY(5) ON : ON KEY(5) GOSUB 4280 ' if F5 is hit go to chosen speed
2240 KEY(6) ON : ON KEY(6) GOSUB 3180 ' manual shutdown
2250 KEY(7) ON : ON KEY(7) GOSUB 4080  ' if F7 is hit return to normal storage
2260 KEY(8) ON : ON KEY(8) GOSUB 4110  ' if F8 is hit go to failure storage rate
2270 KEY(9) ON : ON KEY(9) GOSUB 4140 ' if F9 is hit  go to operating speed
2280 KEY(10) ON : ON KEY(10) GOSUB 4240 ' if F10 is hit go to warmup speed
2290 KBYTE% = LOF(1)/1000  ' kilobytes of memory stored on disk
2300 IF KBYTE% > 328 THEN GOSUB 4040             ' switch drives
2310 LOCATE 2,70  : PRINT SCR$
2320 LOCATE 3,75  : PRINT USING "###";KBYTE%
2330 IF COUNT% > = STORAGE.RATE% THEN COUNT% = 0
2340 GOSUB 3540
2350 IF (MIN% = OLD.MIN) THEN GOTO 2380
```

```
2360 IF((60 - INT(OLD.SEC)) + SEC%) = SAMPLE.SPACING% THEN GOTO 1930
2370 GOTO 2340
2380 IF INT(SEC% - OLD.SEC) = SAMPLE.SPACING% THEN GOTO 1930
2390 GOTO 2340
2400 RETURN
2410 REM subroutine to sample temperarure of motor casing
2420 REM maximum allowable temperature set to 110 C
2430 TYPE% = ASC("K")
2440 CHANNEL% = 1
2450 DEGREES.C! = 1.14
2460 CALL MEASURE.THERMOCOUPLE(TYPE%,CHANNEL%,DEGREES.C!)
2470 T.CAS! = DEGREES.C!
2480 IF T.CAS! < 80 AND RPM.TEST% < 1 GOTO 2530
2490 IF RPM.TEST% = 1 GOTO 2520
2500 PRINT #1, " MAXIMUM ALLOWABLE MOTOR CASING TEMPERATURE
EXCEEDED "
2510 BEEP :LOCATE 3,5 : PRINT " MAXIMUM MOTOR CASING TEMPERATURE
EXCEEDED "
2520 GOSUB 3180 ' call shutdown routine
2530 RETURN
2540 REM subroutine to sample temperature of bearing #1
2550 TYPE% = ASC("k")
2560 T.AMB! = DEGREES.C!
2570 CHANNEL% = 2: DEGREES.C! = 1.14
2580 CALL MEASURE.THERMOCOUPLE(TYPE%,CHANNEL%,DEGREES.C!)
2590 T.B1! = DEGREES.C!
2600 IF T.B1! < 75 AND RPM.TEST% < 1 GOTO 2650
2610 IF RPM.TEST% = 1 GOTO 2640
2620 PRINT #1, " FAILURE IN BEARING #1, MAXIMUM TEMP. EXCEEDED "
2630 BEEP :LOCATE 3,5 : PRINT " FAILURE IN BEARING #1, MAXIMUM
TEMP. EXCEEDED "
2640 GOSUB 3180 ' call shutdown routine
2650 RETURN
2660 REM subroutine to sample temperature of bearing #2
2670 TYPE% = ASC("k")
2680 CHANNEL% = 3: DEGREES.C! = 1.14
2690 CALL MEASURE.THERMOCOUPLE(TYPE%,CHANNEL%,DEGREES.C!)
2700 T.B2! = DEGREES.C!
2710 IF T.B2! < 75 AND RPM.TEST% < 1 GOTO 2770
2720 IF RPM.TEST% = 1 GOTO 2760
2730 PRINT #1," FAILURE IN BEARING #2, MAXIMUM ALLOWABLE
TEMPERATURE EXCEEDED"
2740 LOCATE 3,5
2750 BEEP : PRINT " FAILURE IN BEARING #2, MAXIMUM ALLOWABLE
TEMPERATURE EXCEEDED "
2760 GOSUB 3180 ' call shutdown routine
2770 RETURN
2780 REM          subroutine to sample stator temperature
2790 TYPE% = ASC("K")
2800 CHANNEL% = 4 : DEGREES.C! = 1.14
2810 CALL MEASURE.THERMOCOUPLE(TYPE%,CHANNEL%,DEGREES.C!)
2820 T.STA! = DEGREES.C!
2830 IF T.STA! < 160 AND RPM.TEST% < 1 GOTO 2880
2840 IF RPM.TEST% = 1 GOTO 2870
2850 PRINT #1, " MAXIMUM ALLOWABLE STATOR TEMPERATURE EXCEEDED "
2860 BEEP :LOCATE 3,5 : PRINT "MAXIMUM ALLOWABLE STATOR
```

```
TEMPERATURE EXCEEDED"
2870 GOSUB 3180 ' call shutdown routine
2880 RETURN
2890 REM  subroutine to sample motor speed
2900  CHANNEL% = 5 : VOLTS! = 0!
2910  CALL MEASURE.VOLTS(CHANNEL%,VOLTS!)
2920  RPM% = INT( 2841 * VOLTS!)
2930 RETURN
2940 REM   subroutine to sample accelerometers
2950 CHANNEL% = 6 : VOLTS! = 0
2960 CALL MEASURE.VOLTS (CHANNEL%,VOLTS!)
2970 ACC1! = (VOLTS!) * 9.8039
2980 CHANNEL% = 7
2990 CALL MEASURE.VOLTS (CHANNEL%,VOLTS!)
3000 ACC2! = (VOLTS!) * 9.5329
3010 ' maximum allowable acceleration set to 10 g
3020 IF ACC1! < 10 AND RPM.TEST% < 1 GOTO 3070
3030 IF RPM.TEST% = 1 GOTO 3060
3040 PRINT #1, " EXCESSIVE VIBRATION IN BEARING #1":
3050 BEEP:LOCATE 3,5:PRINT " EXCESSIVE VIBRATION IN BEARING #1"
3060 GOSUB 3180 ' call shutdown routine
3070 IF ACC2! < 10 AND RPM.TEST% < 1 GOTO 3120
3080 IF RPM.TEST% = 1 GOTO 3110
3090 PRINT #1," EXCESSIVE VIBRATION IN BEARING #2 "
3100 BEEP :LOCATE 3,5 : PRINT " EXCESSIVE VIBRATION IN BEARING #2"
3110 GOSUB 3180 ' call shutdown routine
3120 RETURN
3130 REM  subroutine to power up motor
3140 DAC.SELECT% = 0
3150 VVOLTS! = (W.RPM - 400)/3224
3160 CALL GENERATE.VOLTS(DAC.SELECT%,VVOLTS!)
3170 RETURN
3180 '   subroutine to allow rundown to be sampled in case of failure
3190 RPM.TEST% = 1
3200 DAC.SELECT% = 0
3210 VOLTS! = -.1
3220 CALL GENERATE.VOLTS(DAC.SELECT%,VOLTS!)
3230 IF RPM% > 25 GOTO 3260
3240 CLOSE #1
3250 GOTO 4410
3260 RETURN
3270 ' subroutine to print headings for output file
3280 PRINT #1, CHR$(13)
3290 PRINT #1, "TEST NAME = ";TN$
3300 PRINT #1, CHR$(13)
3310 PRINT #1, " INITIAL DATE = ";DATE$
3320 PRINT #1, CHR$(13)
3330 PRINT #1, " LUBRICANT USED = ";LUB$
3340 PRINT #1, CHR$(13)
3350 PRINT #1, " APPROXIMATE MOTOR SPEED = ";O.RPM
3360 PRINT #1, CHR$(13)
3370 PRINT #1, " SAMPLING RATE = ";SAMPLE.RATE%;" SAMPLES/MIN "
3380 PRINT #1, CHR$(13)
3390 PRINT #1, Q1$
3400 PRINT #1, Q3$
3410 PRINT #1, Q2$
```

```
3420 PRINT #1, CHR$(13)
3430 RETURN
3440 ' sudroutine to test for abnormal values
3450 IF T.CAS! > T.CAS.NORM! GOTO 3520
3460 IF T.B1! > T.B1.NORM! GOTO 3520
3470 IF T.B2! > T.B2.NORM! GOTO 3520
3480 IF T.STAT! > T.STAT.NORM! GOTO 3520
3490 IF ACC1! > ACC1.NORM! GOTO 3520
3500 IF ACC2! > ACC2.NORM! GOTO 3520
3510 GOTO 3530
3520 STORAGE.RATE% = FAIL.RATE
3530 RETURN
3540 '  subroutine to sample clocks
3550 'mon = month, dy = day, hr = hour, min = minutes, sec = seconds
3560 SEC% = FNCLK(&H2C2)
3570 MIN% = FNCLK(&H2C3)
3580 HR% = FNCLK(&H2C4)
3590 DY% = FNCLK(&H2C6)
3600 MON% = FNCLK(&H2C7)
3610 RETURN
3615 ' compute screen coordinates for bar graphs
3620 Y% = -1.6 * T.CAS! + 196!
3630 IF Y% > 180 THEN Y% = 180
3640 IF Y% < 52 THEN Y% = 52
3650 RETURN
3660 Y% = -1.6 * T.B1! + 196!
3670 IF Y% > 180 THEN Y% = 180
3680 IF Y% < 52 THEN Y% = 52
3690 RETURN
3700 Y% = -1.6 * T.B2! + 196!
3710 IF Y% > 180 THEN Y% = 180
3720 IF Y% < 52 THEN Y% = 52
3730 RETURN
3740 Y% = -.8 * T.STA! + 180!
3750 IF Y% > 180 THEN Y% = 180
3760 IF Y% < 52 THEN Y% = 52
3770 RETURN
3780  Y% = -.004 * RPM% + 180
3790 IF Y% > 180 THEN Y% = 180
3800 IF Y% < 52 THEN Y% = 52
3810 RETURN
3820 Y% = -16! * ACC1! + 180
3830 IF Y% > 180 THEN Y% = 180
3840 IF Y% < 52 THEN Y% = 52
3850 RETURN
3860 Y% = -16! * ACC2! + 180
3870 IF Y% > 180 THEN Y% = 180
3880 IF Y% < 52 THEN Y% = 52
3890 RETURN
3900 CLOSE
3910 KEY(1) OFF
3920 SCR$ = "DRIVE A"    : K = K + 1 : IF K > 6 THEN K = 1
3930 FILE1$ = A$ + TN$ + E1$(K) : COUNT = 0
3940 OPEN FILE1$ FOR OUTPUT AS #1
3950 GOSUB 3280   ' print headings for file
3960 RETURN
```

```
3965 ' switch to drive B
3970 CLOSE
3980 KEY (2) OFF
3990 SCR$ = "DRIVE B" : K = K + 1 : IF K > 6 THEN K = 1
4000 FILE1$ = D$ + TN$ + E1$(K)
4010 OPEN FILE1$ FOR OUTPUT AS #1
4020 GOSUB 3280         ' call subroutine to print headings for file
4030 RETURN
4040 ' subroutine to switch drives
4050 IF SCR$ = "DRIVE A" THEN GOSUB 3970
4060 IF SCR$ = "DRIVE B" THEN GOSUB 3900
4070 RETURN
4080 ' subroutine to return to normal sampling rate if F7 is hit
4090 STORAGE.RATE% = STRN%
4100 RETURN
4110 ' subroutine to go to failure mode storage rate if F8 is hit
4120 STORAGE.RATE% = FAIL.RATE
4130 RETURN
4140 ' routine to go to operating speed
4150 XDIF = O.RPM - RPM%
4160 XINC = XDIF / 120
4170 FOR I = 1 TO 120
4180 VVOLTS! = VVOLTS! + XINC/3171
4190 CALL GENERATE.VOLTS(DAC.SELECT%,VVOLTS!)
4200 FOR J = 1 TO 250
4210 NEXT J
4220 NEXT I
4230 RETURN
4240 'ROUTINE TO GOTO WARMUP SPEED
4250 VVOLTS! = (W.RPM - 400)/3224.5
4260 CALL GENERATE.VOLTS(DAC.SELECT%,VVOLTS!)
4270 RETURN
4280 ' routine to allow operation at any chosen speed for FFT analysis etc.
4290 CLS
4300 INPUT " ENTER DESIRED SPEED IN RPM ",A.RPM
4310 XDIF = A.RPM - RPM%
4320 XINC = XDIF / 200
4330 FOR J = 1 TO 200
4340 VVOLTS! = VVOLTS! + XINC/3224
4350 CALL GENERATE.VOLTS (DAC.SELECT%,VVOLTS!)
4360 FOR I = 1 TO 250
4370 NEXT I
4380 NEXT J
4390 GOTO 730
4400 RETURN
4410 END
```

Appendix C
Mainframe Plotting Routine

```
*
*
*  PROGRAM TO READ DATA FILES FROM PC-BASED DATA ACQUISITION
*  AND MAKE PLOTS ON THE VERSATEC PLOTTER
*
*  PROGRAM WRITTEN BY KEVIN K. MOYERS     6/28/87
*
*
*
      REAL*4 TCAS(10000),TB1(10000),TB2(5000),TSTAT(5000)
      REAL*4 ACC1(5000),ACC2(5000),TIME(5000),TINIT,HOUR0,RPM(5000)
      REAL*4 XMIN,XMAX,YMIN,YMAX,PLOTSZ,XINC,DX,DY1,YINC,XLEN,YLEN
      REAL*4 MON(5000),DY(5000),HR(5000),MIN(5000),SEC(5000)
      REAL*4 DAY,DAY1
      INTEGER NXTICS,NYTICS,SKIP,NUMP
*
* READ IN INITIAL DATA LINES FROM TOP OF PROGRAM
*
      DO 10 I = 1,23
10    READ(11,100)
*
* ENTER NUMBER OF DATA POINTS TO BE PLOTTED AND INITIAL TIME VALUE
*
      WRITE(6,*) ' ENTER THE NUMBER OF DATA POINTS TO BE PLOTTED '
      READ(5,*) NUMP
      WRITE(6,*) ' ENTER THE DESIRED INITIAL TIME VALUE IN HOURS  '
      READ(5,*) TINIT
*
* READ IN DATA FROM FILE
*
      DO 20 I = 1,NUMP
      READ(11,110)MON(I),DY(I),HR(I),MIN(I),SEC(I),TCAS(I),TB1(I),
     + TB2(I),TSTAT(I),RPM(I),ACC1(I),ACC2(I)
20    CONTINUE
*
* CALCULATE A STANDARD TIME VALUE IN HOURS
*
* CALCULATE INITIAL TIME VALUE
*
```

```
      DAY1 = 0
      DO 40 I = 1,MON(1)

      IF ((I.EQ.4).OR.(I.EQ.6).OR.(I.EQ.9).OR.(I.EQ.11)) THEN
        DAY1 = DAY1 + 30
        ELSE
          IF (I.EQ.2) THEN
          DAY1 = DAY1 + 28
          ELSE
          DAY1 = DAY1 + 31
          ENDIF
        ENDIF
 40   CONTINUE
      HOUR0  = 24*DAY1 + 24 * DY(1) + HR(1) + MIN(1)/60. + SEC(1)/3600.
      DO 50 I = 1,NUMP
      DAY = 0
      DO 60 J = 1,MON(I)
      IF ((J.EQ.4).OR.(J.EQ.6).OR.(J.EQ.9).OR.(J.EQ.11)) THEN
        DAY = DAY + 30
        ELSE
          IF (J.EQ.2) THEN
          DAY = DAY + 28
          ELSE
          DAY = DAY + 31
          ENDIF
        ENDIF
 60   CONTINUE

      TIME(I) = 24 * DAY + 24 * DY(I) + HR(I) + MIN(I)/60. + SEC(I)/3600
     + - HOUR0 + TINIT
 50   CONTINUE


*
*  FORMAT STATEMENTS
*
 100   FORMAT()
C FORMAT FOR LATEST DATA FILE
C110   FORMAT(1X,F2.0,1X,F2.0,1X,F2.0,1X,F2.0,1X,F2.0,2X,F4.1,3X,
C    +  F5.1,2X,F5.1,
C    +  3X,F5.1,3X,F6.0,2X,F6.2,2X,F6.2)
* FORMAT FOR ALL DATA BEFORE 8/87
 110   FORMAT(1X,F2.0,1X,F2.0,1X,F2.0,1X,F2.0,1X,F2.0,2X,F4.1,2X,
     +  F5.1,1X,F5.1,
     +  1X,F5.1,1X,F6.0,2X,F6.2,2X,F6.2)
*
*  BEGIN PLOTTING DATA
*
*  ENTER MAX AND MIN VALUES AND PLOT SCALE FACTOR
*
      WRITE(6,*) 'ENTER NXTICS, NUMBER OF POINTS TO SKIP BETWEEN SYMBOL'
      READ(5,*) NXTICS,SKIP
      WRITE(6,*) 'ENTER NYTICS,PLOTSZ  '
      READ(5,*) NYTICS,PLOTSZ
*
```

```
* INITIALIZE PLOT AND SET SCALE FACTORS
*
      CALL PLOTS (0,0,0)
      CALL FACTOR(PLOTSZ)
      DX = (XMAX - XMIN)/FLOAT(NXTICS)
      XLEN = 5.5
      YLEN = 5.5
      DXLEN = XLEN/FLOAT(NXTICS)
*
*  SCALE DATA
*
      FVALY = 0.
      FVALX = TIME(1)
      DX = (TIME(NUMP)-TIME(1))/NXTICS
*
*  FLAG TO PRODUCE EITHER FIRST TWO GRAPHS OR LAST TWO
*  NECESSARY DUE TO PLOTTER MEMORY LIMITATIONS
*
      WRITE(6,*) ' ENTER 1 TO PLOT TEMPERATURES, 2 FOR SPEED AND
     + ACCELERATIONS'
      READ (5,*) FLAG
      IF(FLAG.EQ.2) GO TO 1010

      WRITE(6,*) 'ENTER MAXIMUM BEARING TEMPERATURE '
      READ(5,*) BMAX
      WRITE(6,*) 'ENTER MAXIMUM STATOR TEMPERATURE TO PLOT '
      READ(5,*) STAMAX
*
*  SCALE DATA
*
      YMAX = BMAX
      YMIN = 0.

*
*  DRAW X AND Y AXES
*
      CALL NEWPEN(3)
      CALL SAXIS(0.5,0.5,13HRUN TIME (HR),-13,XLEN,0.,FVALX,DX,DXLEN,0.)
       DY1 = (YMAX - YMIN)/FLOAT(NYTICS)
      YINC = YLEN/FLOAT(NYTICS)
      CALL SAXIS (0.5,0.5,15HTEMPERATURE (C),15,YLEN,90.0,FVALY,DY1
     + ,YINC,0.0)
*
*  BEGIN PLOT
*
      CALL PLOT(0.5,0.5,-3)
      CALL NEWPEN(1)
      TIME(NUMP+1) = TIME(1)
      TIME(NUMP+2) = (TIME(NUMP)-TIME(1))/XLEN
      TB1(NUMP+1) = 0.
      TB1(NUMP+2) = BMAX/YLEN
      TB2(NUMP+1) = 0.
      TB2(NUMP+2) = BMAX/YLEN
      CALL LINE(TIME,TB1,NUMP,1,SKIP,1)
      CALL NEWPEN(2)
```

```
      CALL LINE(TIME,TB2,NUMP,1,SKIP,2)
*
* FRAME THE PLOT
*
      CALL NEWPEN(4)
      CALL PLOT(0.,0.,3)
      CALL PLOT(0.,YLEN,2)
      CALL PLOT (XLEN,YLEN,2)
      CALL PLOT (XLEN,0.,2)
      CALL PLOT (0.,0.,2)
*
* CREATE LEGEND
*
      CALL SYMBOL(1.5,4.80,0.15,19HCONTROL END BEARING,0.,19)
      CALL SYMBOL(1.5,4.55,0.15,17HSHAFT END BEARING,0.,17)
      CALL NEWPEN(3)
      CALL VPISYM(.5,4.85,0.125,1,0.0,-1)
      CALL VPISYM(1.25,4.85,0.125,1,0.0,-2)
      CALL NEWPEN(3)
      CALL VPISYM(.5,4.60,0.125,2,0.0,-1)
      CALL VPISYM(1.25,4.60,0.125,2,0.0,-2)
*
* MAKE SECOND PLOT
*
*  SCALE DATA
*
      YMAX = STAMAX
      YMIN = 0.
      FVALY = 0.
*
*  DRAW X AND Y AXES
*
      CALL PLOT(7.,0.,-3)
      CALL NEWPEN(3)
      CALL SAXIS(0.5,0.5,13HRUN TIME (HR),-13,XLEN,0.,FVALX,DX,DXLEN,0.)
       DY1 = (YMAX - YMIN)/FLOAT(NYTICS)
      YINC = YLEN/FLOAT(NYTICS)
      CALL SAXIS (0.5,0.5,15HTEMPERATURE (C),15,YLEN,90.0,FVALY,DY1
     + ,YINC,0.0)
*
*  BEGIN PLOT
*
      CALL PLOT(0.5,0.5,-3)
      CALL NEWPEN(2)
      TCAS(NUMP+1) = 0.
      TCAS(NUMP+2) = STAMAX/YLEN
      TSTAT(NUMP+1) = 0.
      TSTAT(NUMP+2) = STAMAX/YLEN
      CALL LINE(TIME,TCAS,NUMP,1,SKIP,1)
      CALL NEWPEN(2)
      CALL LINE(TIME,TSTAT,NUMP,1,SKIP,2)
*
* FRAME THE PLOT
*
      CALL NEWPEN(4)
      CALL PLOT(0.,0.,3)
```

```
      CALL PLOT(0.,YLEN,2)
      CALL PLOT (XLEN,YLEN,2)
      CALL PLOT (XLEN,0.,2)
      CALL PLOT (0.,0.,2)
*
* CREATE LEGEND
*
      CALL SYMBOL(1.5,4.80,0.15,12HMOTOR CASING,0.,12)
      CALL SYMBOL(1.5,4.55,0.15,12HSTATOR COILS,0.,12)
      CALL NEWPEN(3)
      CALL VPISYM(.5,4.85,0.125,1,0.0,-1)
      CALL VPISYM(1.25,4.85,0.125,1,0.0,-2)
      CALL NEWPEN(3)
      CALL VPISYM(.5,4.60,0.125,2,0.0,-1)
      CALL VPISYM(1.25,4.60,0.125,2,0.0,-2)
      CALL NEWPEN(3)
*
      GO TO 1020

*
* MAKE PLOT  OF MOTOR SPEED
*
*  SCALE DATA
*
 1010 YMAX = 30000.
      YMIN = 0.
      FVALY = 0.
      TIME(NUMP+1) = TIME(1)
      TIME(NUMP+2) = (TIME(NUMP)-TIME(1))/XLEN
      WRITE(6,*) ' ENTER MAXIMUM ACCELERATION VALUE '
      READ(5,*) ACCMAX
*
*  DRAW X AND Y AXES
*
      CALL PLOT(7.,0.,-3)
      CALL NEWPEN(3)
      CALL SAXIS(0.5,0.5,13HRUN TIME (HR),-13,XLEN,0.,FVALX,DX,DXLEN,0.)
       DY1 = (YMAX - YMIN)/FLOAT(NYTICS)
      YINC = YLEN/FLOAT(NYTICS)
      CALL SAXIS (0.5,0.5,3HRPM,3,YLEN,90.0,FVALY,DY1
     + ,YINC,0.0)
*
*  BEGIN PLOT
*
      CALL PLOT(0.5,0.5,-3)
      CALL NEWPEN(2)
      RPM(NUMP+1) = 0.
      RPM(NUMP+2) = 30000./YLEN
      CALL LINE(TIME,RPM,NUMP,1,SKIP,1)
*
* FRAME THE PLOT
*
      CALL NEWPEN(4)
      CALL PLOT(0.,0.,3)
      CALL PLOT(0.,YLEN,2)
      CALL PLOT (XLEN,YLEN,2)
```

```
      CALL PLOT (XLEN,0.,2)
      CALL PLOT (0.,0.,2)
*
* MAKE ACCELERATION PLOT
*
*  SCALE DATA
*

      YMAX = ACCMAX
      YMIN = 0.
      FVALY = 0.
*
*  DRAW X AND Y AXES
*
      CALL PLOT(9.,0.,-3)
      CALL NEWPEN(3)
      CALL SAXIS(0.5,0.5,13HRUN TIME (HR),-13,XLEN,0.,FVALX,DX,DXLEN,0.)
      DY1 = (YMAX - YMIN)/FLOAT(NYTICS)
      YINC = YLEN/FLOAT(NYTICS)
      CALL SAXIS (0.5,0.5,20HRMS ACCELERATION (G),20,YLEN,90.0,FVALY,DY1
     + ,YINC,0.0)
*
*  BEGIN PLOT
*
      CALL PLOT(0.5,0.5,-3)
      CALL NEWPEN(2)
      ACC1(NUMP+1) = 0.
      ACC1(NUMP+2) = ACCMAX/YLEN
      ACC2(NUMP+1) = 0.
      ACC2(NUMP+2) = ACCMAX/YLEN
      CALL LINE(TIME,ACC1,NUMP,1,SKIP,1)
      CALL NEWPEN(3)
      CALL LINE(TIME,ACC2,NUMP,1,SKIP,2)
*
* FRAME THE PLOT
*
      CALL NEWPEN(4)
      CALL PLOT(0.,0.,3)
      CALL PLOT(0.,YLEN,2)
      CALL PLOT (XLEN,YLEN,2)
      CALL PLOT (XLEN,0.,2)
      CALL PLOT (0.,0.,2)
*
* CREATE LEGEND
*
      CALL SYMBOL(1.5,4.80,0.15,11HCONTROL END,0.,11)
      CALL SYMBOL(1.5,4.55,0.15,9HSHAFT END,0.,9)
      CALL NEWPEN(3)
      CALL VPISYM(.5,4.85,0.125,0,0.0,-1)
      CALL VPISYM(1.25,4.85,0.125,0,0.0,-2)
      CALL NEWPEN(3)
      CALL VPISYM(.5,4.60,0.125,2,0.0,-1)
      CALL VPISYM(1.25,4.60,0.125,2,0.0,-2)

 1020 CALL PLOT(15.0,0.0,999)
      END
```

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