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The design of a stepper motor torque characterization system

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THE DESIGN OF A
STEPPER MOTOR TORQUE
CHARACTERIZATION SYSTEM

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Christopher G. Moscone
May, 1991

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ABSTRACT

Stepper motors are used in many devices in which precise motion control or positioning control is required. The dynamic torque characteristics of stepper motors become important to the design engineer when selecting a stepper motor to fit the dynamic design requirements of any prototype system. However, accurate dynamic torque data for stepper motors is usually not readily available. Many factors affect the dynamic characteristics of stepper motors, including external inertia, coupling type, driver type, driver voltage, phase current and the design of the particular stepper motor in question. These factors may all serve to alter the dynamic characteristics of a stepper motor as it is moved from one system to another. The stepper motor torque characterization system described in this thesis has been designed to provide accurate dynamic torque data and holding torque data for stepper motors operating in known environments.

One major design requirement for the stepper motor torque characterization system was automatic control over all test parameters and data logging. Other design requirements included the ability to test stepper motors up to 300 oz-in holding torque in half step or full step mode, and the ability to simulate the torque characteristics of either an accelerating or braking load applied to the stepper motor shaft.

The stepper motor torque characterization system described in this thesis meets the specified functional requirements. The torque characterization system can test stepper motors up to 400 oz-in holding torque at test speeds up to 1500 RPM. The theoretical accuracy of the torque characterization system has been held to +1.47 oz-in and -3.94 oz-in over the full scale of a test.

This thesis discusses the design methodology of the torque characterization system, and presents the reader with an overview of the features and operation. The system performance data and an evaluation of the system characteristics are included along with failure modes, recommendations, instructions and a troubleshooting guide.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE **PAGE**

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Stepper motors are an important component in many electromechanical systems. Knowledge of a particular stepper motor's dynamic characteristics- such as holding torque and pull-out torque vs. speed- is essential for optimal system design and for accurate prediction of dynamic performance. However, generation of useful dynamic torque data for stepper motors is rather difficult due to the stepper motor's inherent sensitivity to its immediate environment. External inertia, coupling type, driver type, phase current and the stepper's tendency to resonate at certain frequencies all make generation of a meaningful torque vs. speed curve a difficult task for conventional torque measuring devices. For this reason, work supported by Northern Telecom began in May, 1989 on development of a personal computer controlled stepper motor dynamometer for the purpose of generating holding torque data and torque vs. speed data automatically for a wide range of stepper motors. This dynamometer system will be able to simulate certain working environments that a particular stepper motor may operate in (such as coupling type, inertia, driver type, current, etc.) and generate useful and accurate dynamic torque data while also giving the user some insights into the resonance characteristics of the stepper motor.

Several methods are available for the purpose of measuring stepper motor pull-out torque (torque required to cause phase break in a rotating motor). The hysteresis dynamometer is a commonly used device, with its main disadvantage being the cogging torque generated by its rotating armature.

This cogging torque appears in addition to the generated torque resulting in a pulsating torque being applied to the stepper motor shaft. The result is reduced accuracy, especially in stepper motors having a relatively small step angle. Also, the hysteresis dynamometer usually must be driven to speed by the stepper motor, which may result in problems with resonance upon ramp-up.

Another method of dynamic torque measurement is the prony brake (using a cord) and spring scale. This method relies on friction generated by a cord wrapped around the stepper motor shaft with springs attached to each end of the cord. Knowledge of the cord pulley radius and the tension in each end of the cord allows torque determination through a simple force-times-distance calculation. However, this method requires considerable operator time spent in setup and calculation, especially if many speed ranges are to be tested.

Both the friction method and the hysteresis dynamometer method have several disadvantages with regard to the goal of producing useful dynamic torque data in an automatic fashion. Therefore, other alternatives, such as using a torque transducer or DC motor, were studied. After consulting with IBM Lexington, the decision was made to use a DC motor as a torque measurement device. The DC motor lends itself readily to automatic (PC) control, and the particular motor chosen has the advantage of an ironless armature with zero cogging torque. The result is a smooth non-pulsating torque applied to the stepper motor shaft for increased accuracy. This torque is a linear function of the DC motor current allowing for easy determination of stepper motor pull-out torque. Also, the DC motor may act as a prime mover, driving the stepper motor to each test point.

Control of the UT stepper motor dynamometer is fully automatic. An IBM PC is used to control the DC motor via a Metrabyte Data Acquisition System. The data acquisition system interfaces the PC with all hardware, controls the DC motor and the stepper motor, and collects and outputs data between the PC and all measurement and control systems. Output is in the form of a hardcopy printout of a stepper motor's pull-out torque curve which, with proper set-up of the stepper motor apparatus, can give insights into resonance characteristics.

1.2 Requirements

Overall design requirements for the stepper motor dynamometer include automatic control of the dynamometer system and test procedure, generation of holding torque data, and the ability to simulate either an accelerating or a braking load on the stepper motor shaft during dynamic torque measurements. In addition, the torque measuring device (DC motor) must serve as a prime mover to run the stepper motor to each test speed in order to eliminate the possibility of a test failure due to stepper motor resonance. Functional requirements to meet these goals and additional desired capabilities are listed as follows:

Functional Requirements:

PC control of dc motor
PC control of stepper motor
PC control of data acquisition system
Stepper motor size range: Up to 300 oz-in
Maximum speed for dynamometer: 1500 RPM
Generation of hardcopy torque data

1.3 SCOPE

The scope of this project entails designing a dynamometer system which meets all of the above requirements. This includes selection of all necessary mechanical and electrical hardware, design of mechanical supports, design of all necessary control and data acquisition circuitry, and design of software to provide fully automatic control. Performance and evaluation testing will be done upon completion of the system to determine actual performance limits, capabilities, repeatability, and failure modes of the dynamometer system. Also included in Appendix A is a complete set of operating instructions and,in Appendix B, a troubleshooting guide.

CHAPTER 2

OVERVIEW OF OPERATION

2.1 TEST SYSTEM STRUCTURE

The UT stepper motor test system is designed to be a fully automatic unit capable of generating holding torque data and dynamic torque data for stepper motors of up to 300 oz-in holding torque. A block diagram of the system hardware is shown in Figure 2.1. Numbers in parenthesis refer to the corresponding blocks in Figure 2.1.

Central to the test system is a DC motor (1), which serves as both a torque measurement device and as a prime mover for the stepper motor (2). The DC motor lends itself readily to the task of torque measurement due to its nearly linear torque vs. input current curve, simplifying determination of output torque. Also, the DC motor is easily controlled by a PC interfaced with a programmable power supply (3), allowing its control to be fully automatic. The particular DC motor chosen utilizes an ironless armature resulting in zero cogging torque; thus, test data accuracy and repeatability are increased due to the absence of DC motor torque pulsations commonly associated with the cogging effect. An IBM personal computer (4) serves as the control device for the entire system. The PC is interfaced directly to a Metrabyte data acquisition system (5). The data acquisition system main board is installed inside the PC and is accessed through a screw terminal interface board (6) mounted outside the PC. All system controlling outputs are sent through the interface via the data acquisition system and all inputs such as torque (DC motor current) data and motor speed data are transferred back to the data acquisition system and PC through the interface. The data acquisition system

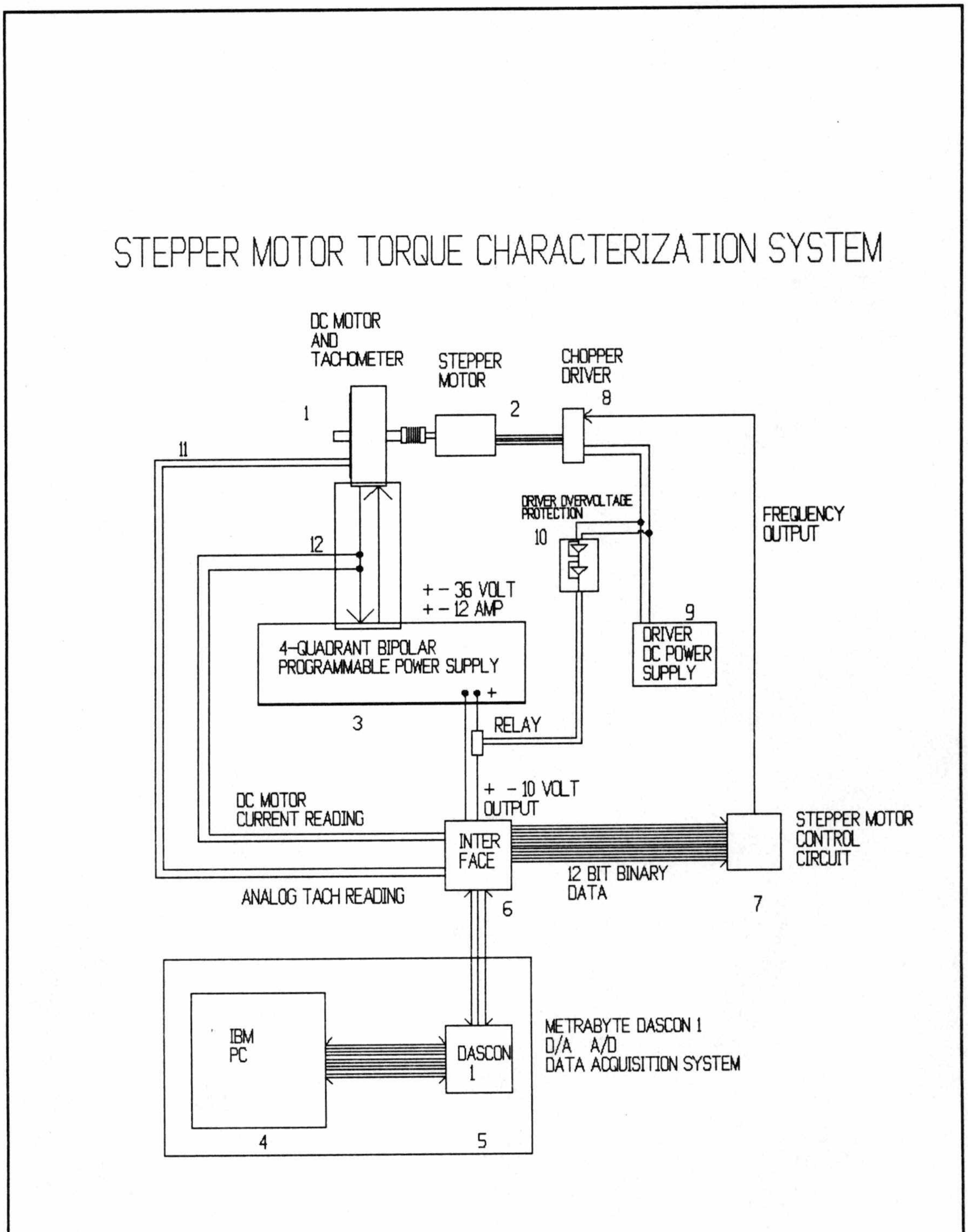


FIGURE 2.1 Stepper Motor Test System Hardware.

also handles all Analog/Digital and Digital/Analog conversions. A BASIC program within the PC directs the data acquisition system; the data acquisition system thereby controls all system hardware from the BASIC program instructions and writes all necessary data back to the BASIC routine which interprets the data, closing the loop from hardware to software.

The stepper motor under test is directly coupled to the DC motor by a flexible coupling. Alignment of the motor shafts is not a problem since a frame has been designed to securely mount different size stepper motors in such a way that correct shaft alignment is always ensured. Axial movement of the stepper motor mount with relation to the DC motor is provided to compensate for different size motors, couplings, etc. This axial movement is not allowed once the stepper motor is bolted solidly to the frame; all parts are tightened to withstand vibration and shock encountered during a typical torque test.

The PC controls the DC motor through the interface, which sends a plus or minus 10 volt signal into the input of a DC programmable power supply. The programmable supply responds to the input by outputting plus or minus 36 volts to the DC motor. This particular DC supply is a 4 quadrant bipolar power supply, meaning that it can act as a power source or a power sink at 100% of its output rating and can output plus or minus voltage and current to the DC motor. These features are necessary due to the fact that the DC motor must apply torque in both directions to the stepper motor shaft, functioning as a motor, generator, and brake during the course of a torque test. DC motor speed and output torque are controlled solely by the DC motor input voltage.

Speed control for the stepper motor is also controlled directly by the PC. The data acquisition system has 12 bits of digital output available for independent use which in this case are used to control the stepper driver.

The PC commands the data acquisition system to produce and output a 12 bit binary sequence through the interface corresponding to the required stepper motor speed. This binary sequence, or number, is converted to a square wave frequency by the stepper motor control circuit (7) which is fed directly into the stepper motor driver (8). The driver pulses the stepper motor at the rate of 1 pulse per 1 cycle input frequency.

At times during a torque test, the stepper motor may temporarily operate as a generator driven by the DC motor and induce a large voltage across the stepper motor driver common DC power supply input terminals. Stepper motor size and speed determine the magnitude of severity of this induced voltage, which can be very dangerous to both the driver and driver power supply (9). Normally during a dynamic torque test, an overvoltage condition may occur at three different points. The first point occurs during system ramp-up as the DC motor drives the stepper motor to speed. If the test speed is too high, the stepper motor generator voltage will be greater than the driver's voltage rating. The generator voltage induced across the driver at this point becomes a function of stepper motor speed. The second most common point of overvoltage occurs during braking mode while the DC motor applies a torque to the stepper motor shaft in the direction of rotation. If the stepper motor is large enough, the driver voltage will begin to rise after a certain amount of torque has been applied to the stepper shaft. The driver voltage is now controlled by the stepper motor and is a function of how much torque is being applied to the stepper motor shaft. No motor speed change is necessary for this occurrence. The third, and least common condition, occurs after stepper phase break in braking mode when the DC motor temporarily overspins the stepper motor. In this case the induced voltage is a function of stepper motor speed and is analogous to the first condition. A voltage-sensitive circuit (10) has been incorporated into the system to sense this potential overvoltage condition. During an overvoltage condition, this circuit immediately shuts off the DC motor by opening the programmable power supply input line, thereby eliminating any stepper motor generator action.

An analog tachometer is integral to the DC motor; the voltage signal from the tach (11) is sent to the PC through the interface and is used as a stepper motor phase break detection system as well as a DC motor speed control device. The PC constantly monitors the tach signal in order to drive the stepper motor to each test speed, and also monitors the signal during application of torque to the stepper motor shaft. Any sudden large speed change is interpreted as a phase break, signaling the PC to save the stepper motor's phase break torque value and proceed to the next test point.

Finally, the DC motor current is read by the interface through the use of a current shunt (12). DC motor current appears as a voltage across the shunt which is sent to the interface and on to the PC via an A/D converter. DC motor torque may therefore be determined with knowledge of the DC motor current and precalibrated values of DC motor friction torque.

The result of this hardware and software is a test system that produces highly repeatable and accurate data of stepper motor holding torque and of torque vs. stepper motor RPM. The DC motor drives the stepper motor to each test speed and then applies a gradually increasing torque (2.47 oz-in per step with a torque ramp variable of 5) to the stepper motor shaft until stepper phase break occurs. This torque may be applied in both directions to the stepper motor shaft in order to simulate the stepper motor trying either to accelerate or decelerate a load.

2.2 OPERATION OF TEST SEQUENCE

Operation of the stepper motor test system is achieved through a sequence of events controlled completely through the PC by way of the data acquisition system and interface board. A flow diagram of the controlling events is presented in Figure 2.2. The following text pertains to the Figure 2.2 diagram. Numbers in parenthesis refer to the corresponding blocks in the diagram.

The first step of any torque test is to mount the stepper motor securely in the frame, check all wiring, and make sure that the stepper motor turns in the right direction (see instructions). Upon start-up of the test program and power-up of all hardware, the PC will prompt the user for several test parameters (1) including starting RPM, finishing RPM, test increment, half/full step mode, and acceleration/braking mode. The program will also give the user the option of performing a holding torque test (4), and writing torque data to the a:drive disk. Test parameters are discussed in more detail in Section 2.4. Once the test parameters have been entered a short delay will occur as the program initializes startup test conditions. If a holding torque test has been selected, the PC will instruct the user with the wiring connections and then conduct the test. The holding torque test is a fairly simple matter; the driver is enabled, torque is applied to the stepper motor via the DC motor, and phase break is indicated by a change in tach voltage. At this point the highest recorded torque value is saved, the DC motor is powered down and the stepper driver is disabled. The user is prompted to reconnect the wire he/she was prompted to disconnect earlier, and the dynamic torque test is now started.

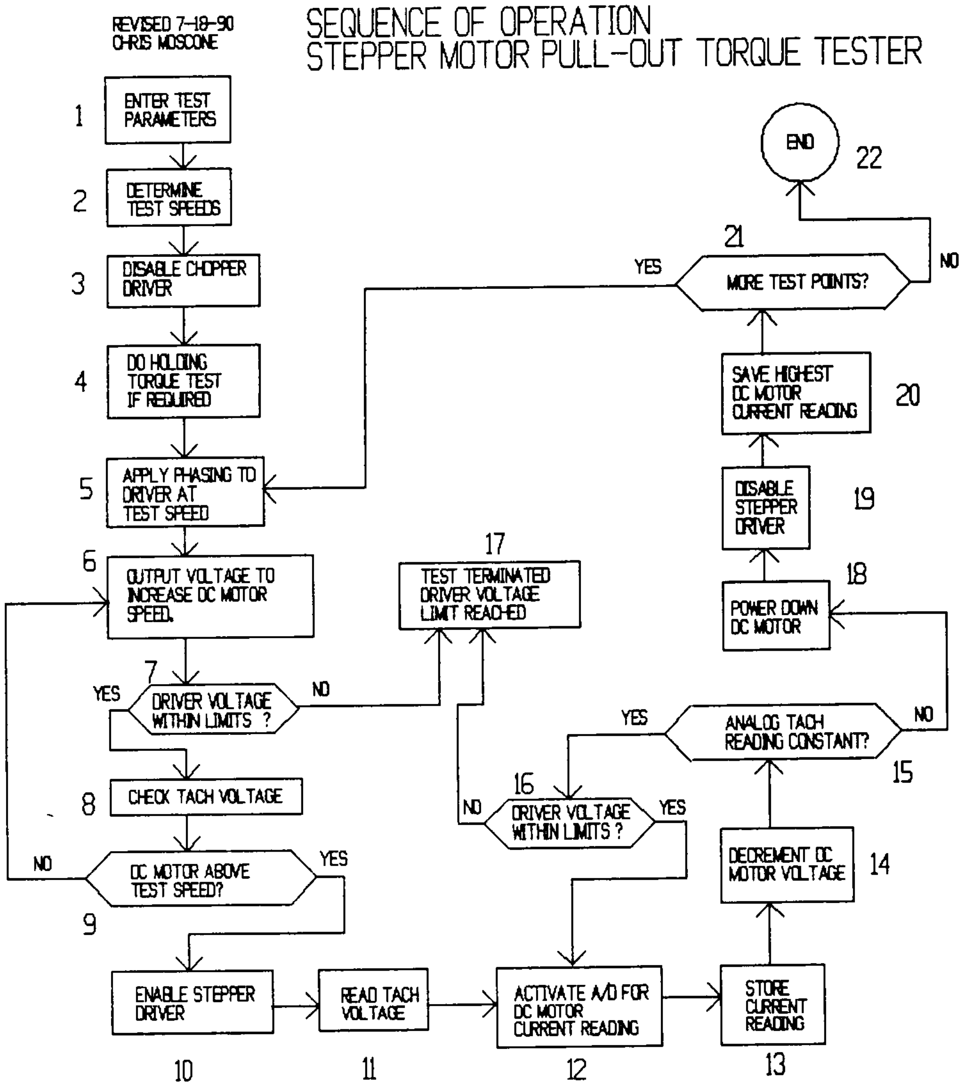


FIGURE 2.2 Flow Diagram Of Operation.

Upon start of the dynamic torque test, the DC motor is not spinning and the stepper driver is disabled. Disabling the driver is a very important feature; when disabled, the driver puts out no current, allowing the stepper motor to spin freely. This is essential for a smooth ramp-up to each test speed. Now the computer applies phasing to the stepper motor (5) at the corresponding test speed while the driver is disabled and the system is not spinning. Phasing the driver has no effect on the system until the driver is enabled. After phasing the driver, the PC ramps the disabled stepper motor to slightly above (within 10 RPM) the required test speed by incrementing the DC motor voltage (6, 7, 8, and 9). During ramp-up the driver overvoltage protection circuit checks that the driver voltage is within limits (7). When the DC motor reaches its desired speed, the stepper driver is enabled (10). Since the driver is already being phased at the required test RPM, and the DC motor is spinning the stepper motor within 10 RPM of the test RPM, enabling the driver causes the stepper motor to lock into the driver phasing speed. A short time delay is incorporated at this point to allow any stepper motor oscillations to damp out, and a speed reading is taken from the tach voltage for reference later (11).

Now, both motors are energized at the test speed and the stepper motor feels very little torque on its shaft. The DC motor voltage will now be incremented to steadily increase the torque applied to the stepper motor shaft (the direction of applied torque depends on the mode; acceleration or braking). After each DC motor voltage increment, the data acquisition system checks the analog tach for stepper motor phase break and, if not detected, activates the A/D converter for a DC motor current reading (12, 13, 14, 15). The driver overvoltage protection circuit constantly checks the driver voltage during torque application (16). This loop continually saves each successively higher torque reading and discards all others. Upon phase break, the DC motor is powered down (18) and the stepper driver is disabled (19). The highest torque reading almost always occurs just prior to phase break, and this value is stored and printed to the screen along with the test speed (20). If more speeds are to be tested, the sequence starts over at (5).

2.3 OPERATING LIMITS OF TESTER

Limits of operation for the UT stepper motor test system are governed mainly by the controlling hardware in the system. These limits are listed as follows:

Maximum stepper motor size --------------- 400 oz-in holding torque.

Minimum stepper motor size --------------- 20 oz-in holding torque, torque data accurate down to 15 oz-in.

Maximum test RPM ----------------------- 1500 RPM

Stepper motor drive modes ---------------- Half and full step.

DC motor test modes --------------------- May simulate either an accelerating or a braking load.

The maximum stepper motor size is governed by the maximum torque output of the DC motor, which is in turn governed by the output capabilities of the programmable power supply. Increasing the maximum output current of the programmable supply will increase the maximum output torque of the DC motor, while increasing the maximum output voltage of the supply will increase the maximum operating speed of the tester. The minimum stepper motor size is governed by the total friction torque within the DC motor. DC motor friction torque rises with speed, with a maximum friction torque value of about 15 oz-in at 1500 RPM. If a stepper motor smaller than 15 oz-in were tested, the results would probably be useless as virtually no DC motor armature current would be required to cause a phase break. For example, the tester would indicate 15 oz-in of torque for a stepper motor actually outputting 5 oz-in of torque.

2.4 USER CONTROLLABLE INPUT PARAMETERS

At the beginning of a test the user is prompted to enter several test parameters that vary test controls, test limits and data logging. The user has the option of printing torque vs. RPM data to the screen and writing it to the a:drive disk or screen output only. The holding torque test is optional and is performed before any dynamic test parameters are entered; this sequence of operation saves the user a small amount of time and possible confusion if only a holding torque test is desired.

If a dynamic torque test is required several prompts are displayed concerning dynamic test parameters. The user has the choice of either acceleration test mode or braking test mode, of stepper motor half-step or full-step mode, and of starting RPM, finishing RPM, and the test increment RPM. Another parameter not so obvious is the DC motor torque ramp function. The DC motor torque ramp function (a variable integer) controls the rate of change of the DC motor input voltage and consequently, the rate of change of the DC motor output torque during the loading cycle in which the DC motor attempts to break the phase of the stepper motor. This variable prompt is presented with a recommended value and explanation during the parameter input stage of a torque test. The recommended value represents a somewhat optimal tradeoff between accuracy and speed. For example, a very fast rate of change of DC motor torque on the stepper motor shaft during the load phase results in a short test duration because the torque required to stall the stepper motor is reached quickly. However, accuracy is sacrificed because this results in a larger step change of DC motor voltage each time through the load loop. That is, instead of incrementing the DC motor output torque by 2 oz-in at a time, a fast voltage ramp function may, for example, increment DC motor output torque by 10 oz-in at a time. This situation may be satisfactory for a 350 oz-in motor when time is short and many speed points are to be tested, but obviously will not work well with, say, a 40 oz-in motor.

By the same context, it would seem that a ramp function should be included controlling the rate of change of the DC motor speed while ramping the stepper motor up to each test speed. This sequence has been tried but does not result in a very good tradeoff. Experimentation revealed that a large rate of change of DC motor speed during ramp-up resulted in a correspondingly large overshoot past the desired test speed. Due to the relatively slow A/D sampling rate and the tachometer RC filter, the DC motor speed upon ramp-up will always be slightly faster than where the computer thinks it really is. Coupling these effects with a large step incrementation of DC motor speed each time through the ramp-up loop produces the overshoot. In other words, when the PC indicates that the system is at the desired test speed, the system (DC motor and stepper motor) are actually rotating somewhat faster. The difference between the desired test speed and the actual test speed is termed the overshoot. For example, assume that the required test speed is 500 RPM. A slow ramp-up might result in the stepper motor being placed at, say, 505 RPM before the driver is enabled. A fast ramp up might result in the stepper motor being placed at 530 RPM before enable. A problem results in that if the disabled stepper motor driver is phasing the stepper motor at 500 RPM, the stepper motor is actually turning at 530 RPM, and the driver is suddenly enabled as happens during a test, the stepper motor may not produce enough torque to attain a 30 RPM jump and lock into the required phase speed of 500 RPM. This overshoot condition usually causes faulty data from premature phase break. Therefore, the DC motor speed ramp-up is internally set to a value that allows the maximum rate of change of motor speed during speed ramp-up while maintaining good stepper motor enable characteristics.

2.5 TEST SYSTEM ACCURACY

An immediate advantage of using a DC motor as a torque measurement device is its simplicity with respect to variables which determine how accurate a torque measurement is. While the overall test system requires a certain amount of complexity to perform effectively, system accuracy is basically a function of how accurately the DC motor parameters are known. Stepper motor torque at phase break (same as DC motor output torque at phase break) is a function solely of DC motor current and DC motor friction torque. Since the DC motor friction torque characteristics have been tabulated and the DC motor torque/current relation is linear and has been calibrated, the only significant sources of error come from uncertainty values in the current-measuring resistors and possible temperature related or time related drift of motor constants. The DC motor operates at a relatively constant temperature during testing, and no noticeable drift of DC motor characteristics has been noticed in prior testing.

A discussion of accuracy determination is discussed in Chapter 4, Section 2. The overall results indicate that the test system will provide torque data accurate to +1.47 oz-in and -3.94 oz-in over the full range using a DC motor torque ramp variable of 5.

Test system repeatability has been established through examination of multiple test results using the same stepper motor, hardware, and operating parameters. Overall repeatability is excellent; deviations of test results on a 350 oz-in holding torque stepper motor amounted to roughly plus or minus 2.5 oz-in from the average value. This repeatability is, however, somewhat a function of test parameters and the particular stepper motor under test.

System repeatability may vary considerably if the correct test parameters are not entered and understood by the user. Of particular concern here is the DC motor torque ramp variable. A fast rate of change of applied DC motor torque can cause inconsistent stepper motor torque data due again to the relatively slow A/D converter sampling rate. This inconsistency is usually reproducible and can be eliminated by manipulation of the DC motor ramp variable if the ramp variable is initially set too high. The ramp variable recommended during test parameter initialization generally produces very repeatable results. More information on this feature is included in the operating instructions.

Repeatability is also affected by the particular stepper motor under test. Most stepper motors will not break phase at exactly the same value of applied torque every time due to the complex dynamics of the motor and drive circuitry. This deviation is usually only a small percentage of the total output torque but can sometimes be seen in the test results. Stepper motor resonance may also affect repeatability at and around data points where it occurs. In general, repeatability as a percentage of total stepper motor output torque will be better for large (300 oz-in) motors than for small (40 oz-in) motors.

CHAPTER 3

DESIGN METHODOLOGY AND COMPONENT SELECTION

3.1 DC MOTOR ANALYSIS AND REQUIREMENTS

The DC motor used in the stepper motor torque characterization system performs several different functions during the course of a torque test. These functions include serving as a motor to ramp the stepper motor up to each desired test speed, acting as a stepper motor torque measurement device during braking mode testing and acceleration mode testing of stepper motors, and providing rotational speed feedback through the use of a tachometer integral to the DC motor. In addition the particular DC motor selected must meet requirements with respect to maximum speed capability and maximum torque capability. These requirements dictate how large a stepper motor may be tested and also govern the speed range over which a stepper motor may be tested. Main functional requirements of the DC motor are listed as follows:

DC Motor Requirements:

Output torque at 0 RPM ------------------ 300 oz-in
Operating speed range ------------------ 0 - 1500 RPM
Continuous stall current ----------------- Less than 13 amps
Maximum friction torque ---------------- Less than 20 oz-in
Maximum cogging torque ---------------- Less than 1 oz-in

The particular DC motor used in the tester is a model number U16M4T permanent magnet motor manufactured by Printed Motors Industries (PMI), and it exceeds all of the aforementioned requirements. This DC motor utilizes an ironless armature in which the armature wires spiral outward radially on a printed-circuit style base. This design allows for low rotor inertia and high output torque at the same time. Rated output torque for this motor is 256 oz-in for extended periods and 2748 oz-in for short durations. This DC motor is capable of producing 400 oz-in of torque during a stepper motor torque test by slightly exceeding the rated DC motor current of 9.2 amps. Peak current for the DC motor, according to the PMI catalog specifications, is 94.9 amps for short durations. The PMI U16M4T motor meets the functional requirements as follows:

DC motor actual ratings:

Output torque at 0 RPM -------------- 400 oz-in with Kepco 400 watt programmable power supply
Operating speed range --------------- 0 - 3000 RPM
Continuous stall current ------------- 9.21 Amps
Maximum friction torque --------------15 oz-in
Maximum cogging torque ------------- Nonexistent

Actual DC motor torque and speed are controlled by the power supply used. DC motor output torque is a function of power supply output current and DC motor speed is a function of power supply output voltage. The PMI DC motor can produce 400 oz-in of holding torque and can also attain approximately 1500 RPM with the Kepco programmable power supply used in the test system.

A nice feature of the PMI DC motor is its ironless armature and resultant zero cogging torque. Cogging torque occurs in a conventional DC motor as a result of the iron armature interacting with the internal magnetic field. When the conventional DC motor rotates, cogging torque appears and constantly fluctuates as the iron armature aligns itself with the magnetic field. This fluctuation can be felt on the DC motor output shaft. Concerning the procedure of testing stepper motors, this cogging torque is very undesirable because it will cause the actual output torque of the conventional DC motor to fluctuate slightly and introduce error into the stepper motor torque data. The PMI DC motor used in the stepper motor tester applies a steady nonfluctuating torque to the stepper motor shaft as a result of its ironless armature design.

Integral to the PMI DC motor is a tachometer that converts DC motor speed to a voltage output. The tach added about 300 dollars to the cost of the DC motor but is a necessary item that needed to be included. The tachometer produces a voltage signal that is linear with respect to rotational speed; the voltage output is fed directly into a first order RC filter and on to the PC by way of the interface, providing a convenient means of velocity checks and stepper motor phase break detection. Voltage output of the tach is extremely ripple-free; the filter is necessary only to filter out low-speed variations caused by the stepper motor running at a low enough speed such that stepper rotational motion consists of a series of steps, which will translate to pure rotary motion at a higher speed. This step motion causes a wavy tach signal which, when unfiltered, will be interpreted by the A/D board as a stepper motor phase break. Tach filter design is covered in more detail in Section 3.7.

As mentioned at the beginning of this section, the DC motor acts as both a motor and a brake during the course of a torque test. DC motors are generally recognized as being able to operate both as a motor and a generator. Less well known is the DC motor operating as a brake, a mode that somewhat resembles a generator. Section 3.2 shows the relation of the programmable power supply to the DC motor mode and covers power flow, current flow, and output torque direction versus mode for the DC motor/power supply combination.

3.2 DC MOTOR POWER SUPPLY REQUIREMENTS AND ANALYSIS

Requirements for the DC motor power supply were very stringent. The main functions of the DC motor power supply are to drive the DC motor as it ramps the stepper motor up to each test speed and also to provide power to load the stepper motor shaft during the torque test. The supply has to be able to act as both a power source and a power sink while providing current and voltage in both directions with a smooth transition through zero voltage and zero current. This four-quadrant operation is necessary in order for the DC motor to be able to apply torque to the stepper motor shaft in both directions (acceleration and braking mode). Also, in order for the test system to be fully automatic, the supply needs to be compatible for automatic control with the PC and data acquisition system. Main functional requirements for the DC motor programmable power supply are listed as follows:

DC motor power supply requirements:

Type -------------------- 4 quadrant, bipolar supply, must act as a source and a sink

Minimum output voltage ---- 35 volts

Minimum output current --- 10 amps

Operation ----------------- Programmable to respond to a voltage input

The only power supply found which meets all requirements is the Kepco model BOP 36-12M (1). This supply is fully programmable to respond to automatic control using either an IEEE 488 bus directly linked to a PC or by a voltage input. In this case a voltage input from the data acquisition system to the power supply front panel controls all outputs. The Kepco supply is rated at 400 watts, 36 volts, and 12 amps. The 36 volt rating is sufficient to drive the DC motor at close to 1600 RPM, while the 12 amp rating enables the DC motor to provide enough torque to stall a 400 oz-in stepper motor.

Some confusion has arisen at this stage concerning the role of the DC motor and power supply, and how they function together during a stepper motor torque test. The DC motor functions not only as a motor but also as a DC brake. To add to the confusion, the DC motor acts as a motor during braking mode testing and as a brake during acceleration mode testing. As such, the terms DC brake and braking mode should be differentiated between; they do not pertain to the same thing. The terms DC motor and DC brake refer to the power flow in and out of the DC motor during a torque test. Braking mode refers to a simulation of the stepper motor trying to decelerate a load, and acceleration mode refers to a simulation of the stepper motor trying to accelerate a load. Perhaps braking mode should have been named deceleration mode, but the name caught on at an early stage so it will be left alone. Figure 3.1 differentiates graphically between the various DC motor modes, while Figures 3.2 and 3.3 demonstrate the difference between acceleration mode testing and braking mode testing.

At this point a discussion of acceleration mode and braking mode individually will show the relationship of the programmable DC power supply to each mode. The power supply determines in what mode the DC motor

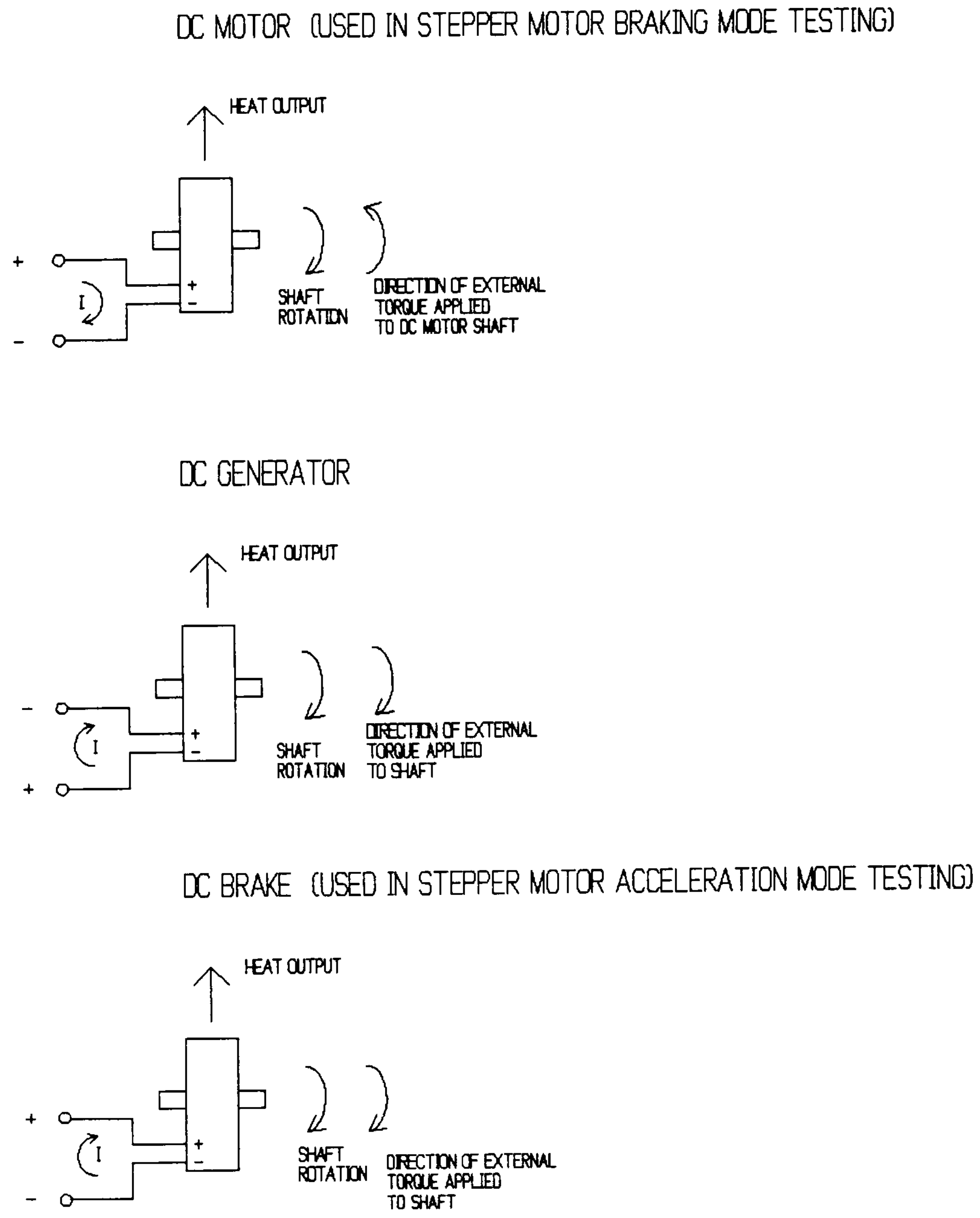
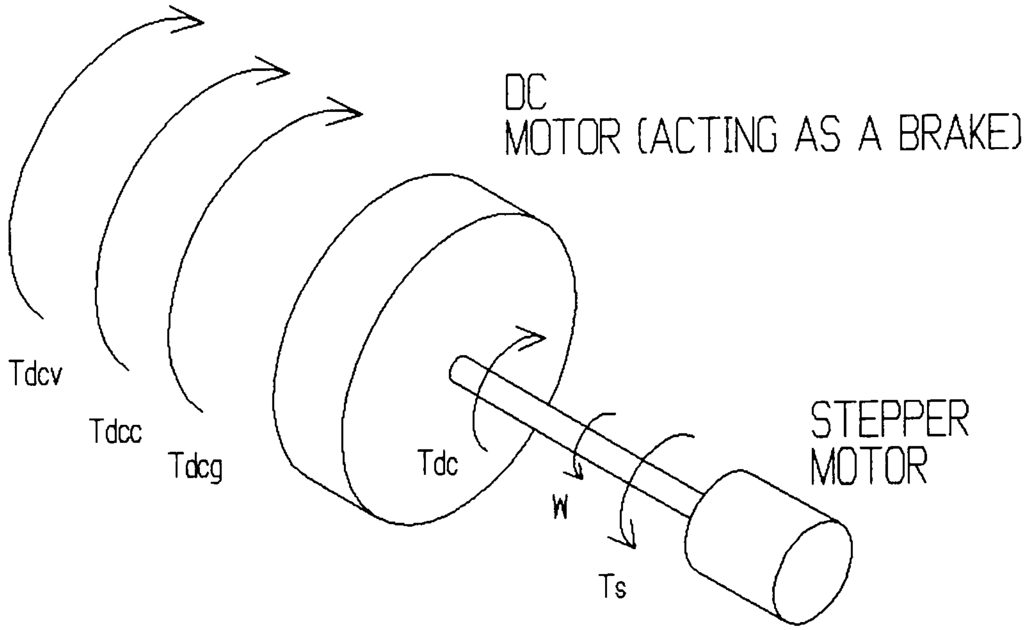


FIGURE 3.1 DC Motor Modes of Operation.

TORQUE DIAGRAM --- ACCELERATION MODE



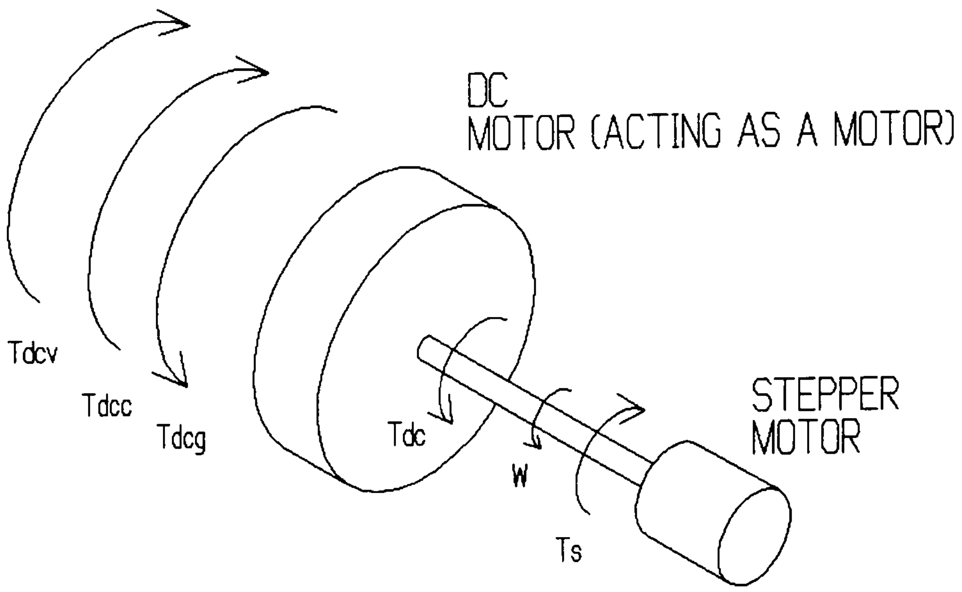
Ts = Tdc = Tdcg + Tdcc + Tdcv

STEPPER MOTOR:
Ts = TORQUE APPLIED BY STEPPER TO SHAFT
W = ANGULAR VELOCITY

DC MOTOR:
Tdcv = DC MOTOR VISCOUS FRICTION TORQUE
Tdcc = DC MOTOR COULOMB FRICTION TORQUE
Tdcg = DC MOTOR GENERATED TORQUE
Tdc = DC MOTOR OUTPUT TORQUE APPLIED TO SHAFT BY DC MOTOR

FIGURE 3.2 Acceleration Mode Diagram.

TORQUE DIAGRAM --- BRAKING MODE



Ts = Tdc = Tdcg − Tdcc − Tdcv

STEPPER MOTOR:
Ts = TORQUE APPLIED BY STEPPER TO SHAFT
W = ANGULAR VELOCITY

DC MOTOR:
Tdcv = DC MOTOR VISCOUS FRICTION TORQUE
Tdcc = DC MOTOR COULOMB FRICTION TORQUE
Tdcg = DC MOTOR GENERATED TORQUE
Tdc = DC MOTOR OUTPUT TORQUE APPLIED TO SHAFT BY DC MOTOR

FIGURE 3.3 Braking Mode Diagram.

operates and consequently what type of loading the stepper motor under test experiences.

Assume that we are at the beginning of an acceleration mode test. Refer to Figures 3.1 and 3.3 for a graphical representation of this type of test. At the beginning, assume that the power supply outputs a positive voltage to the DC motor in order to ramp the DC motor and stepper motor up to the required test speed. The stepper motor driver is disabled at this point. As soon as the system attains the test speed, the stepper motor driver is enabled and applies power to the stepper motor. Now both motors are motoring themselves at the same speed. Since this is an acceleration mode test, the DC motor must now apply a torque to the stepper motor shaft that will try to slow the stepper motor down. In order to do this, the power supply must begin to reverse the direction of voltage and therefore current going into the DC motor. As the power supply does this the voltage across the DC motor terminals begins to drop, and the current going through the DC motor slowly drops, goes to zero, and then flows in the opposite direction. At the instant when the DC motor current is zero (DC motor voltage will not be zero yet), the stepper motor is driving the DC motor and the stepper motor feels only the DC motor friction torque on its shaft. As the DC motor current passes zero and begins to flow in the opposite direction, the stepper motor begins to feel a torque on its shaft opposite to its direction of rotation. The total torque that the stepper motor now feels is the sum of the DC motor friction torque and the DC motor electromagnetic torque. The DC motor, which behaved as a motor when the current was positive, begins to behave as a brake at the instant the current passes the zero mark and reverses itself. The current continues to increase in this reverse direction until the stepper motor feels a torque sufficient to cause phase break. This entire process is controlled by the power supply; as the power supply drops its output voltage, this forces the current to go to zero and then reverse itself. Since the current goes to zero and reverses before the voltage reaches zero, the power supply actually has a positive voltage across its terminals but the DC motor is forcing a current into the supply which opposes this voltage. The power supply now must act as a power sink to dissipate this power input.

Now assume that we are at the beginning of a braking mode test. As before, the power supply produces a positive voltage to the DC motor which ramps the DC motor and stepper motor up to the required test speed. The stepper motor driver is enabled and power is applied to the stepper motor at the test speed. Both motors are now motoring themselves at the test speed, and the DC motor has a positive voltage and a positive current across its terminals. Since this is a braking mode test, the DC motor must apply a torque to the stepper motor in the same direction as that of rotation. In order to do this, the power supply must increase the voltage across the DC motor terminals (make it more positive) thereby increasing the DC motor current. It is important to note that DC motor voltage and current never reverse directions during this mode. As the DC motor current increases, it has to first overcome all DC motor friction torque occurring at the test speed before it applies any torque to the stepper motor shaft. Therefore, the torque that the stepper motor feels is the DC motor electromagnetic torque minus the DC motor friction torque. This situation arises because the direction of applied torque to the stepper motor shaft is in the same direction as rotation; this torque, provided by the DC motor, first must overcome the DC motor friction. In acceleration mode, DC motor friction was totally overcome by the stepper motor at the point of zero current. In order to apply a torque in the same direction as rotation to the stepper motor shaft, the power supply must augment the DC motor current in the positive direction by augmenting DC motor voltage in the positive direction. The power supply now acts as a power source. The power supply continues to increase the DC motor voltage until a high enough current in the DC motor causes the DC motor to break the phase of the stepper motor in the direction of rotation.

3.3 STEPPER MOTOR DRIVER AND POWER SUPPLY

The stepper motor test system uses an IMS IB104 stepper motor chopper driver (2) as the standard driver for the system. This driver outputs a phase current of 1 to 4 amps adjustable and operates from a supply voltage of 20 to 100 volts. Two Acopian nonregulated DC power supplies rated at 38 volts each and 5 amps each are connected in series to run the driver. Connecting the supplies in series doubles the voltage output but leaves current output unchanged.

The IMS IB104 driver has several advantages over smaller drivers. Initially, an IMS IB463 40 volt driver was tried but several failed during the course of testing. The larger IB104 is required to provide a satisfactory test speed range for larger stepper motors. Large stepper motors (those with high torque and phase current ratings) tend to put out a large AC back emf into the driver under certain conditions (see Section 3.8 for a detailed description of this and the driver overvoltage protection system). The RMS value of this AC voltage appears as a DC voltage across the driver and driver power supply terminals once the DC RMS value exceeds the driver DC voltage across the driver power supply terminals. This extra voltage across the driver power input terminals is potentially harmful to both the driver and the power supply. A higher voltage driver such as the IB104 can tolerate a much higher back emf; the IB104 driver extends the test speed range both in system ramp-up and in braking mode. These are the two points in a stepper motor torque test at which a large back emf is likely to be induced across the driver terminals. Another advantage of the IB104 driver is its increased surface area which facilitates cooling and promotes a lower operating temperature. The IB463 drivers typically would operate right at their temperature limits when full current was demanded; the IB104 tends to run much cooler.

The Acopian DC power supplies that power the driver were selected because of their relatively low cost. These supplies, when hooked in series as in this test system, output anywhere from 76 to 88 volts depending on the line voltage. This is sufficient to power the 100 volt IB104 driver with a margin left over for any overvoltage conditions.

3.4 DATA ACQUISITION SYSTEM

During a stepper motor torque test, many variables which control both the sequence of operation and the task of stepper motor torque measurement are under the direct control of the PC. The PC, however, only contains a BASIC program which tells the data acquisition system what to do. The data acquisition board within the PC is the unit which does most of the work during a stepper motor torque test. Figure 3.4 shows a simplified operation diagram of the data acquisition system used in the stepper motor test system.

Early on it was decided that, rather than trying to control all operation directly from the PC printer ports, operation should be controlled from a separate system (the data acquisition system) which would provide an easy

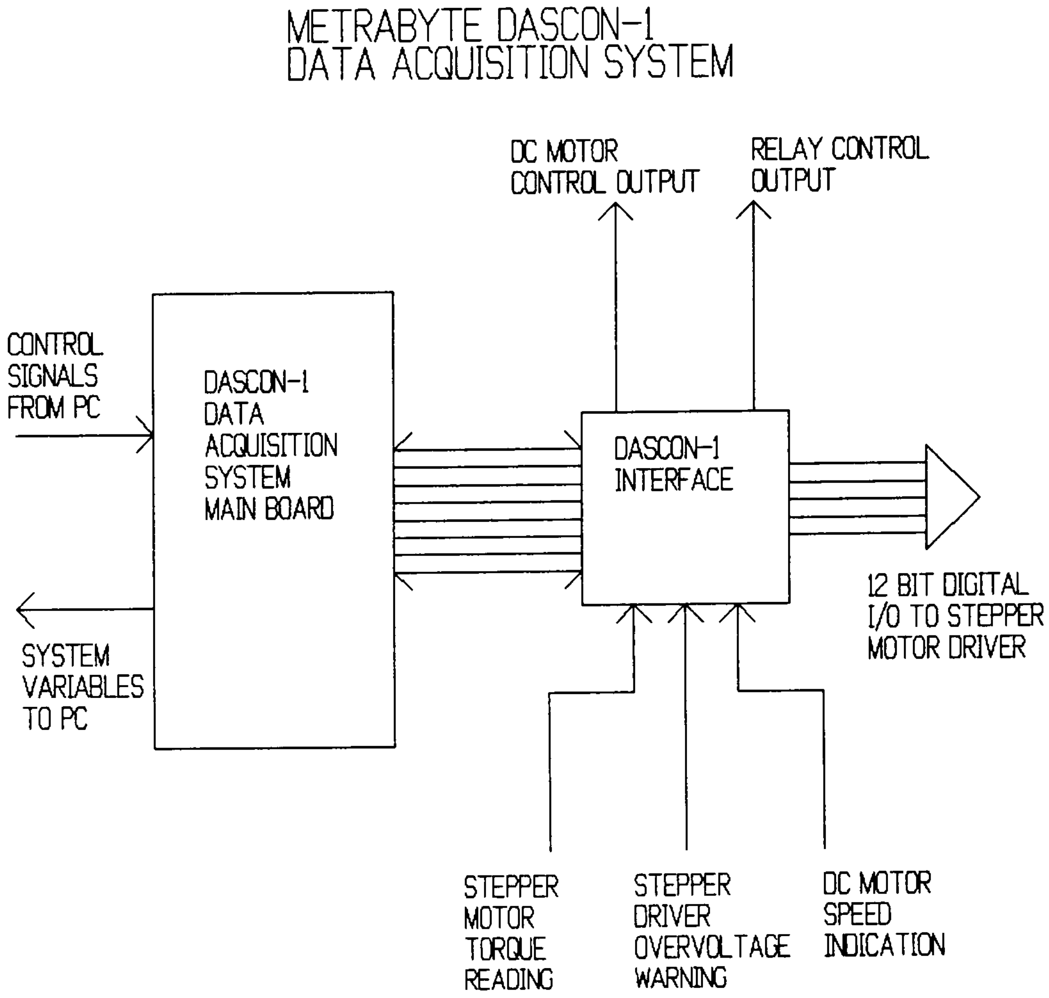


FIGURE 3.4 Data Acquisition System.

interface between the PC and all test system hardware. The data acquisition system must serve several purposes, including control of both the DC and the stepper motor, relaying tach feedback into the PC, detecting stepper motor phase break, and measuring stepper motor torque.

The data acquisition system selected to interface with the stepper motor test system is a Metrabyte Dascon-1 data acquisition system (3). This system consists of the Dascon-1 main board which mounts directly inside the PC on the PC accessory board. Also included is an outside interface board for easy access to all of the Dascon-1 functions. Dascon-1 system features include 4 channels of analog inputs (converted to digital through an A/D converter) with a sampling rate of 30 samples/second, 2 channels of analog output, and 12 bits of digital output for independent use.

The DC motor is controlled from one channel of the analog output. This analog output, consisting of a plus or minus 10 volt signal which is varied by the controlling software within the PC, is fed directly into the input of the DC motor programmable power supply. Direct automatic control of the DC motor is thus allowed. The stepper motor under test is controlled using the 12 bits of digital I/O. This digital signal, or binary number, is relayed into a binary-to-frequency converter (stepper motor control circuit) which pulses the stepper motor driver. All inputs, such as the DC motor speed signal, the DC motor output torque reading, and the stepper motor driver overvoltage signal, are relayed back into the Dascon-1 through 3 separate analog input channels. The BASIC program within the PC has access to all Dascon-1 inputs and also has control of all outputs, providing a direct link between the controlling software and the system hardware.

3.5 DESIGN OF A STEPPER MOTOR CONTROL SYSTEM

A fundamental problem in the initial stages of the design of the stepper motor test system was how to control the stepper motor under test. The stepper motor is run by the stepper motor driver, which relies on a frequency input to operate. The driver converts the input frequency to the proper stepper motor phase sequence for either half or full step mode. For example, in full step mode an input frequency of 200 hertz corresponds to the stepper motor rotating at 200 steps per second. For a 200 step per revolution stepper motor, this corresponds to 60 RPM. Therefore, the problem of controlling the stepper motor condenses to that of producing the necessary driver frequency.

Producing a frequency is not a problem for the PC. A loop in a BASIC program can alternate the voltage at one of the printer port outputs and this cyclic voltage can be fed directly to the stepper motor driver. This method, however, will not work for this particular test system. The PC does not operate fast enough to complete all of its program instructions while pulsing the stepper motor each time through the loop. For this reason an alternate form of stepper motor control was implemented that frees the PC to control and monitor the torque test.

The main controller for the stepper motor during a torque test is an external circuit that converts a binary number into a frequency that is routed directly to the stepper motor driver. Figure 3.5 shows a block diagram of the operation of this circuit. A detailed design description and circuit diagram is given in Appendix E.

The sequence of operation of this system starts when the PC determines the test speed at which the stepper motor requires phasing. The PC then commands the Dascon-1 data acquisition system to output a 12-bit binary

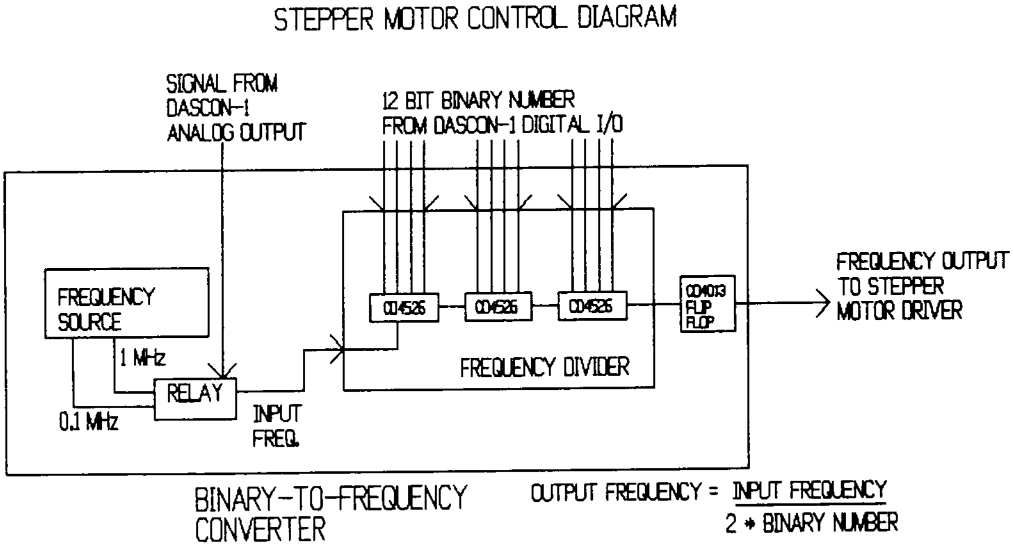


FIGURE 3.5 Stepper Motor Control Circuit Diagram.

number from the 12 bits of digital I/O available. This binary number is directed from the Dascon-1 main board to the interface. From the interface the 12-bit output is routed into the stepper motor control circuit. This circuit sends the corresponding stepper motor phase frequency to the stepper motor driver.

The stepper motor control circuit uses a frequency division system to accomplish its purpose. The circuit has two internal input frequencies. One frequency is used at and below 50 RPM while the other higher frequency is used above 50 RPM. The circuit operates basically by taking the input frequency and dividing it by the decimal equivalent of the binary number from the Dascon-1 to get the output frequency. The divider can divide the input frequency by any decimal integer from 1 to 4095. A 100 KHZ input frequency is used below 50 RPM to provide a reasonable lower bound for the stepper motors' slowest test speed. For example, if a 10 MHZ frequency were used here, the slowest speed that a stepper motor could be run would be 366 RPM in full step mode. However, using a 100 KHZ frequency to control the low RPM operation of the stepper motor results in unsatisfactory high-RPM operation. This unsatisfactory operation occurs because the step change in stepper motor RPM as it increases from one speed to the next is nonlinear. This nonlinearity is the result of the frequency division system. Dividing the input frequency by 4095, 4094, 4093, etc., produces a small change in the output frequency, but when the divider reaches the stage where it is dividing the input frequency by 6, 5, 4, etc., the output frequency changes by a large amount. For this reason, above 50 RPM an input frequency of 1 MHZ is used. In the operating range of the stepper motor (up to 1400 RPM), the system is calibrated to divide the input frequency by a large decimal number to keep the step size between consecutive speeds close together.

As an example of the characteristics of the circuit, the slowest that a stepper motor may be run in full-step mode is 3.6630 RPM. The next highest speed of which the circuit is capable is 3.6639 RPM. At this low RPM the circuit can increment the stepper motor speed by approximately 0.0009 RPM each step. Now, assume the stepper motor is at 40.000 rpm. The next higher speed is 40.107 RPM. If this were allowed to continue the circuit would be incrementing the stepper motor's speed by 20 RPM or more at 400 RPM. In order to be able to test the stepper motor up to 1400 RPM with a step speed change of less than 10 RPM, the 1 MHZ frequency is used above 50 RPM. This input frequency allows speed increments of 1/100 of an RPM at 50 RPM. This increment increases to 6 RPM at 1000 RPM, which was deemed satisfactory for the purpose of testing stepper motors. Since stepper motor torque curves tend to have steep slopes at low speeds and flatten out at high speed, it is important to have a small test speed increment at low RPM in order to properly show the torque curve. At high RPM it is not so important.

3.6 DC MOTOR CURRENT MEASUREMENT SYSTEM

Stepper motor output torque at phase break is determined by the DC motor output torque at phase break. Up until stepper motor phase break, the DC motor and stepper motor shaft acceleration is zero. This means that the output torque of the DC motor equals the output torque of the stepper motor up to the point of stepper motor phase break. An accurate determination of the DC motor's output torque can only be accomplished through an accurate determination of the DC motor armature current. Once the armature current is known, the DC motor output torque is determined by

$$\text{Torque} = (K_t * I_a) +- \text{Friction Torque}$$

where K_t is the DC motor torque constant, I_a is the DC motor armature current, and the DC motor friction torque is the combined effect due to coulomb and viscous friction within the DC motor. This friction torque is either added or subtracted depending on whether the torque test is operating in acceleration or braking mode.

Figure 3.6 shows the current measurement system used in the stepper motor test system. The current measurement device used is a simple current shunt consisting of four precision resistors connected in parallel. The current shunt is connected directly in one of the DC motor input terminal lines so that the armature current flows through the current shunt. The armature current causes a proportional voltage to appear across the shunt. This voltage is an accurate measurement of the DC motor armature current and is calibrated to be used as an analog input to the data acquisition system. Appendix H provides the calibration data for the data acquisition system.

3.7 DC MOTOR TACHOMETER FILTER

Integral to the PMI DC motor used in the stepper motor test system is an analog tachometer. This tachometer outputs a DC voltage signal that is a linear function of DC motor speed. The voltage output is routed into the Dascon-1 interface to provide the data acquisition system and PC information about system speed and is also used to detect stepper motor phase break.

At low test speeds, a problem arises when using the DC motor tachometer alone with no filter. Low speed operation of any stepper motor

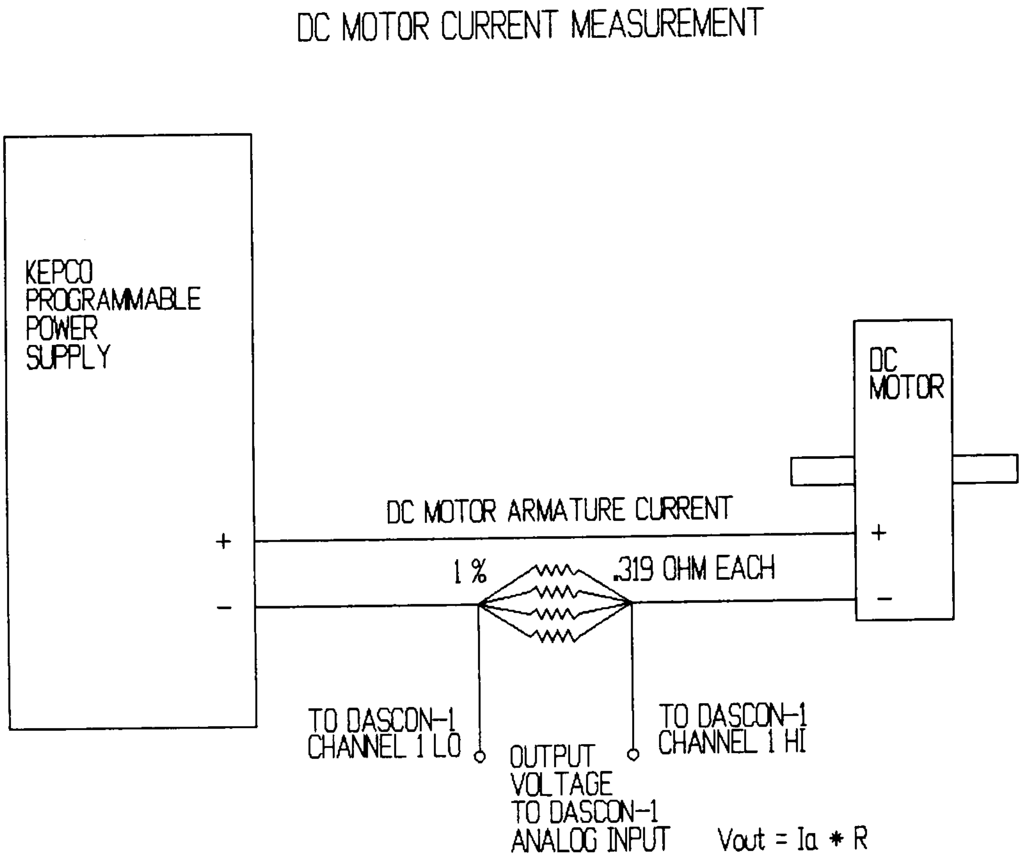


FIGURE 3.6 DC Motor Current Measurement.

consists not of smooth rotary motion but of a wavy step-like motion. This wavy motion occurs at low speed because the stepper motor rotating assembly has time to slow down between receiving step pulses from the driver. At higher speed, the inertia of the stepper motor prevents it from appreciably slowing between steps. Since the stepper motor under test and the DC motor are directly coupled, at low speed the DC motor is forced to rotate in a series of steps in sequence with the stepper motor. This step motion of the DC motor and tachometer causes the tachometer to produce an oscillating voltage of the same frequency as the stepper motor pulse rate. Since the data acquisition system constantly monitors tachometer output, any variation of the tach from the speed/voltage calibration curve is interpreted as a stepper motor phase break. The wavy tach signal generated at low speed is of sufficient amplitude to cause the data acquisition system to proceed as if a stepper motor phase break had just occurred. Since the DC motor has not had time to load the stepper motor shaft with any considerable torque, the result is a premature shutdown of hardware and an erroneously low stepper motor pull-out torque reading.

In order to alleviate this problem, a low-pass RC filter has been incorporated into the tachometer output between the tach and the Dascon-1 interface input. Figure 3.7 shows the relation of the tach filter to the hardware. The filter consists of a voltage divider to scale the tach voltage to the Dascon-1 analog input limits, and an RC network through which the voltage divider output must pass.

The design of the tach filter is a compromise between filtering capability and system response to a tachometer input. In order to filter out the voltage oscillations adequately and pass DC voltage, a low-pass filter is required. The

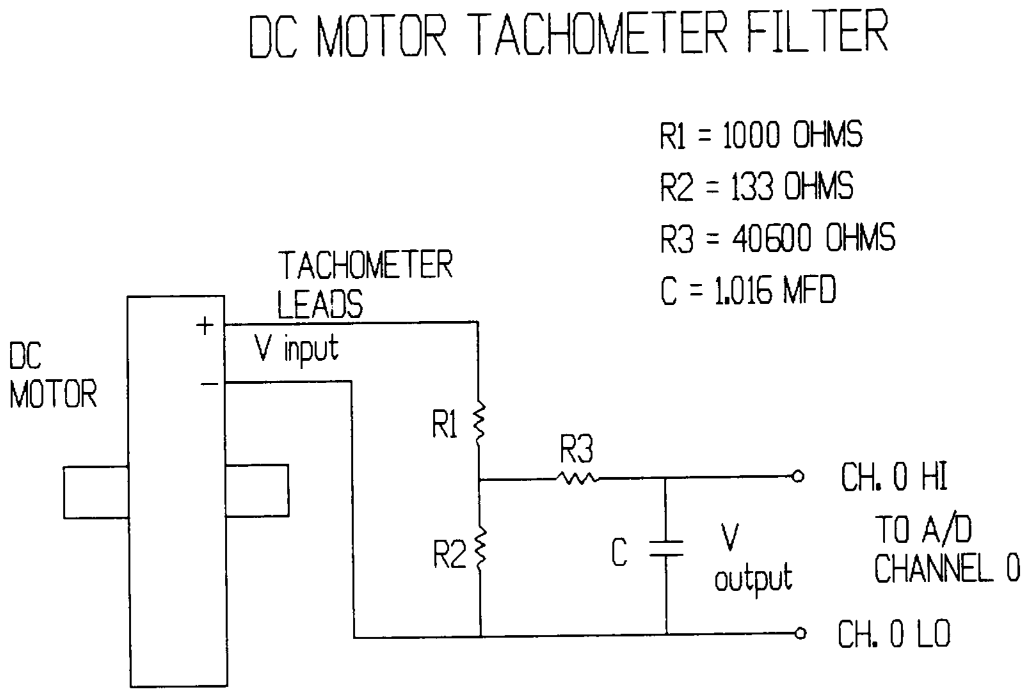


FIGURE 3.7 DC Motor Tach Filter.

lowest anticipated stepper motor speed seen during a dynamic torque test is roughly 3 RPM. This corresponds to a noise frequency of 10 hertz generated by the stepper motor. The noise frequency corresponds to the stepper motor driver step input frequency. The filter must filter out all noise at this frequency and above in order to provide the Dascon-1 input with a smooth signal and ensure that a false phase break is not triggered. Therefore the breakpoint of the RC filter is set as far below the 10 HZ minimum frequency as possible. The actual break frequency of the RC filter used is 4.42 Hz. If the breakpoint is too low, however, the filtered signal will lag behind the actual tach signal. This time lag, if left relatively large, will cause the DC motor actual speed to be faster than what the PC thinks it really is during ramp-up. It will also cause a time delay in detection of stepper motor phase break. The DC motor will actually be spinning faster (or slower) than what the filtered tach voltage represents. The difference in speed between the actual motor speed and the filtered motor speed may be represented by

$$\text{Delta RPM} = K * dV/dT * \text{tau}$$

where dV/dT is the time rate of change of the tach voltage, K is a constant relating tach voltage to speed, and tau is the filter time constant. A more complete mathematical analysis of the actual RC filter used in the test system is given in Appendix F.

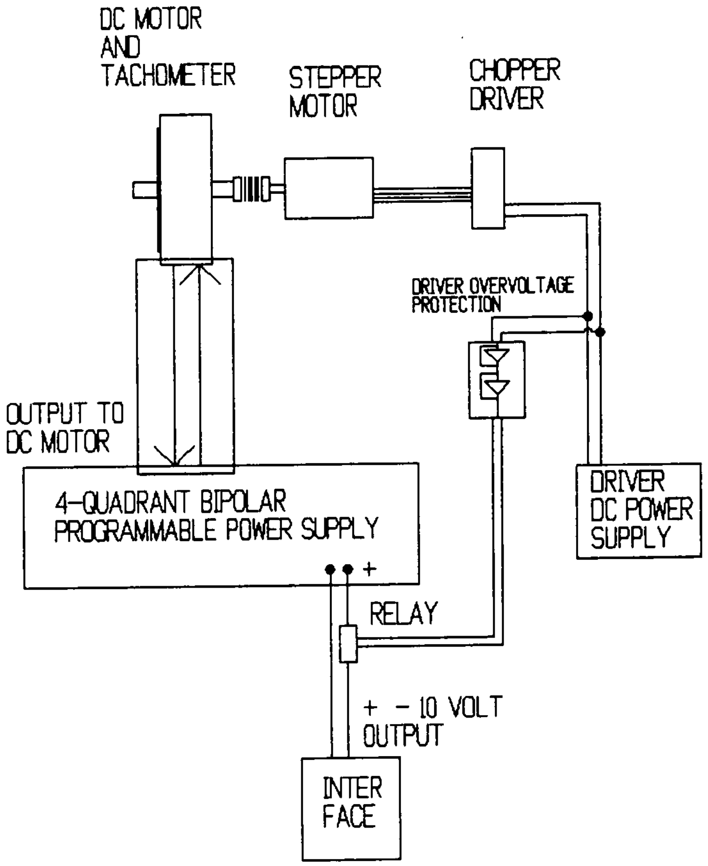
The actual tach filter used has the minimum breakpoint possible to ensure good filtering characteristics while still maintaining an acceptable voltage input/output time lag. The maximum speed lag seen during dynamic operation is approximately 7.2 RPM, which is well within the limits needed by the data acquisition system to ensure proper phase break detection and speed detection.

3.8 DESIGN OF STEPPER DRIVER OVERVOLTAGE PROTECTION

The initial design of the stepper motor test system did not include any safeguards against stepper motor driver overvoltage. A stepper motor driver is said to be in an overvoltage condition when the voltage appearing across its power supply terminals rises above its rated voltage. Early experimentation and several failed drivers revealed the causes of this condition. An overvoltage detection circuit has been implemented in the system to prevent future stepper motor driver failures. A hardware diagram of this system is shown in Figure 3.8.

The stepper motor driver overvoltage condition is a direct result of the stepper motor acting as a generator. Power input through the stepper motor shaft by the DC motor will cause the driver voltage (the voltage across the driver power supply terminals) to rise beyond an acceptable limit. This voltage change is a direct function of three different criteria: stepper motor size (output torque), stepper motor speed, and the torque applied to the stepper motor shaft by the DC motor. It is also thought that stepper motor voltage and current/phase ratings may have an effect, but the reasons and mathematics for this condition appear to be rather complicated and are beyond the scope of this work.

What facts are known about the driver overvoltage phenomenon are listed as follows. The stepper motor has the capability of behaving as an AC generator. When the stepper motor shaft is rotated, an AC voltage appears across its phase windings. In general, when a large enough stepper motor is turned by the DC motor to a high enough speed, the RMS value of the generated AC stepper motor voltage will exceed the DC driver power supply voltage. If the stepper motor speed is increased further, the voltage across



SEQUENCE OF OPERATION:

1. DRIVER DC POWER SUPPLY AND DRIVER EXPERIENCE INCREASING VOLTAGE
2. DRIVER OVERVOLTAGE CIRCUIT SENSES VOLTAGE AND TRIPS RELAY
3. PROGRAMMABLE POWER SUPPLY SHUTS DOWN, SHUTTING DOWN THE DC MOTOR WITH IT
4. DRIVER VOLTAGE IMMEDIATELY DROPS
5. TO PREVENT OSCILLATION CAPACITOR MUST CHARGE TO TURN POWER SUPPLY AND DC MOTOR BACK ON
6. BEFORE CAPACITOR IN THE CIRCUIT CHARGES, THE PC SHUTS DOWN ALL POWER SUPPLY CONTROLS
7. CAPACITOR REACHES SPECIFIED CHARGE LEVEL AND COMPARATOR RESTORES POWER SUPPLY RELAY TO THE OPERATING CONDITION
8. PC EITHER RESTARTS TEST OR SHUTS THE SYSTEM DOWN

FIGURE 3.8 Driver Overvoltage Protection.

the driver and power supply terminals, which are common, will increase. This voltage appears to be roughly equal to the stepper motor AC voltage RMS value. As stepper motor speed is increased the net effect is to apply a dangerously high voltage across the driver terminals, which almost always causes a driver failure.

Driver voltage also is torque dependent to an extent. This condition usually shows up after the stepper motor has engaged itself at a certain speed. The DC motor does not have to be driving the stepper motor, but does have to apply a torque to the stepper motor shaft. Again, this situation applies to a large stepper motor turning at a high speed. When a stepper motor is being phased at a certain speed and the DC motor applies a torque opposing shaft rotation, after a point the voltage across the driver power supply input terminals will drop a small amount. This voltage is common to the driver DC power supply output terminals. However, when a torque is applied by the DC motor to the stepper motor in the direction of shaft rotation, after a point the driver voltage across the driver power input terminals will rise. After a point means that, initially, as the torque is first applied no voltage change is seen. After a certain torque limit the driver voltage becomes dependent on how much torque is applied to the stepper motor shaft. An increase in applied torque, after this limit, corresponds to an increase in the driver voltage. This voltage increase is very unusual because in most cases the voltage output of a DC generator is proportional to its speed. However, the stepper motor does not behave exactly as a DC generator and when connected to the driver the total electrical circuit becomes very complicated.

During a stepper motor dynamic torque test, a stepper motor driver overvoltage condition may be encountered at three different points of the test.

In case 1, a driver overvoltage may be encountered during DC motor ramp-up of the stepper motor to the desired test speed. In this case the driver voltage becomes speed dependent. In case 2, a driver overvoltage may be encountered after the stepper motor is locked in phase at the desired test speed and the DC motor applies a torque to the stepper motor shaft in the direction of rotation. In this case the driver voltage becomes torque dependent. In case 3, a driver overvoltage may be encountered after a stepper motor phase break in braking mode. The DC motor tends to temporarily overspeed the stepper motor and the driver voltage is, as in case 1, a function of speed. Case 3 and case 1 are really the same thing happening at two different points of a torque test.

The circuit incorporated to sense and eliminate this overvoltage will, in cases 1 and 2, terminate the entire test and provide the user with an explanation of what happened and a warning. In case 3 the overvoltage protection circuit will eliminate the overvoltage condition but will also allow the test to continue only if phase break is detected before the overvoltage is detected and until either case 1 or case 2 is reached. From constant performance evaluation of the tester, case 3 has almost never been seen; case 2 is almost always reached first.

The overvoltage protection circuit uses a dual comparator circuit with an RC network to accomplish its task. The circuit is calibrated to trigger when a dangerous voltage level occurs across the driver power supply input terminals. As the driver voltage rises beyond a set point, the first comparator almost instantly triggers a second comparator, which trips a relay, thereby shutting down the Kepco DC motor programmable power supply. The relay opens in about 50 microseconds, which is necessary to stop the DC motor from excessively overspinning the stepper motor after a phase break. Shutting down the programmable power supply stops the DC motor and eliminates all stepper motor generator action. As the voltage now drops back to a normal level, the first comparator triggers the RC network. The capacitor must charge to a certain level before the second comparator will turn the DC motor power supply back on. This time delay is incorporated to give the PC time to shut down all hardware, preventing an on/off oscillation of the overvoltage protection circuit and DC motor. Figure 3.8 shows a system diagram and simplified operation of the overvoltage protection system, while Appendix G provides a detailed circuit diagram and sequence of operation of the circuit.

3.9 FRAME ASSEMBLY

The frame for the stepper motor tester consists of flat aluminum plates which serve to rigidly mount both the DC motor and the stepper motor under test. Aluminum was selected due to its light weight and its good heat dissipation characteristics. Consequently, overheating the DC motor has never been a problem, and motor characteristics remain relatively constant during testing. The stepper motor mount is designed to positively retain the stepper motor under test using the mounting holes in the stepper motor case. This mounting method more closely simulates the actual mounting configuration of the stepper motor as intended by the stepper motor manufacturer, and should allow the tester to more closely simulate actual operating conditions for the stepper motor under test. Most stepper motors use a common mounting hole pattern, and an adapter is provided for those motors which will not fit in the main mount. Figure 3.9 shows a diagram of the frame assembly and all related components.

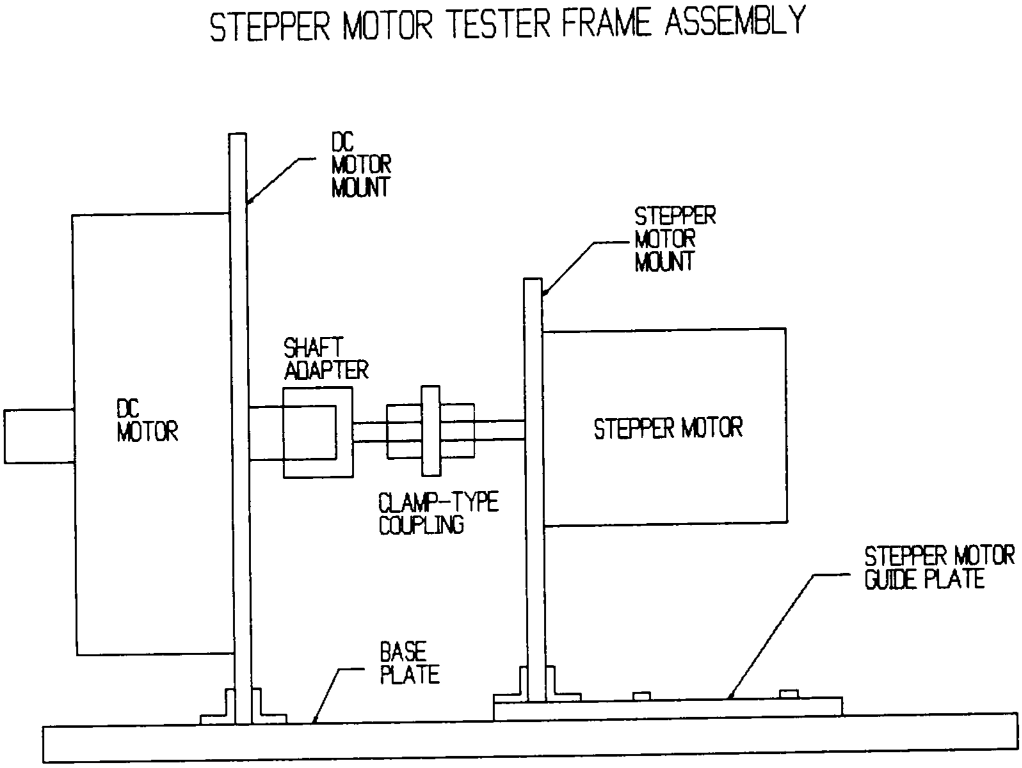


FIGURE 3.9 Frame Assembly.

The frame consists of a base plate upon which all components are rigidly mounted. The DC motor is permanently mounted with respect to the base plate. The stepper motor under test is rigidly mounted to the stepper motor mount, which in turn is mounted to the stepper motor guide plate. The stepper motor guide plate rests in a slot in the base plate and is affixed to the base plate by four bolts. During mounting of the stepper motor, the bolts are loosened and the guide plate may slide along the base plate allowing axial movement of the stepper motor with respect to the DC motor. The axial guide plate movement is useful for mounting different size stepper motors and couplings where the shaft-to-shaft distance between the DC motor and the different stepper motors may not be constant. The frame assembly has been machined to close tolerances to ensure correct shaft alignment in all cases. Detailed drawings of the individual frame components are provided in Appendix J.

CHAPTER 4

PERFORMANCE AND EVALUATION OF TESTER

4.1 ACTUAL PERFORMANCE LIMITS

Testing and evaluation of the stepper motor torque characterization system over a period of months have revealed many of the unit's major operating characteristics. Most major design objectives which were required during the initial design phase have been met and are summarized in the following paragraphs.

Automatic control of the test procedure and system has been implemented through the use of an IBM PC. The PC is responsible for providing the user with a selection of test parameters at the beginning of each test which allow the user to customize the test procedure. The user may select, for example, half or full-step mode, acceleration or braking mode, holding torque, DC motor torque ramp variable, starting RPM, finishing RPM, and the test RPM increment. After all parameters have been entered, the PC assumes full control of the test procedure and data logging. Once the torque test has started, the user is free from performing any other work until the end of the test has been reached. Upon reaching the end of the test, the PC will disable both motors and the programmable DC motor power supply, leaving the user to turn everything off.

Set-up time for a typical torque test averages about 15 to 20 minutes for a user who is familiar with the system and operating instructions. A first time user will probably take much longer. Set-up involves physically mounting the stepper motor into the frame and making the connections between the stepper motor and the stepper motor driver. The mounting system has been designed to simulate the way that the stepper motor will probably be mounted in use, in order to more closely simulate resonance characteristics. Once the stepper motor has been mounted, the user must verify that it turns in the right direction using a test program called TEST9.BAS provided with the software. Torque output for a stepper motor is the same for clockwise and counterclockwise rotation, so the tester is set up to operate in one direction only. When the stepper motor is securely mounted, the user is left to start the test software and enter the test parameters to begin a test. Actual test performance limits are listed in the summary as follows:

Performance limits:

Mode Capability:	Half/Full step Acceleration or Braking mode
Stepper Motor Size Range:	20 - 400 Oz-In: Does not give valid data below 15 oz-in.
Speed Range Of Test:	0 - 1500 RPM
Time to Test One Data Point:	7 - 15 Seconds
Output:	Screen Data and Disk Torque vs. RPM
Accuracy:	Theoretical +1.47 oz-in -3.94 oz-in
Repeatability:	Actual +- 5 oz-In

The stepper motor size range is limited to 20 oz-in on the low end due to the DC motor friction torque. The maximum friction torque of the DC motor is roughly 15 oz-in; any stepper motor with less output than 15 oz-in cannot overcome the DC motor friction torque during a dynamic test. A stepper motor smaller than the recommended 20 oz-in minimum size may be tested, but the user must discard any torque data of 15 oz-in or below.

During a holding torque test, the DC motor shaft is not rotating. As a result, the friction torque consists only of coulomb friction, which amounts to about 8.2 oz-in. Holding torque test data below 8.2 oz-in must therefore be discarded.

The DC motor has the capability to drive almost any stepper motor up to 1500 RPM. The top speed of the DC motor is limited by the maximum voltage output of the Kepco programmable power supply. However, it is not always possible to get torque data up to 1500 RPM with some larger stepper motors. Larger stepper motors (on the order of 200 oz-in or above) tend to generate a large back emf when driven up to speed and an even larger back emf when loaded at high speed in the direction of shaft rotation (braking mode). This back emf will cause the overvoltage protection circuit to terminate the test once a back emf has been reached that is approaching the safety limits of the stepper motor driver.

The average time taken to test one data point varies. It is dependent on the output torque of the stepper motor and the value of the user selected DC motor torque ramp variable. The DC motor torque ramp variable varies the speed at which the DC motor loads the stepper motor shaft (see Section 2.4). For a constant DC motor ramp variable, a higher torque stepper motor will take more time to test because the DC motor has to reach a higher torque output at each test point. For a constant stepper motor output torque, lowering the DC motor ramp variable will cause the DC motor to load the stepper motor shaft more slowly, thereby increasing the test time. With the recommended DC motor ramp variable of 5, one test point on a 100 oz-in motor takes about 7 seconds to test and log the data. Under the same conditions, a 400 oz-in stepper motor may take up to 20 seconds to test and log the data. A typical torque test consisting of 150 data points on a 400 oz-in motor will take anywhere from 30 to 50 minutes depending on the stepper motors torque curve. The same test on a 100 oz-in motor may take anywhere from 20 to 30 minutes.

Output is in the form of torque vs. RPM data on the screen and, as an option, written to disk. The torque data is written to the A: drive disk under the filename Torque.PRN in order to be compatible with Lotus123.

Accuracy and repeatability are discussed further in Sections 4.2 and 4.3.

4.2 ACCURACY

This discussion of the accuracy of the stepper motor torque tester system begins with a definition of what exactly is meant by accuracy and the parameters under which this definition remains valid. System accuracy is a measure of how closely the system output (torque data) matches the exact torque output of the stepper motor under test. As such, accuracy can only be measured within the bounds of the torque testing system. Once the stepper motor is removed from the tester and placed in its actual operating environment, its torque curve may change slightly due to differences in couplings, load inertias, motor drivers, etc. The accuracy limit presented in this writing does not reflect any of these external changes that will always be present when the motor is removed from the tester. At best, the test system user can know the system accuracy within certain limits and, barring no significant differences between the test system and the real operating environment, use the torque data with a degree of confidence. When significant differences exist between the test system and the actual operating system, the user may have to extrapolate the test system results by experience in order to anticipate any differences between the test system data and the actual "operating conditions" torque.

The stepper motor torque testing system uses a DC motor as a torque measuring device. Output torque of the DC motor is a linear function of DC motor current. Since the DC motor and the stepper motor are directly coupled, both motor shaft velocities are equal and constant up until stepper motor phase break. Thus, the stepper motor phase break torque equals the DC motor output torque at phase break. An accurate measurement of the stepper motor phase break torque really consists of an accurate measurement of the DC motor torque at phase break via the DC motor current and DC motor friction torque data. Factors that affect these measurements are discussed in the following paragraphs.

Several factors affect the accuracy of the stepper motor torque testing system. These factors include: The DC motor torque ramp variable, DC motor friction torque calibration, DC motor output torque/current calibration, DC motor heat buildup, and the internal accuracy of the A/D converter which controls the DC motor current data assimilation. These factors are discussed independently in the following paragraphs.

The DC motor torque ramp variable is the only factor affecting accuracy that is directly controllable by the user. The torque ramp variable controls the speed at which the DC motor applies torque to the stepper motor shaft. The DC motor increments its output torque in a series of steps, with the step size being a direct relation to the DC motor torque ramp variable. A numerically larger ramp variable corresponds to a larger step change in the DC motor output torque. For example, the recommended ramp variable of 5 increments the DC motor output torque value by 2.47 oz-in. The ramp variable of 5 directly increments the D/A output by 5 bits at a time, which in turn controls the power supply output which controls the DC motor's output torque. If the user wishes to speed up the torque test by selecting a torque ramp variable of 10, the software will ramp up the DC motor output torque twice as fast as with a ramp variable of 5. In this case the DC motor increments its output torque in steps that are twice as big as with a ramp variable of 5. Therefore, accuracy is compromised for speed as the torque ramp variable is numerically increased. Considering the DC motor torque ramp variable only, accuracy with respect to this variable is +0.00 and -2.47 oz-in with the recommended torque ramp variable of 5. Total system accuracy with a torque ramp variable of 5 is +1.47 oz-in and -3.94 oz-in.

The DC motor current shunt/armature resistance has been calibrated by direct measurement. DC motor voltage and current were measured to determine the armature and current shunt combined resistance. The uncertainty in the voltmeter used to calibrate the DC motor is +- 0.01 volts. This error produces an error in the DC motor output torque of +- 0.28 oz-in over the operating range of the DC motor.

DC motor friction torque was determined by directly measuring the no-load current required to overcome the internal friction of the DC motor. The no-load current is directly related to torque by the motor constant K_t. The friction torque is a nonlinear function of motor speed. Coulomb friction remains fairly constant while viscous friction theoretically is a function of the second power of the motor speed. The total DC motor friction torque is the sum of the viscous and coulomb friction torques. A fifth order curve has been found to fit the friction torque data better than a second order curve, so the fifth order curve is used in the software with an uncertainty of +- 1 oz-in over the operating speed of the DC motor. This curve is shown in Appendix C.

Heat buildup in the DC motor is a factor that, has not been observed in the stepper motor torque testing system. The DC motor's outer case and aluminum mounting frame operate at near ambient temperature under use. Before calibration of the DC motor, the system was allowed to run in order to let the DC motor attain a steady state temperature. The DC motor calibration was then performed to ensure no deviation in motor constants due to temperature would be present. In actual testing, no difference in stepper motor torque data has been detected when comparing a "cold run" (DC motor not allowed to warm up) and a "warm run" (after several test runs to allow the DC motor to warm up). The DC motor manufacturers catalog indicates some output torque deviations during forced convection cooling of the DC motor, which is why there was some concern over this area.

The last source for error in the system is the A/D converter that converts the analog DC motor torque measurement into digital form and transmits it to the operating software. The A/D converter's internal error is rated by the manufacturer at +- 1 bit out of 4095 bits. This translates to an inaccuracy in the DC motor output torque measurement of +- 0.19 oz-in over the operating range of the system.

The A/D converter measures the DC motor torque by taking an indirect measurement of the DC motor current. The particular A/D converter used in the Metrabyte board has a sampling rate of 30 samples per second, which seemingly will introduce some sampling error into the torque data. This digital sampling error is taken into account by the error introduced by the DC motor torque ramp variable. Also, the A/D converter samples a steady state system instead of a constantly ramping system. The highest current reading that appears and which is measured by the A/D actually is the last of a series of current "steps" generated by the DC motor torque ramp variable. The A/D measures this last "step" of current that goes into the DC motor to cause the stepper motor to break phase. The stepper motor phase break is detected before the DC motor current is ramped up any farther. After each step change in the DC motor current, a check is done to determine if the stepper motor has broken phase. Because of this method of first increasing the DC motor torque and immediately checking for phase break, the A/D sampling error is actually taken into account by the error caused by the DC motor torque ramp variable. This is due to the fact that in between the time that the A/D samples the DC motor current and the time that the A/D checks for phase break, the DC motor current does not change significantly, so that phase break, for all practical purposes, occurred either at the exact A/D current reading or somewhere within the bounds of the DC motor torque ramp variable error.

The preceding sources of error in the stepper motor torque testing system are all additive except for the A/D digital sampling error (not to be confused with the A/D converter internal error). The DC motor tachometer filter introduces no error into the torque data because it has no effect on the torque reading. Nonvarying errors include the DC motor current/torque calibration, the DC motor friction torque calibration, and the A/D converter internal error. These sources of error all add with the error associated with the user-prescribed DC motor torque ramp variable. Error bounds for the system are given in the following summary.

Table 4.1 System Errors

DC Motor Torque Ramp Variable	Ramp Variable Error (oz-in)	System Error (oz-in)
1	+0.00 -0.49	+1.47 -1.962
2	+0.00 -0.98	+1.47 -2.45
3	+0.00 -1.48	+1.47 -2.95
4	+0.00 -1.98	+1.47 -3.45
5	+0.00 -2.47	+1.47 -3.94
6	+0.00 -2.97	+1.47 -4.44
7	+0.00 -3.46	+1.47 -4.93
8	+0.00 -3.95	+1.47 -5.42
9	+0.00 -4.45	+1.47 -5.92
10	+0.00 -4.94	+1.47 -6.41
11	+0.00 -5.44	+1.47 -6.91
12	+0.00 -5.93	+1.47 -7.40
13	+0.00 -6.43	+1.47 -7.89
14	+0.00 -6.92	+1.47 -8.39
15	+0.00 -7.41	+1.47 -8.88
20	+0.00 -9.89	+1.47 -11.35
25	+0.00 -12.36	+1.47 -13.82
50	+0.00 -24.72	+1.47 -26.18

If needed, the ramp variable error in oz-in may be calculated by:

Positive Ramp Error = 0.00
Negative Ramp Error=0.4943*(Ramp Variable)

The system error in oz-in is given by:

Positive Error = +1.47 oz-in
Negative Error = Negative Ramp Error - 1.467

4.3 REPEATABILITY

Repeatability of the stepper motor torque testing system is defined as the system's ability to generate consistent torque data for a given stepper motor subjected to many torque tests all under the same conditions. Experimentation has revealed that the system has an average repeatability of about +- 5 oz-in for the average stepper motor. The DC motor torque ramp variable, when set too high, will cause errors in repeatability and accuracy. Some of the repeatability error may be attributed to the stepper motor itself. Most stepper motors will not break phase at exactly the same applied torque every time at a given speed. Many stepper motors also exhibit an oscillatory torque curve when run below their rated current and at high speed. These oscillations are repeatable but vary from test to test, and are much larger than normal variations in torque data. The repeatability value of +- 5 oz-in was taken from a series of 20 run repeatability tests on a stepper motor with non-oscillatory torque characteristics.

4.4 FAILURE MODES

During the course of testing and evaluation of the stepper motor torque testing system, several failure modes and their effects have been identified. Although design improvements have reduced the occurrence of most of the machine failure modes, human error plays a large part in the satisfactory operation of the system. For this reason, failure modes are separated into two categories: machine error and human error. Machine error failure modes deal with aspects of the stepper motor torque testing system that may fail regardless of the system user. Human error failure modes deal with system failure due to incorrect set-up and operating procedures initiated by the user.

Machine error failure modes include the following:

1. Coupling Failure
2. Coupling Clamp Failure
3. Metrabyte Board Main Fuse Failure
4. Stepper Motor Driver Failure
5. Sensitivity to Static
6. 60 Hz. Interference
7. Stepper Driver 20000 Hz. Interference
8. Stepper Motor Failure To Engage At Speed

1. Coupling Failure:

The coupling between the DC motor shaft and the stepper motor shaft has undergone two failures at the time of this writing. The first coupling to fail, an aluminum alloy Helical coupling, had a torque rating slightly above the maximum torque output of the DC motor (around 400 oz-in). This coupling broke in half after 1 month of use while transmitting approximately 250 oz-in of torque at around 500 RPM. A second coupling was selected with a safety factor of about 1.7 with regard to torque.

The second coupling, a Berg delrin coupling, failed after three weeks while transmitting a load of about 400 oz-in of torque. At this point it was determined that the coupling failures were due the large shock and vibration load produced by the abrupt stepper motor phase break during the applied DC motor torque. The coupling also must undergo a reversing load prior to the stepper motor phase break.

The third and present coupling was selected from the Schmidt coupling design guide. The coupling was selected to transmit the maximum torque output of the DC motor while carrying a severe shock and vibration load at the same time. The safety factor of this coupling with respect to the DC motor maximum torque is roughly 3.1. No coupling failures have been observed in the six months that this coupling has been in service.

2. Coupling Clamp Failure:

Early testing revealed that a set-screw type coupling does not provide satisfactory shaft clamping ability over the duration of a torque test. The present coupling uses clamp style hubs in which there is no direct set-screw-to-shaft contact. These clamp hubs have never failed or allowed either shaft to slip during the course of testing.

The DC motor shaft adapter utilizes a set screw to attach to the DC motor shaft. Although the original set-screw type couplings always loosened during a torque test, the DC motor shaft adapter's set-screw has not loosened during the course of a test. For this reason it has been left alone, although a clamp type adapter would really be better suited for the job.

The main effect and symptom of a loose coupling is to cause the system to report a premature stepper motor phase break. A loose coupling, even if it is still tight enough to slip only slightly, will cause a differential in speed between the DC motor shaft and the stepper motor shaft upon loading the stepper motor shaft. This speed differential is interpreted by the system as a stepper motor phase break. The resulting torque reading will be both low and inaccurate. Further loosening of the coupling will result in major shaft slippage between the two motors. This type of failure can almost always be prevented by making sure that the coupling and adapter screws are tight at the beginning of each test.

3. Metrabyte Board Main Fuse Failure:

The Metrabyte Dascon-1 Board main fuse has undergone two failures within 6 months. These failures are most likely the result of voltage overloads that occurred early in testing of the system. Each fuse failure happened during testing of new circuitry within the system. Needless to say, the "new" circuitry obviously did not work and was updated. The fuse is actually a soldered-in picofuse and replacing it entails removing the Dascon-1 board from the PC and soldering in a new fuse.

A main board fuse failure reduces power to the Dascon-1 interface board. Symptoms include a loss of 5 volt signals at the appropriate outputs on the interface board and a reduction in brightness of the interface board LEDs.

The interface board and Dascon-1 main board will not function after a fuse failure; the result is a failure of the test system to operate after startup.

4. Stepper Motor Driver Failure:

Failure of the stepper motor driver was a problem during early testing of the system. The first drivers used were the IMS IB463 40 volt drivers. These drivers failed due to voltage overloads occurring due to the back emf generated by the stepper motor under certain conditions. This phenomenon is discussed more thoroughly in Section 3.8. At the present time an IMS IB104 driver with a 100 volt rating is used in conjunction with a driver overvoltage protection circuit. No driver failures have occurred since switching to this system.

Symptoms of a driver failure include the stepper motor failing to engage at the required test speed. A driver that fails due to an overvoltage caused by the stepper motor will usually not be able to run the stepper motor at all. If a driver failure occurs in this manner it may be the result of a failure of the driver overvoltage protection circuit. The driver must be replaced if this happens.

5. Sensitivity To Static:

The stepper motor testing system is not normally static sensitive. Sensitivity to static has been observed after disassembly and subsequent incorrect re-wiring of the grounds. Symptoms include a premature stepper motor phase break indication and a low torque reading after touching some metal part of the system. Correct wiring of the grounds (all A/D inputs utilized in conjunction with the low-level ground) has solved the problem, but it is generally not a good idea to expose the unit to static charges during the operation of a test.

6. 60 Hz. Interference:

The stepper motor driver power supply operates from 60 Hz. AC wall power. If the system is improperly grounded, this frequency will interfere will the stepper motor driver overvoltage protection circuit. The main symptom of this interference is a "test terminated" indication on the computer screen. A "test terminated" message indicates that the overvoltage protection circuit has terminated the test due to a possible driver overvoltage. The 60 Hz signal to the driver power supply can cause a false signal into the comparator on the driver overvoltage protection circuit if the system is improperly grounded. No false signals of this sort have been recorded with the unit properly grounded. Proper grounding in this case means that the driver power supply DC ground is connected to the driver power supply AC ground.

7. Stepper Driver 20000 Hz Interference:

The symptoms of interference from the stepper motor drivers 20000 Hz chopping frequency are identical to those of the interference from the 60 Hz wall power. The main circuit affected is the driver overvoltage protection circuit, and the cause is improper grounding. Once again, proper grounding of the driver power supply has eliminated this problem.

8. Stepper Motor Enable Failure:

Stepper motor enable failure is characterized by the stepper motor failing to lock into the required test speed after being driven to the test speed by the DC motor. This failure primarily happens when a small stepper motor (low torque) is driven to a high test speed (over 1000 RPM). The small motor may not have enough torque to lock into phase at the required RPM. The result is a very low torque reading for the motor.

Stepper motor enable failure has only been seen two times, both at the maximum system RPM and with a small stepper motor. Enable failure is not a result of the stepper motors inability to run at such a high RPM. The actual cause is the DC motor and the way in which it ramps the stepper motor up to each test speed. The DC motor ramps the stepper motor up to speed in a series of steps rather than by a perfectly smooth ramp. Therefore, the software is set up so that the DC motor always overshoots the desired test speed by a small amount. When a small stepper motor with low torque is suddenly enabled at the test speed when the DC motor is turning slightly faster than the test speed, the stepper motor must slow down the DC motor shaft speed slightly. In some small motors (with less than 25 oz-in torque as an estimate) this may cause a phase break before the DC motor even tries to load the stepper motor shaft. This type of failure has rarely occurred, though, and the author feels that it is of very minor concern. Of the two times in which this occurred, the system was operating at the limit of the systems speed capability (1500 RPM), and the failure was probably due in part to the DC motor possibly missing the desired stepper motor test speed due to its speed limitation (The DC motor is speed-limited by the Kepco power supply voltage).

The DC motor speed ramp variable, which sets the step speed increments in which the DC motor ramps the stepper motor up to speed, is not user-variable in order to prevent stepper motor enable failure. The speed ramp variable is set within the software to place the DC motor speed close enough to the desired test speed to avoid enable failure. A more detailed discussion of the DC motor speed ramp variable is presented in Section 2.4.

Failure modes due to human operator error are more likely to occur than machine failure modes. Human error failure modes are listed as follows:

1. Coupling Clamp Tightness
2. Frame Bolt Tightness
3. Failure Due To Improper Wiring
4. Too Large Or Too Small Stepper Motor
5. Incorrect Power-Up Sequence
6. Use Of Improper Stepper Driver
7. Improper Ground Connections
8. Improper Stepper Motor Rotation Direction
9. DC Motor Torque Ramp Too Large

1. Coupling Clamp Tightness:

At the beginning of each torque test the user is instructed to check the tightness of both coupling clamps and the adapter set screw to ensure that no shaft slippage exists. If a coupling clamp or set screw is loose at the start of a test, the test results become invalid. Symptoms of this are discussed above in the Machine Failure Modes section. Testing has revealed that this failure mode is rarely caused by machine error and is almost always caused by human error.

2. Frame Bolt Tightness:

After the stepper motor under test is placed in the frame, the frame bolts must be tightened by the user. Failure to secure the frame bolts will result in vibration which may invalidate the test data and will also result in possible relative shaft movement between the stepper motor shaft and the DC motor shaft. This relative movement will usually cause the software to signal a premature phase break and the resulting torque data will be invalid.

This failure mode may be avoided by properly securing all frame bolts after mounting the stepper motor in the frame. Once this is done, the frame bolts should not need to be retightened during the course of testing.

3. Improper Wiring:

Most of the wiring in the stepper motor torque testing system is fixed; only when a stepper motor is removed or replaced in the system or when a new current limiting resistor is placed in the driver does the potential exist to disturb the wiring.

Care should be exercised when wiring the stepper motor phase leads into the driver. The user will not actually have to disconnect any system wiring, but the potential exists to accidentally disturb the wiring due to the close proximity to the driver.

When a new current limiting resistor is placed in the driver, it must be connected to the negative power supply side of the driver. This terminal on the driver also contains a ground wire as well as the negative power supply terminal.

If the power supply wire is accidentally left loose, the stepper motor will not enable during the test. In this case it is usually obvious that something is wrong. However, if the ground wire is left off accidentally, the tester will still give repeatable and seemingly valid results but they may actually be inaccurate due to the presence of a floating ground in the stepper motor driver - power supply network. This failure mode is important because it is usually not an obvious problem - until the test stops due to a driver overvoltage error.

A loose ground wire on the stepper motor driver significantly lowers the threshold voltage required to trip the driver overvoltage protection circuit.

The end effect of a loose ground wire on the driver will therefore be a driver overvoltage error occurring at a very low RPM - usually as low as 10 RPM. Driver overvoltage errors usually only occur with large stepper motors at or above 1000 RPM in acceleration mode or, at or above 100 to 300 RPM in braking mode with average size stepper motors. An overvoltage error occurring well outside these boundaries usually signals the presence of a loose ground wire.

4. Stepper Motor Too Small Or Too Large:

The size range for stepper motors that may be tested ranges from 20 oz-in as a lower boundary to 400 oz-in as an upper boundary. A stepper motor with torque capabilities outside this range will cause either invalid data to be reported or a general failure of the test system to complete the test.

If too small a stepper motor is tested, the DC motor internal friction torque may exceed the pull-out torque of the stepper motor under test. If this occurs, torque data will be recorded but it will be inaccurate. The only symptom of this may be a stepper motor enable failure. An enable failure will occur when the stepper motor fails to lock into phase at the required test speed. This condition is hard to detect, but usually an experienced user will notice that the stepper motor is not locking into phase by the sound of the system.

If too large a stepper motor is introduced into the system, the DC motor may not have enough torque to break the phase of the stepper motor. As the DC motor ramps up the torque applied to the stepper motor shaft, the A/D converter constantly looks for a stepper motor phase break. If the DC motor cannot break the phase of the stepper motor, the DC motor's programmable Kepco power supply will hold the DC motors output torque constant once the DC motor torque reaches the maximum attainable value (this value corresponds to the point of maximum power supply output current). The software will now be caught in a loop because the A/D will never sense a phase break and the system will stay this way until the user steps in. Symptoms of this failure mode include the DC motor and stepper motor spinning at constant speed with no change while the Kepco power supply voltage is stopped at the limit.

Since stepper motor pull-out torque usually decreases with speed, the user may elect to manually help the DC motor overcome the stepper motor torque until the stepper motor torque drops below the DC motors maximum output level. If the system is turning slowly enough, the user may manually break the phase of the stepper motor by applying an external torque to the shaft in the direction of the DC motor's applied torque. This will not allow the system to provide accurate torque data at the aforementioned speeds, but once the system attains a level at which the DC motor torque is greater than the stepper motor torque the test may proceed as usual.

5. Incorrect Power-Up Sequence:

Whenever a torque test is started from a zero-power state the user must go through a power-up sequence that involves turning on the computer and both power supplies. A fixed sequence must also be followed when starting a torque test with all power already on. Failure to follow these sequences will result in erroneous data or possible damage to the system.

Failure to follow the starting sequence from zero-power (everything turned off) may result in the DC motor suddenly overspinning the stepper motor if the DC motor power supply is turned on at the wrong time. Under these conditions, the driver overvoltage protection circuit will not stop the DC motor since the software is not running. The stepper motor driver may consequently fail if a large enough stepper motor is connected in the system and an incorrect power-up sequence occurs.

Failure to follow the operating sequence of the software once the system is turned on and the software is running may cause the stepper motor driver to engage the stepper motor in "wave drive" mode. This failure mode will occur if the driver power is not disconnected and reconnected at the appropriate times during the test initialization before the actual torque test starts. The capability to test in wave drive mode has not been included in the software because of the difficulty in achieving and verifying operation in this mode and also because stepper motors are rarely run in this mode in practice.

Wave drive mode is engaged by the stepper motor driver in this manner: when "full step" mode is selected with the driver in an even numbered state, wave drive mode is engaged. If the correct sequence in the software instructions is not followed at the beginning of a torque test, wave drive mode may be accidentally engaged at the following times: 1- When switching from half to full step mode between tests with all power on, 2- Upon start of the test with full step mode selected, and 3- After performing a holding torque test.

It is important that the software instructions be followed exactly, because wave drive mode cannot be detected by any external means. The driver does not indicate which mode it is in and if the voltage across the half/full step input is checked, it will indicate that the driver is in full step mode. Wave drive mode produces torque readings much less than that of full step mode, which is the mode that the user will think the stepper motor is being tested in. Wave drive mode has a fifty-fifty chance of engaging if the software instructions are not followed properly.

6. Use of Improper Stepper Motor Driver:

The stepper motor torque testing system is designed to utilize an IMS IB104 stepper motor driver with a 100 volt rating. Many applications utilize the popular IMS IB463 driver rated at 40 volts. The IB104 and IB463 drivers are similar except for their voltage ratings, and it is probably not worth it to substitute the IMS IB463 in place if the IB104, as the torque characteristics of a stepper motor with either driver should be the same provided the driver output current and the driver power supply input voltage are the same for both conditions. In order to simulate the IB463 driver using the IB104 driver, the IB104 driver will have to be operated at the same voltage as the IB463 driver (40 volts maximum). The driver overvoltage circuit will still work for this condition, since the IB104 driver is not in any danger until the 100 volt limit is reached.

If the IB104 is replaced with an IB463, the driver overvoltage protection circuit will have to be recalibrated for 40 volts instead of 100 volts as it is presently set. Recalibrating this circuit is a touchy procedure - the overvoltage circuit utilizes high resistances and the system circuit characteristics change slightly when the circuit is connected to the rest of the system. A recalibration of the comparator trip voltage - the voltage that the comparator compares a fixed internal voltage to - can be performed, but this voltage changes slightly when the circuit is introduced into the system. This caused much confusion in the early stages of the circuit design.

If the IB463 driver is introduced into the system with no recalibration of the circuit (see Appendix G) the driver will possibly fail do to an overvoltage condition.

7. Improper Ground Connections:

The wiring diagram of Appendix I shows the correct wiring for the grounds. In the event of any disassembly of the system, the ground connections will have to be reconnected. It is very important that the grounds are installed in **exactly** the same locations as in the diagram.

The stepper motor torque testing system utilizes three different ground levels, two of which are tied together, for a total of two independent ground levels consisting of a power ground and a low-level ground. With respect to grounding, the following was observed but not explained: If a ground wire is mistakenly connected to the wrong ground, the test system will exhibit very unstable characteristics. Symptoms of a misplaced ground wire include sensitivity to static electricity (system stops when someone touches it), premature detection of stepper motor phase break (system stops and a low torque reading is presented), premature triggering of the driver overvoltage circuit, and, if none of the above happen (which is doubtful), the torque data will probably be inaccurate.

In the event that any of the aforementioned symptoms occur, a probable cause is an improper ground in the system.

8. Improper Stepper Motor Rotation Direction:

The stepper motor test system is set up to test stepper motors while rotating in a clockwise direction when viewed from the front. In following the instructions the user is directed to connect the stepper motor to the driver in such a manner as to cause clockwise rotation. In the recommendations a method is suggested to automatically accomplish this, but it has not been implemented at the present time.

If a stepper motor is accidentally connected in such a manner as to cause counterclockwise rotation, upon enable the stepper motor will try to back-drive the DC motor and no valid torque data will be collected. This problem is easily circumvented by following the instructions concerning the stepper motor hook-up presented in Appendix A.

9. DC Motor Torque Ramp Too Large:

The DC motor torque ramp variable is a user-dependent variable that varies the ramp steepness of the DC motor output torque application on the stepper motor shaft. This variable provides the user with a compromise on test speed and accuracy.

Selecting this variable too large can significantly reduce the accuracy of the system. This accuracy reduction as a percentage of the stepper motor output torque is dependent upon the stepper motor size as well as the value of the ramp variable. Using the recommended value of 5 almost always produces an acceptable combination of speed and accuracy. Section 4.2 discusses the accuracy with respect to this variable in more detail, but suffice it to say that if this variable is selected too large (how large is "too large" is left up to the user) accuracy will be compromised.

4.5 RECOMMENDATIONS

The following recommendations are presented in order to suggest possible improvements in the design and operation of the stepper motor torque testing system. These recommendations are listed as follows:

1. Use Of A High Speed A/D
2. Use Of A Clamp-Type Adapter
3. Driver Overvoltage Protection
4. Automatic Stepper Motor Rotation Initialization
5. Driver Variable Resistor
6. Driver Power Supply Switch

1. Use Of A High Speed A/D:

The A/D converter used to measure the DC motor current and to check for stepper motor phase break has a sampling rate of 30 samples per second. While this does not introduce any significant error into the system, it does allow the DC motor to slightly backdrive the stepper motor after phase break. During this time vibration is transmitted to the frame and surroundings. A high speed A/D would allow the system to power down closer to the instant of phase break resulting in less noise and vibration in the system. Also, a high speed A/D would more readily permit the use of a faster programming language if the speed of the test system ever becomes a concern.

2. Clamp-Type Coupling Adapter:

The DC motor shaft adapter utilizes a set screw to firmly attach itself to the DC motor shaft. This set screw has never loosened during a test after being properly tightened, and has in fact lasted through many torque tests without needing to be retightened. However, this set screw is exposed to a reversing load with vibration, conditions which usually mandate a clamp-type coupling. Although the set screw has not been a problem so far, replacing it with a clamp-type adapter would be good design practice and would greatly reduce any chance of future problems.

3. Stepper Driver Overvoltage Protection:

The present stepper motor driver overvoltage protection relies on a circuit which directly senses any driver overvoltage condition and signals the software to immediately shut down the DC motor. In this manner the stepper motor is prevented from causing a driver failure due to a large back-emf. This circuit/software combination works very well and has never failed under testing.

The only shortcoming of this overvoltage protection system is that the software must be on for it to work. Nothing is in place to protect the driver if someone should happen to accidentally turn on the DC motor power supply without first running the software. If this occurs the DC motor may suddenly accelerate to its maximum speed. If a stepper motor is connected into the system when this happens, there is a chance that a driver failure might occur.

A more permanently reliable solution would be to incorporate an overvoltage protection circuit which would directly limit the driver voltage to its rated boundary regardless of the DC motor speed and independent of any software. While this is a good idea, in practice it may be difficult to implement and the time and effort required might not be justified.

4. Automatic Stepper Motor Rotation Initialization:

When first connecting a stepper motor into the test system, the user must check to see if the stepper motor rotates in the right direction for the test system. A preliminary program which runs the stepper motor only is referenced in the instructions and is included with the test system. If the stepper motor does not run in the correct direction, the user must reconnect the phase leads to change the direction of rotation. This is done at the phase leads because an output to the stepper motor driver's clockwise / counterclockwise input is not present.

An alternative which would save time and which would further automate the system is described as follows: First, connect an output from the PC printer port to the CW/CCW input on the stepper motor driver. Once the stepper motor is connected into the system, the software would, at the beginning of the test, rotate the stepper motor. Based on the sign of the DC motor tachometer voltage, the software would output to the driver either to change the direction of rotation or to allow it to remain the same. This procedure would involve some changes to the software, especially in the areas in which the PC printer ports are already utilized.

5. Stepper Driver Variable Resistor:

The stepper motor driver relies on an external current limiting resistor to limit the output torque of the stepper motor which it drives. In order to change this resistor, a screw terminal must be loosened which also contains a ground wire and a power supply wire. Reconnection of these three wires into one common screw terminal is tricky and invites problems if not done with care.

An alternative solution is to incorporate an externally variable resistor into the stepper motor driver terminals so that no wire removal is necessary to change the driver current output. Any chance for a loose driver connection would be greatly reduced and changing the driver output current would be simplified when necessary.

6. Driver Power Supply Switch:

When the software for performing a torque test is first started, the user is instructed to disconnect the driver power to ensure proper mode selection. Since the driver power supply did not come with an on/off switch, it must be unplugged at this point. Incorporating a manual switch for the driver power supply would ease this part of the test procedure. This recommendation may be taken one step further by incorporating a relay into the power supply and actuating it at the appropriate times automatically through the software to reset the driver. A relay utilized as such would serve to increase the level of test automation and would further reduce user responsibility.

4.6 EFFECT OF COUPLING

The coupling between the DC motor and the stepper motor can have a large effect on the measured stepper motor torque data. No data on this subject has been collected while using the torque characterization system. Kenjo (4) illustrates the effect of different couplings on the measured pull-out torque of a stepper motor. These coupling effects are shown in Figure 4.1. Due the differences in vibration-transmitting properties of various couplings, stepper motor resonance points will vary between different couplings. As such, the stepper motor under test will tend to exhibit different dynamic torque characteristics with different couplings. The user of the torque characterization system, when trying to model a stepper motor's actual operating environment, should try to use the same coupling in the test system as is used in the actual operating environment.

4.7 TYPICAL TORQUE CURVES

Section 4.7 provides some typical stepper motor pull-out torque curves that were generated using the stepper motor torque characterization system. Figure 4.2 shows typical torque curves for a stepper motor tested twice under the same conditions in order to examine system repeatability. Figure 4.3 shows a typical stepper motor torque curve when tested in both half-step and full-step mode, with an acceleration mode test. Figure 4.4 compares the difference in typical torque data between acceleration mode and braking mode for a stepper motor, with all other variables equal. The particular stepper motor tested in Figure 4.4 exhibits oscillatory torque characteristics above about 300 RPM in acceleration mode. It is interesting to note that these oscillations disappear somewhat in braking mode. Figure 4.5 illustrates how half-step mode and full-step mode can affect the resonance characteristics of a stepper motor in acceleration mode. Figure 4.6 illustrates how typical torque curves may vary in braking mode, with both half-step and full-step mode engaged.

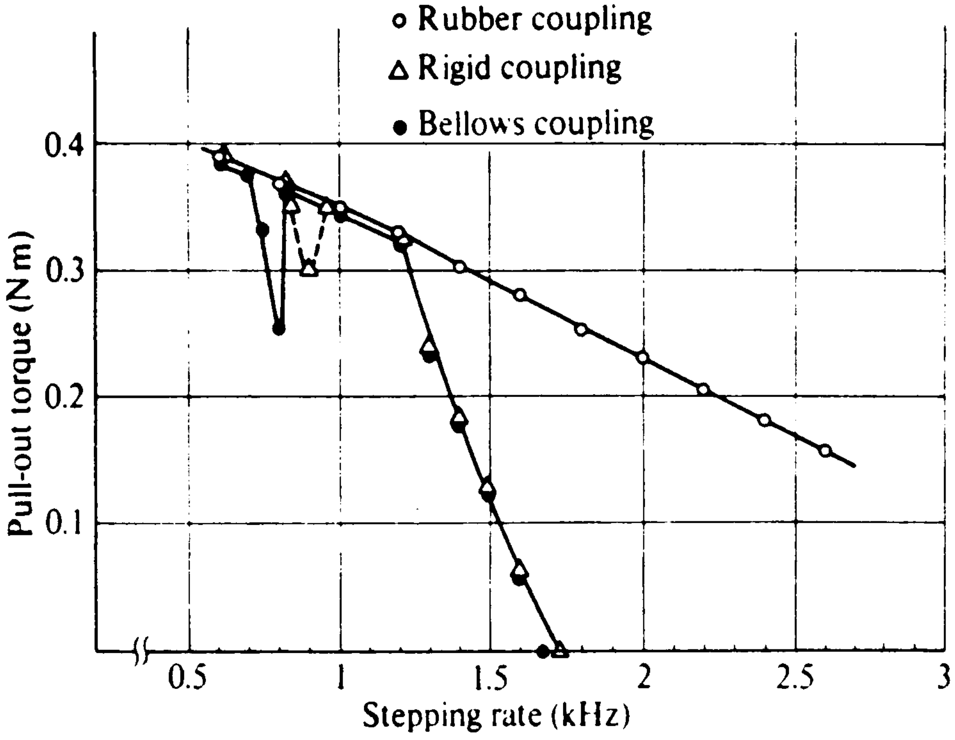


FIGURE 4.1 Effect Of Coupling On Torque Data (4).

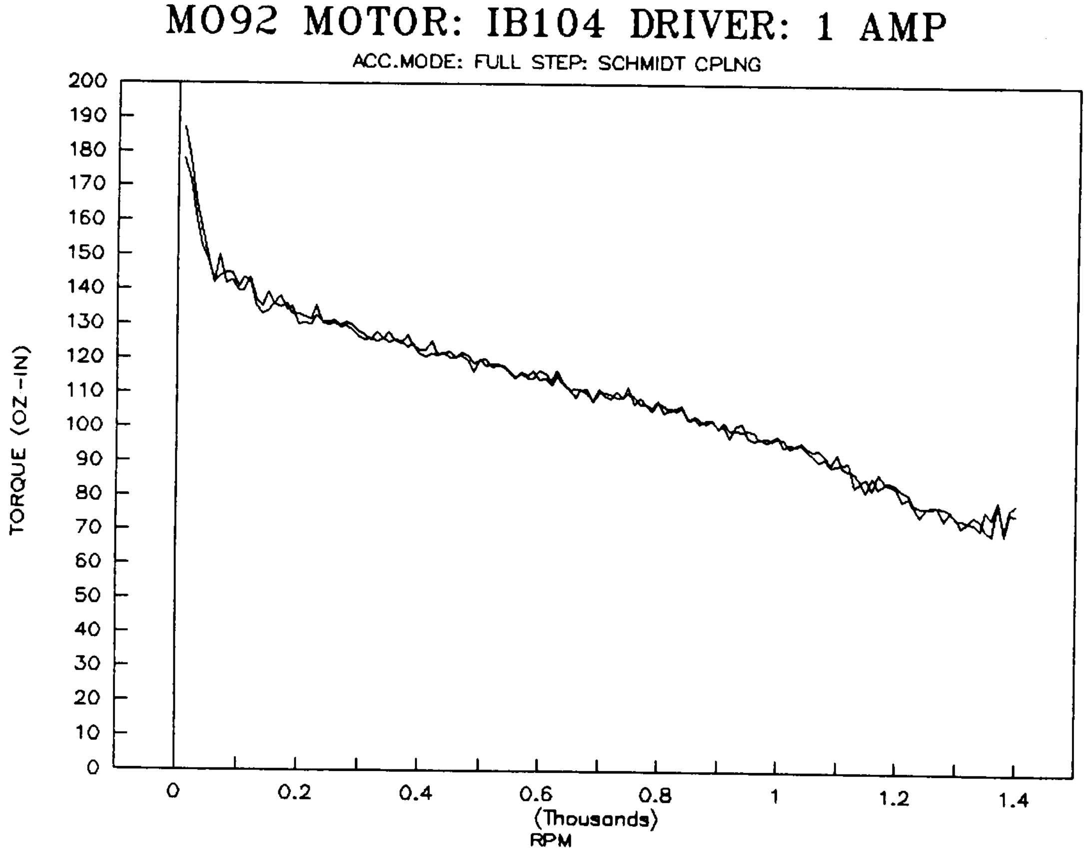


FIGURE 4.2 Repeatability Test.

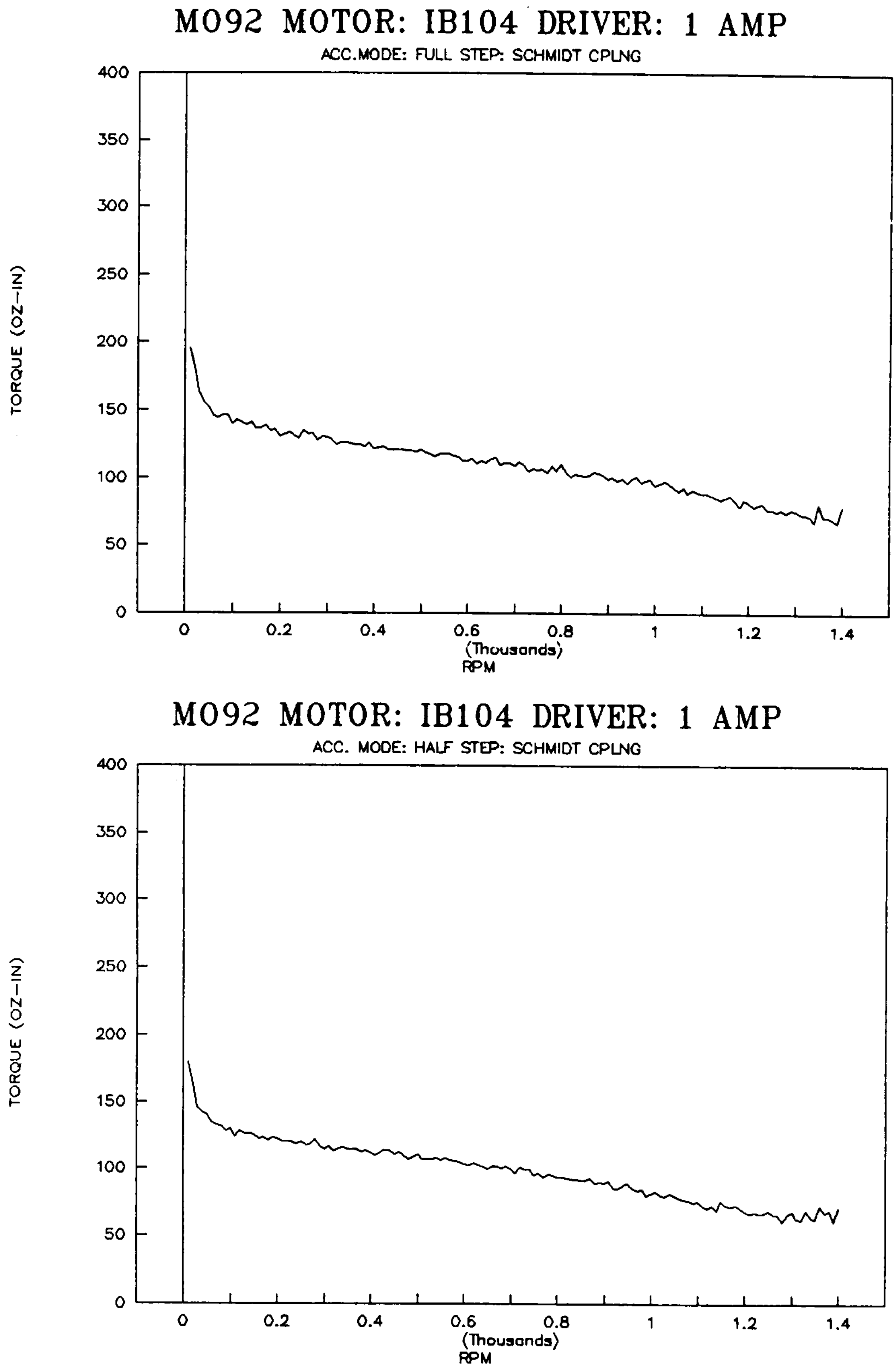


FIGURE 4.3 Comparison Of Acceleration Mode Half And Full Step Mode.

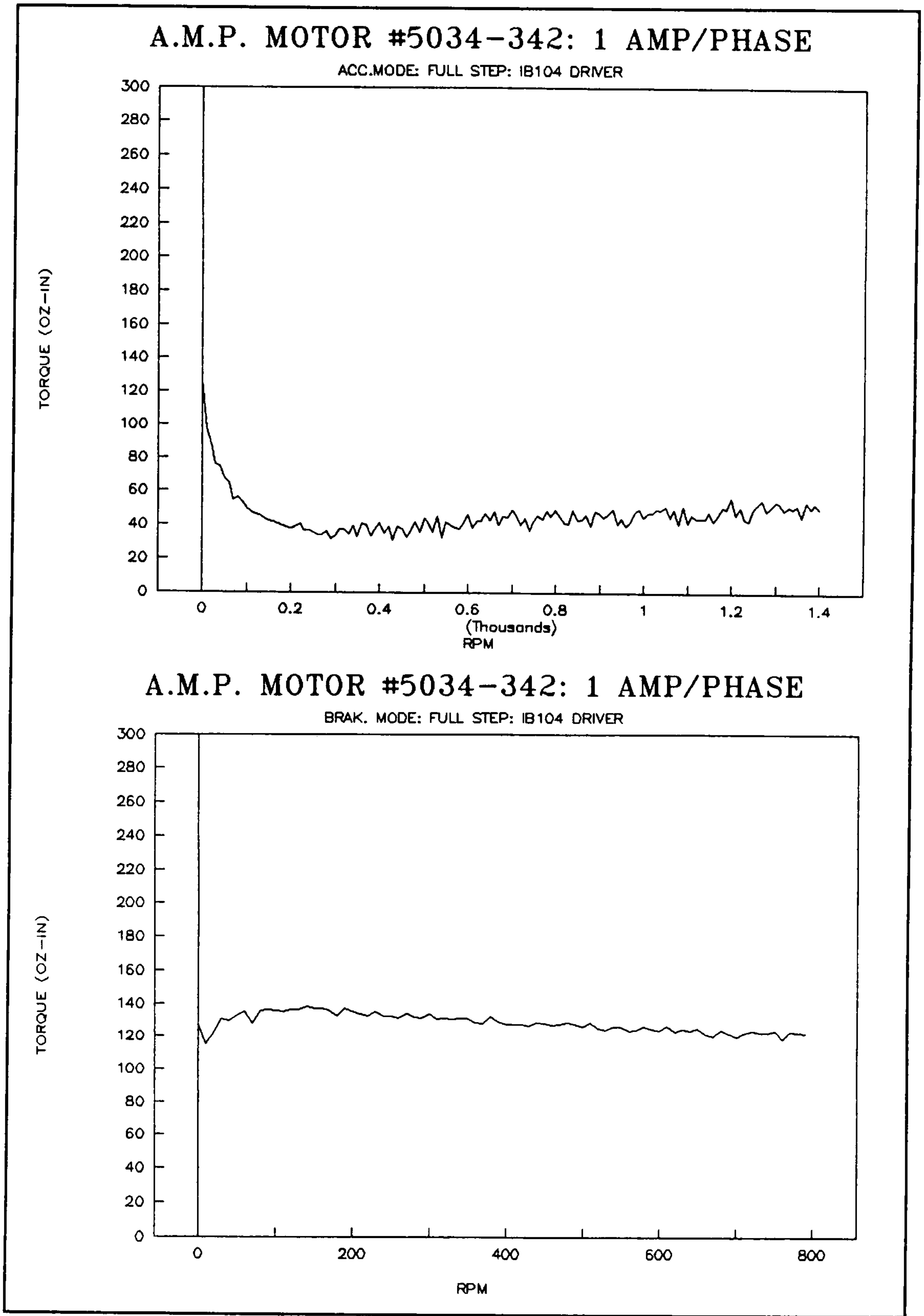


FIGURE 4.4 Comparison Of Acceleration And Braking Mode.

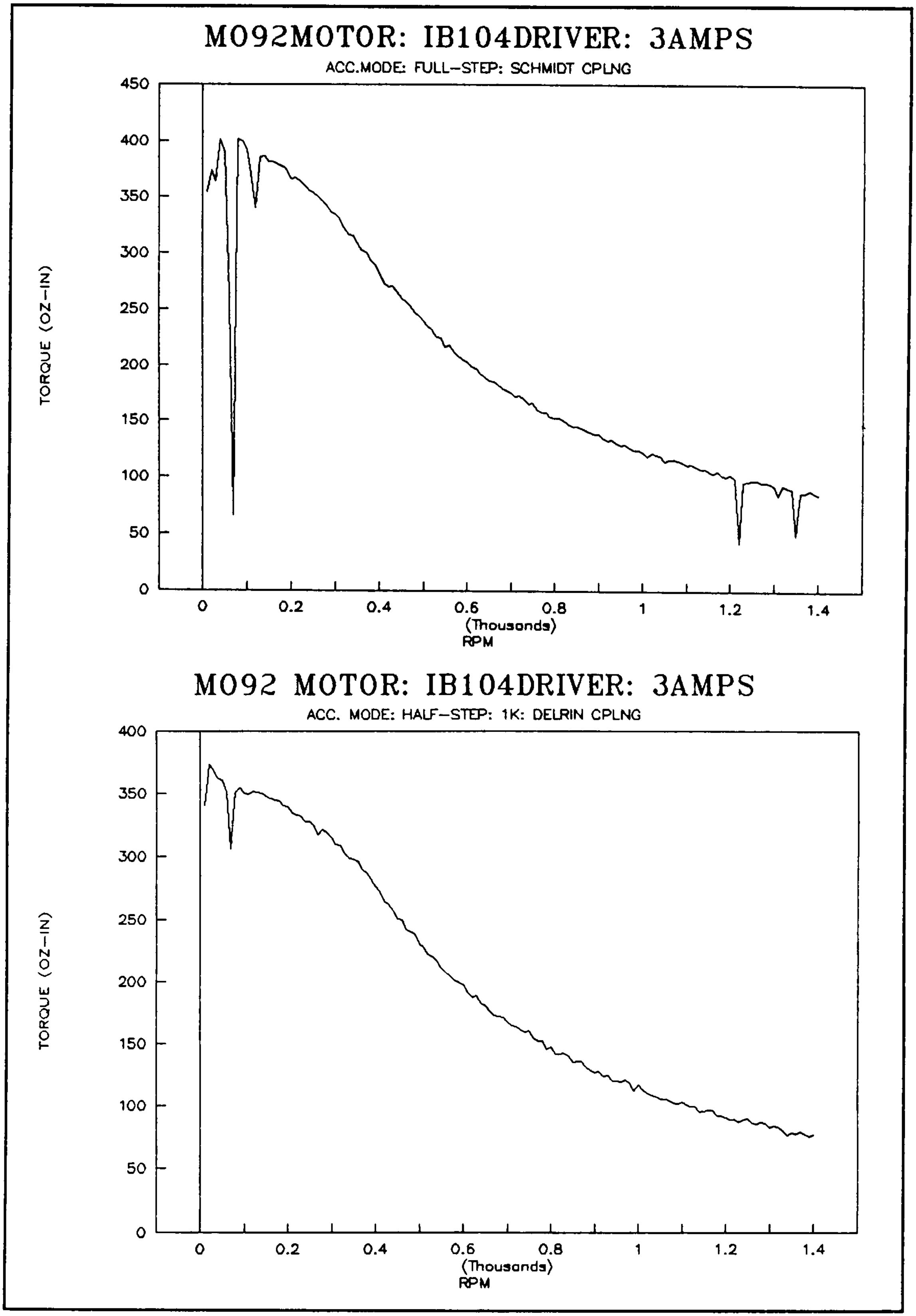


FIGURE 4.5 Resonance characteristics / Half and Full Step Mode.

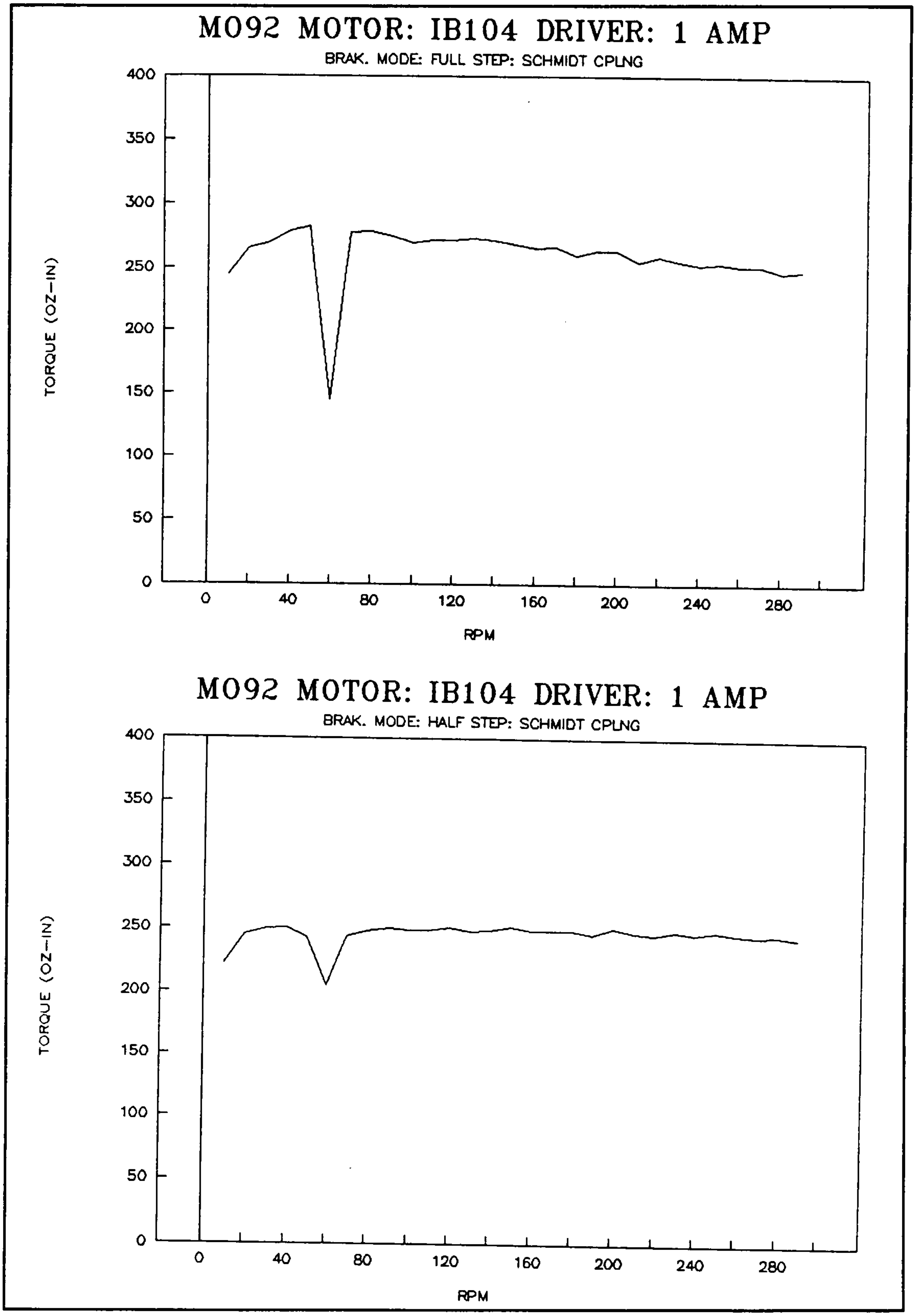


FIGURE 4.6 Comparison Of Braking Mode Half And Full Step Modes.

LIST OF REFERENCES

LIST OF REFERENCES

(1) Bipolar Operational Power Supply Manual, Kepco, Inc., 1979.

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(3) Dascon-1 Manual, Metrabyte, Inc., 1983.

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(5) Walker, Peter. Direct Current Motors - Characteristics And Applications. Pennsylvania: Tab Books, 1978.

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(7) Lancaster, Don. CMOS Cookbook. Indiana: Howard W. Sams, 1977.

APPENDICES

APPENDIX A

INSTRUCTIONS FOR USE

The following set of instructions is provided to guide the user in set-up and operation of the stepper motor torque testing system. Other sections and appendices of this Thesis are referred to occasionally in case the reader/operator requires more in-depth knowledge about the torque testing system. Starting from the beginning, these instructions assume that the reader is a first time user of the system. Consequently, the experienced user may elect not to follow the instructions from beginning through end. Also, if the stepper motor to be tested is already properly fastened and wired into the system, steps 1 through 6 may be skipped.

Instructions:

Step 1: External Wiring

Check the system for proper external wiring. This step may be skipped if the system is known to be operational. If the system has been moved or taken apart, it is a good idea to make sure that all interconnections between parts are in place correctly. Refer to Appendix I for all external wiring diagrams.

Step 2: System Startup

Ensure that the Kepco programmable power supply is turned off and that the stepper motor driver power supply is turned off. Turn on the computer and access the Dascon directory. The 8 red LEDs' and the 4 yellow LEDs' in the Dascon-1 interface board should turn on automatically with the computer. If not, refer to the troubleshooting guide. Do not, under any circumstances, turn on the Kepco programmable power supply at this point. Doing so may cause a stepper motor driver failure.

Step 3: Stepper Motor Mounting

The stepper motor to be tested should now be securely mounted into the frame and coupled to the DC motor. 4 bolts hold the stepper motor in its mount, while another 4 bolts hold the mount/guide plat assembly to the base plate. All bolts should be securely tightened to prevent vibration during the test. The stepper motor shaft attaches to the DC motor shaft via a clamp-type coupling. The coupling attaches to an adapter mounted on the DC motor shaft. Ensure that both screws in the clamp coupling are tight so that no shaft slippage can occur. Also ensure that the set screw on the DC motor shaft adapter is tight on the DC motor shaft.

Step 4: Stepper Motor Wiring

Wire the stepper motor into the stepper motor driver. 4 leads from the stepper motor connect to the phase outputs on the stepper motor driver. A test will be run next to determine the proper direction of rotation for the stepper motor.

Step 5: Stepper Motor Rotation Direction

The torque testing system tests the stepper motor in one direction of rotation only. The stepper motor must now be initialized to turn in the proper direction.

With the PC turned on, apply power to the stepper motor driver power supply. From the Dascon directory in the PC, access and run the BASIC program TEST9.BAS. The first prompt the program will ask is:

```
Desired Configuration Number <0-5>?
```

Enter a 1 for the desired configuration number. The next prompt the program will ask is:

PB Output Data <0-255>

Enter 255 for the PB output data. The final prompt the program will ask is:

PC Output Data <0-15>

Enter 15 for the PC output data. When this is entered, all 12 LEDs' in the Dascon-1 interface board should remain on and the stepper motor will run for about 3 seconds. Observe the direction of rotation of the stepper motor shaft looking at the stepper motor's front face (the face that is towards the DC motor). The DC motor/stepper motor shaft should turn clockwise. If the shaft turns counterclockwise, alter the phase wiring by reversing the wires going into one phase of the driver until the motor shaft turns clockwise. To re-observe the stepper motor's rotation, rerun the TEST9.BAS program. When the shaft turns clockwise, proceed to the next step.

Step 6: Power Supply Settings

The stepper motor driver power supply should now be turned off. The Kepco programmable power supply should remain off at this point. The main switch for the Kepco power supply is located on the left side of the front panel. Next to the main switch is the "voltage control" switch. This switch should be set to the "off" position. When on, the voltage control switch allows manual control of the DC motor voltage by adjusting the potentiometer located below the switch. At the top center of the front control panel is a "mode" switch. This switch should be set to "voltage". The mode switch switches the programmable power supply between constant voltage and constant current mode. The stepper motor torque testing system has been designed to utilize the programmable power supply in constant voltage - variable current mode only.

Step 7: Software Operation

With the stepper motor now in place and all wiring and settings in the correct positions, the torque test may be started. The first step is to access and run the BASIC program STEPPER1.CGM from the PC's Dascon directory. The user is first instructed to turn off the stepper motor driver's power supply. The screen will say:

> "The stepper motor driver should be unplugged at this point to ensure proper mode selection later."
>
> "Unplug driver and hit any key to continue."

Periodically during the test set-up the user will be instructed to turn off and then turn back on the driver power supply. This sequence is done in order to ensure that the driver properly selects the mode (full-step or half-step) requested by the user later on. If this step is omitted, the driver may improperly select "wave drive" mode. Wave drive mode cannot be distinguished from full-step mode by checking driver settings or voltages. The user will never know if wave drive mode has been selected, as the stepper motor will behave as if it is in full-step mode. However, stepper motor output torque will be significantly reduced, causing invalid torque data for the required conditions.

With the driver powered down, the software asks if torque data is to be written to disk. The screen will appear as follows:

> "DO YOU WANT DATA READ TO THE A:DRIVE DISK? (Y/N)"

If yes, then the software will prompt the user to insert a disk into drive A and will write the torque data vs. RPM to the A:Drive disk as well as to the screen. Torque data written to the disk will be stored in a file called TORQUE.PRN. This file format is compatible with LOTUS123. The torque vs. RPM data will be written to the screen only if the user selects "no" for this prompt.

The user is next prompted to enter the DC motor torque ramp variable. An explanation of the DC motor torque ramp variable will appear on the screen, as follows:

"The DC motor ramp variable controls the rate of change of torque applied to the stepper motor shaft. The DC motor does not apply a perfectly linear ramp torque to the stepper motor's shaft; rather, it increments the torque up in a series of steps. This step size is set by the DC motor torque ramp variable."

"A numerically small ramp variable results in a small step increment of the applied torque. This step size results in greater accuracy of the test results but the test will take a longer time to complete. A numerically high ramp variable results in reduced accuracy and increased speed. See the instructions for a table of recommended ramp values."

"A ramp variable of 5 usually produces an acceptable combination of speed and accuracy."

"ENTER THE DC MOTOR RAMP VARIABLE (INTEGER)".

This variable controls how fast the DC motor increments the torque applied to the stepper motor shaft. The numerical value of the DC motor ramp variable entered here corresponds to the step change in the D/A converter's output, in bits, which goes into the Kepco power supply. The recommended value to enter here is 5; this will allow the test to proceed at a reasonable rate while maintaining good accuracy. System accuracy vs. the DC motor torque ramp variable is presented in Table 4.1. This information is reprinted here for convenience. Sections 2.4 and 4.2 contain more detailed information on this variable including how it controls the Kepco programmable power supply output and its effect on the overall system error.

System Errors

DC Motor Torque Ramp Variable (D/A Output in Bits)	Ramp Variable Error (oz-in)		System Error (oz-in)	
1	+0.00	-0.49	+1.47	-1.96
2	+0.00	-0.98	+1.47	-2.45
3	+0.00	-1.48	+1.47	-2.95
4	+0.00	-1.98	+1.47	-3.45
5	+0.00	-2.47	+1.47	-3.94
6	+0.00	-2.97	+1.47	-4.44
7	+0.00	-3.46	+1.47	-4.93
8	+0.00	-3.95	+1.47	-5.42
9	+0.00	-4.45	+1.47	-5.92
10	+0.00	-4.94	+1.47	-6.41
11	+0.00	-5.44	+1.47	-6.91
12	+0.00	-5.93	+1.47	-7.40
13	+0.00	-6.43	+1.47	-7.89
14	+0.00	-6.92	+1.47	-8.39
15	+0.00	-7.41	+1.47	-8.88
20	+0.00	-9.89	+1.47	-11.35
25	+0.00	-12.36	+1.47	-13.82
50	+0.00	-24.72	+1.47	-26.18

The ramp variable error is the error component contributed to the system error by the DC motor torque ramp variable. The system error is the maximum error that the user may expect to have when using the torque testing system.

After the ramp variable has been entered, the system will ask if a holding torque test is required for the stepper motor with the following prompt:

"IS A HOLDING TORQUE TEST REQUIRED? (Y/N)"

If a holding torque test is not required, the holding torque test sequence is skipped and the software proceeds to the dynamic torque test. If a holding torque test is required, the user is prompted to reconnect the driver power supply power and to disconnect the step clock input on the stepper motor driver as follows:

"RECONNECT POWER TO THE STEPPER MOTOR DRIVER."

"HIT ANY KEY TO CONTINUE."

"DISCONNECT THE STEP CLOCK INPUT TO THE STEPPER DRIVER."

"HIT ANY KEY TO CONTINUE."

When this is done, the holding torque test will commence and the measured holding torque will be displayed on the screen and on the disk if required. The user is now prompted to reconnect the step clock input on the stepper motor driver, disconnect and then reconnect the driver power supply as follows:

"RECONNECT STEP CLOCK INPUT ON DRIVER, DISCONNECT DRIVER POWER AGAIN AND HIT ANY KEY TO CONTINUE."

"RECONNECT DRIVER POWER AT THIS TIME TO ENSURE PROPER DRIVER INTERNAL MODE SELECTION."

The software will now prompt the user to enter the parameters for the dynamic torque test.

The first prompt for the dynamic torque test requires the user to select either acceleration or braking mode as follows:

"ENTER 1 FOR ACCELERATION MODE; ENTER 2 FOR BRAKING MODE."

In acceleration mode, the DC motor behaves as a brake and applies torque to the stepper motor shaft in a direction opposite of the stepper motor's shaft rotation. This mode simulates the stepper motor trying to accelerate a load.

In braking mode, the DC motor acts as a motor and applies torque to the stepper motor shaft in the direction of rotation of the stepper motor shaft. Braking mode simulates the stepper motor's ability to slow down, or decelerate, a moving load.

The user may now select either full-step mode or half-step mode for the stepper motor driver as follows:

"ENTER 1 FOR FULL-STEP MODE OR 2 FOR HALF-STEP MODE."

The IMS drivers have the capability for wave drive mode, but this mode is rarely ever used and cannot be accessed directly by the torque testing system.

The user should now enter the starting RPM for the dynamic torque test.

"ENTER THE STARTING RPM (INTEGER 3 OR GREATER)."

This number should be an integer 3 or greater. If a number less than 3 is entered, the test will automatically start at 3 RPM. The finishing RPM should also be entered as an integer less than 1500.

"ENTER FINISHING RPM (INTEGER 1500 OR LESS)."

If an integer is not entered for either the starting or finishing RPM, the software will round the selected number to the nearest integer. 1500 RPM is the maximum speed attainable by the DC motor; entering a finishing RPM greater than 1500 may cause the test sequence to hang up. Never enter a finishing RPM that is less than the starting RPM; the torque testing system tests from lower speed to higher speed only. If the dynamic torque test is instructed to start at a high RPM and finish at a lower RPM, the stepper motor may fail to engage at the desired speed during the test due to the relay on the stepper motor control circuit not switching at the appropriate time.

The next prompt is for the user to enter the number of steps per revolution for the stepper motor being tested, as follows:

"ENTER THE STEPPER MOTOR STEPS PER REVOLUTION."

The final prompt is for the test RPM increment, as follows:

"ENTER THE TEST RPM INCREMENT (INTEGER 2 OR GREATER)."

The test RPM increment determines the step size between data points tested. For example, suppose the starting RPM is 10, the finishing RPM is 200, and the test RPM increment is 10. The system will test 20 data points, starting at 10 RPM and finishing at 200 RPM.

After the test RPM increment is entered, the test system software will begin the dynamic torque test after 2 - 15 seconds. The torque data will appear on the screen and will also be written to the A:Drive disk if requested. Torque data written to the disk is stored in a file called TORQUE.PRN, compatible with Lotus123.

The dynamic test is fully automatic. Each data point tested takes from 7 to 15 seconds, depending on the stepper motor's output torque and the value selected for the DC motor ramp variable. For each data point, the DC motor drives the stepper motor to the required speed, the test system locks the stepper motor into phase at the required speed, and then the DC motor begins incrementally increasing its applied torque to the stepper motor shaft. When phase break occurs, the system powers down to zero RPM, torque data is displayed, and the system starts over at the next data point. When the test has been completed, the user should turn off the Kepco programmable power supply and power down the driver power supply. Upon beginning another test, if the same stepper motor is tested again with the same phase wiring into the driver, step 5 may be omitted.

APPENDIX B

TROUBLESHOOTING GUIDE

This appendix covers many problems, both common and uncommon, that the user may experience while using the stepper motor torque testing system. These problems usually manifest themselves as a symptom or unusual occurrence: thus, it is left up to the user to correctly identify the symptom. This guide serves as a reference for identifying the possible problems and solutions for many given symptoms. It should be realised that, as with any complicated system, problems may arise that have more than one solution or probable cause. Thus, some degree of intuitive thought is usually required in addition to this writing. Once the problem has been correctly identified, the user should proceed to the section or appendix in this writing that describes in detail the area of concern.

Troubleshooting Guide

Symptom	Problem	Possible Solution
No power in interface board: All LEDs' out or dim.	Fuse in Dascon-1 main board. Loose connector cable to PC.	Replace fuse as instructed in Metrabyte manual. Reattach cable.
Driver overvoltage error during motor ramp up.	Test RPM too high. Incorrect driver power supply in place.	Reduce finishing test RPM if further testing is required with the same motor. Replace power supply with 80 - 88 volt supply or recalibrate the overvoltage protection circuit. It is much easier to use the correct power supply.

Symptom	Problem	Possible Solution
Driver overvoltage error at unusually low (inconsistent) DC motor output torque or speed. The level of DC motor output torque may be seen from the current meter on the Kepco power supply.	Noise in system. (Not very common)	Check and adjust location of AC lines and/or stepper motor phase wiring and/or stepper motor driver wiring. Also check for an incorrect ground wire.
	Driver power supply.	Check that driver power supply voltage is not over 88 - 89 volts. (Should rarely or never happen)
	Static discharge or presence of voltmeter in circuit while test is running.	Avoid touching circuitry during testing in static-weather conditions. Do not attempt to use a voltmeter on the overvoltage circuit or power supply voltage divider when running a torque test.
	Incorrect grounding of components.	See Appendix I for correct wiring and grounding diagrams.
	Driver overvoltage circuit.	Check for correct operation. Check comparator in circuit. Must use a high impedance meter for best results. Do not test while connected to the torque testing system, because the presence of a meter will possibly (usually) affect operation. See Appendix G.

Symptom	Problem	Possible Solution
Driver overvoltage error during applied load.	Combination of motor speed and output torque too great, most likely in braking mode.	Reduce finishing test RPM if further testing is required with the same motor.
	Incorrect driver power supply in place.	System is calibrated for an 80 - 88 volt unregulated supply. Replace supply or recalibrate overvoltage protection (Appendix G).

Symptom	Problem	Possible Solution
Stepper phase break occurs with an unusually low torque reading.	Stepper motor resonance.	No solution needed. Torque readings should increase after resonance stops.
	Loose set screw on clamp coupling or shaft adapter.	Tighten set screw. If set screw remains loose, torque readings will remain low and/or inconsistent.
	Loose frame bolts allowing movement of the stepper motor.	Tighten frame bolts.
	Improper ground connection in system wiring.	Check wiring; refer to Appendix I.
	Improper system software startup. Driver may be in "wave drive" mode.	Start test again, pay careful attention to the stepper motor driver power supply power-off and power-on sequences.

Symptom	Problem	Possible Solution
Stepper motor fails to enable after being driven to speed by the DC motor.	Stepper driver inputs or outputs burned out.	Replace driver.
	Test RPM too high.	Reduce finishing RPM. Make sure the finishing RPM > starting RPM.
	DC motor speed ramp variable in software set too high.	DC motor speed ramp variable should be permanently set to a value of 10 in the software, under "Bring DC Motor to Test Speed" section of software.
	Relay in stepper motor control circuit.	If not operational, driver may output an incorrect frequency to the stepper motor. Replace relay. Refer to Appendix E.
	Wiring loose or incorrectly located.	Check wiring on driver, PC printer port, stepper motor control circuit, driver power supply, and Kepco power supply.
	Stepper motor is too small.	Stepper motor must have at least a 20 oz-in dynamic torque capability in order to enable at speed.
	Incorrect stepper motor rotation direction.	Run TEST9.BAS to confirm stepper motor rotation problem. See instructions.
	Stepper motor control circuit not outputting a frequency.	Check circuit for correct frequency output. See Appendix E. This circuit may be tested using the digital I/O. With the relay set to pass 50000 Hz and the digital I/O outputting 12 high bits (all LEDs on) into the circuit, the output frequency should be 6.105 Hz into the driver.
	Dascon-1 digital I/O problem.	Run TEST9.BAS, check digital I/O. See Metrabyte manual for help.

Symptom	Problem	Possible Solution
DC motor drives the stepper motor to speed then the system hangs up.	Stepper motor output torque is too high for the DC motor to overcome.	The test may proceed if the user manually helps break the phase of the stepper motor (usually at low speed) until a higher speed (lower stepper output torque) is reached. If not feasible, stepper motor cannot be tested as set up.
	Finishing RPM is too high.	Interrupt and re-run the software in order to power the system down. Select a lower finishing RPM.
Excess vibration occurs in the frame during testing.	Frame bolts loose.	Tighten bolts.
DC motor overspins the stepper motor upon Kepco power supply power-up.	Incorrect startup sequence was followed.	Follow the instructions.
	Incorrect Kepco power supply front panel settings.	See instructions for correct settings.
General loss of repeatability.	DC motor torque ramp variable set too high.	Reset variable and re-run test. See Section 2.4 and 4.2, also instructions.
	Loose set screw in coupling or loose frame bolts.	Check and retighten if necessary.
	Improper ground in system wiring.	See Appendix I for wiring diagrams.

Symptom	Problem	Possible Solution
General loss of system accuracy.	Dascon-1 data acquisition system calibration.	Recalibrate using the basic program CAL.BAS. This must be done if switching PCs' or PC power supplies.
	DC motor torque ramp variable set too high.	Reset ramp variable.
	DC motor current shunt - A/D path broken.	Fix circuit path. Refer to external wiring diagram .
	Incorrect Kepco power settings.	See instructions for correct settings.
	Loose coupling or frame bolt.	Check and re-tighten if necessary.
	Change in DC motor friction torque characteristics.	Recalibrate as discussed in Appendix C.
	Change in K_e and K_t of DC motor.	Recalibrate as discussed in Appendix C.
	Heat buildup in DC motor (almost never occurs).	Allow to cool. This has never been a problem as of yet.

APPENDIX C

DC MOTOR CALIBRATION

This section provides information on the calibration of the DC motor used in the stepper motor torque testing system. Included is data on the DC motor tach calibration, DC motor current/torque calibration, and DC motor friction torque measurements.

The DC motor tachometer outputs a voltage which is linearly proportional to the speed of the DC motor. This voltage is applied across a voltage divider, and the voltage divider output is sent directly into the data acquisition system. Two sets of data are given for the DC motor tach calibration: data for the actual DC motor tach voltage vs. RPM output as it comes directly from the tachometer, and also DC motor tach voltage vs. RPM output as it comes from the voltage divider. A circuit diagram of the voltage divider is given in Appendix E and also in Section 3.7. Calibration data for the output of the voltage divider is helpful when using the A/D readout (in bits) to determine the DC motor speed.

All calibration values for the DC motor tachometer were obtained by running the DC motor up to speed and then locking an attached stepper motor into phase at the desired speed in order to provide a known DC motor speed. Tachometer output in volts was then measured. Page 103 provides both DC motor tach voltage vs. RPM and voltage divider output vs RPM for the DC motor. The voltage divider output is located on the stepper motor control circuit board. This output goes directly to the interface board where it is sampled by the A/D converter.

DC Motor RPM	Tach Voltage	Voltage Divider Output Voltage
0.000	0.000	0.000
50.095	-0.518	-0.060
100.000	-1.037	-0.121
150.000	-1.559	-0.181
200.000	-2.076	-0.242
240.000	-2.492	
300.000	-3.117	-0.363
340.134	-3.536	
400.000	-4.160	-0.485
441.174	-4.590	
500.000	-5.203	-0.607
561.795	-5.847	
600.000	-6.246	-0.729
652.170	-6.791	-0.792
700.932	-7.300	-0.852
750.000	-7.812	-0.911
802.134	-8.354	-0.975
852.270	-8.874	-1.037
903.609	-9.409	-1.099
955.410	-9.948	-1.162
1000.00	-10.413	-1.218
1102.935		-1.345
1200.000		-1.464
1304.340		-1.593
1401.861		-1.714
1500.000		-1.835

Since knowledge of the DC motor's output torque vs. current is essential for a determination of the stepper motor output torque, the DC motor has undergone a calibration to accurately determine the motor torque constant K_t. For a DC motor, the output torque is equal to the torque constant K_t times the armature current.

In order to determine K_t, one must know the DC motor output torque and the corresponding armature current. Armature current is very easy to measure, but the DC motor's output torque proved difficult to measure accurately with available equipment. The following method was therefore used to derive the DC motor's torque constant K_t.

When the DC motor is driven as a generator by an external source, the power output of the DC generator is given by:

$$\text{Output Power} = I_a * V_b$$

$$= I_a * K_e * \text{Omega}$$

where I_a is the armature current out of the DC motor (generator), V_b is the motor back emf, K_e is the DC motor voltage constant and Omega is the speed. Power output from the DC motor in terms of the output torque is given by:

$$\text{Output Power} = T * \text{Omega}$$

$$= K_t * I_a * \text{Omega}$$

where T is the output DC motor torque, Omega is the DC motor speed, K_t is the torque constant of the DC motor, and I_a is the armature current. Output power of the generator may be equated to the output power of the motor as follows:

$$I_a \times K_e \times (KRPM) = K_t \times I_a \times (rad/s) \times \frac{746}{550} \times \frac{1}{12 \times 16}$$

In this equation I_a is the armature current in amps, K_e is the DC motor voltage constant in volts/KRPM, KRPM is the DC motor speed in thousands of RPMs, K_t is the DC motor torque constant in oz-in/amp, and RAD/S is the DC motor speed in radians per second. Carrying out the math, the relation between the DC motor voltage constant and the DC motor torque constant may be expressed as

$$1.3517 K_e = K_t$$

where K_e is in units of volts per KRPM and K_t is in units of oz-in per amp. Using this method, the torque characteristics of any DC motor may be verified. The DC motor efficiency does not affect the calculations because the back emf constant k_e is measured with the DC motor acting as a generator, with the external source driving the DC motor overcoming all internal DC motor friction torque. In this manner, output power of the DC generator may be equated with output power of the DC motor to determine the DC motor constants.

K_e for the DC motor is easily measured by running the DC motor and measuring the voltage across its terminals. In doing so, a stepper motor driving the DC motor shaft was locked into phase at speed in order to correctly measure the DC motor shaft speed. With the stepper motor driving the DC motor, a voltage appears across the DC motor terminals with no current flowing through the armature. Measuring this back-emf voltage and the corresponding DC motor speed provides K_e. K_e as measured is **22.05 v/KRPM** and K_t as calculated by the relation between K_t and K_e is **29.805 oz-in/amp**. This value of K_t is used in the software to calculate the DC motor output torque based on the DC motor armature current.

Measuring K_t in this manner provides no information about the friction torque and related losses inside the DC motor. This is because a stepper motor was used to drive the DC motor with no armature current in the DC motor present. This method allowed the output power (I_a*K_e*Omega) of the DC generator and the output power of the DC motor (K_t*I_a*Omega) to be set equal while ignoring the internal losses and friction torque.

A final calibration of the DC motor included determining the DC motor friction torque. To determine the true output torque of the DC motor, the software must calculate the theoretical output torque of the DC motor from K_t and then either add or subtract the friction torque depending on whether the DC motor torque testing system is operating in acceleration or braking mode, respectively.

The DC motor friction torque was measured by measuring the no-load current required to drive the DC motor at various speeds. Without a load on the shaft, all the no-load current has to overcome is the internal friction within the DC motor. Multiplying the no-load current by the DC motor torque constant K_t yields the DC motor friction torque. DC motor friction torque information is provided below on page 106. Shown is the DC motor friction torque vs. speed for the DC motor. The friction torque is given in both oz-in and in bits as read by the A/D converter.

DC Motor RPM	Friction Torque oz-in	Friction Torque bits
0	8.207	-45
100	8.207	-45
200	8.207	-45
400	8.57	-47
600	9.48	-52
802.1	10.03	-55
1000	10.94	-60
1200	11.31	-62
1401.8	11.85	-65
1500	12.77	-70

DC motor friction torque is given in column 2. The friction torque was measured by sampling the DC motor armature current with the Dascon-1 A/D converter using the DC motor current shunt. Column 3 lists the corresponding A/D output in bits.

As can be seen, the DC motor friction torque does not increase linearly. The friction torque is composed of two things: coulomb friction and viscous friction. Coulomb friction is what shows up at zero motor speed and is equal to approximately 8.2 oz-in. As the DC motor gains speed, the viscous losses increase nonlinearly. The total DC motor friction torque is the sum of the coulomb and viscous friction torques. The total friction torque (shown in column 2) has been fitted to a fifth-order polynomial with respect to DC motor speed for use in the software. This polynomial is of the form

$$y=C_1+C_2\times X+C_3\times X^2+C_4\times X^3+C_5\times X^4+C_6\times X^5$$

where Y is the DC motor friction torque and X is the DC motor speed in revolutions per minute. The software uses this polynomial to calculate the DC motor friction torque at each test speed.

APPENDIX D

SOFTWARE OPERATION

This section details the operation of the software used to control the stepper motor torque testing system. All software has been written in BASIC in order to simplify access to the Metrabyte data acquisition system. The test system software referred to in this appendix is listed at the end of the appendix.

Lines 10 - 240:

Lines 10 - 240 of the software load a machine language program called "DASCON-1.BIN" into memory from the data acquisition board. Throughout the software, a call statement is used to access the A/D, D/A, and digital I/O contained in the data acquisition system. This call statement in the software makes use of the assembly language program "DASCON-1.BIN" in order to communicate with the data acquisition system. After contracting BASIC's working space to 32K and finding the start of BASIC's segment, DASCON-1.BIN is loaded at the end of BASIC's working space. The software may now communicate directly with the data acquisition system through the call statement and DASCON-1.BIN.

Lines 250 - 490:

All arrays used in the software are dimensioned at lines 260 and 270. The stepper motor driver is then disabled and set to full step mode by commanding printer port 3BC. Lines 310 and 320 utilize the call statement to cause D/A channel 1 to output 0 volts into the voltage programming input of the Kepco power supply, thus setting the voltage going into the DC motor to 0 volts and preventing premature operation. D/A channel 0 sets the relay in the stepper motor control circuit to pass the 100000 Hz signal by outputting 0 volts into the controlling FET. This signal is used for low speed operation (below 50 RPM) of the stepper motor. If the test is later started at a speed higher than 50 RPM, the software will reset the relay. The software then prompts the user to power down the stepper motor driver and prepares either screen or screen-and-disk data format for later use.

Lines 500 - 690:

Lines 500 - 690 prompt the user to enter the DC motor ramp variable (See Sections 2.4 and 4.2). This variable controls rate at which the DC motor increases the applied torque to the stepper motor shaft.

Lines 700 - 1080:

The user is now asked whether or not a holding torque test is required. If not, the software proceeds to the dynamic torque test. If a holding torque test is required, the software instructs the user on how to prepare the stepper motor driver for a holding torque test. The stepper motor driver must be powered down in order to ensure proper mode selection (full-step mode may become confused with wave-mode if this is not done). The step clock must be disconnected because the stepper motor control circuit cannot output a zero-hertz frequency which is required for the stepper motor not to rotate. After the driver has been prepared for a holding torque test, the software enables the driver in line 840. Lines 870, 880, and 890 increment the DC motor output torque by commanding D/A channel 1 to increment the voltage going into the Kepco power supply voltage programming input. Lines 900 and 910 read the A/D channel 0 (DC Motor Tachometer) to see if phase break has occurred. If phase break has not occurred, the software saves the highest DC motor current reading and repeats the loop, incrementing the DC motor output torque further and again looking for a phase break. When phase break is finally detected, lines 970 - 990 command D/A channel 1 to output 0 volts in order to reset the Kepco power supply to output 0 volts and power down the DC motor. Line 1000 commands printer port 3BC to disable the stepper motor driver in full-step mode. The highest DC motor current reading measured is then converted to torque and is written to either the screen or screen and disk.

Lines 1090 - 1410:

Lines 1090 - 1350 prompt the user to enter the parameters for the dynamic torque test. Lines 1360 - 1410 count from the starting RPM to the finishing RPM in the test RPM increment selected by the user. Each speed is translated into a decimal integer number and written into an array. This integer number will later be converted to binary and sent to the stepper motor control circuit so that the stepper motor will be enabled at the correct RPM. The integer decimal numbers are stored in the array BN(J). For a given stepper motor RPM J, BN(J) is the decimal equivalent of the binary number going into the frequency divider chips in the stepper motor control circuit. This binary number is outputted by the Dascon-1 digital I/O to the stepper motor control circuit later in the software.

Lines 1420 - 1470:

The DC motor tachometer has been calibrated and its voltage-speed curve has been fit to a fifth order polynomial. Lines 1420 - 1470 use this polynomial to calculate the DC motor tach voltage that corresponds to each user-selected test RPM. The tach voltage for each test speed is written into an array called TACH(J). TACH(J) is used when ramping the DC motor up to each test speed later in the test.

At this point, the main loop in the dynamic torque test is initiated. Every RPM point to be tested requires its own iteration through this loop. For any given torque test, lines 10 - 1510 are only executed once. Looping once through lines 1520 - 2790 corresponds to testing one RPM point on the test range. If 100 points are to be tested, the software will loop through lines 1520 - 2790 100 times.

Lines 1500 - 1670:

In line 1510 the variable Z is introduced as the relay switch point. This variable determines the RPM at which the relay in the stepper motor control circuit switches to pass the 1 MHZ frequency. It has been set at 50 RPM and should not be changed. Line 1520 begins the loop which, with each iteration, tests one speed point. Lines 1530 - 1650 translate the decimal integer number BN(J) into its corresponding binary number. Again, BN(J) is the binary number that is sent into the frequency division chips in the stepper motor control circuit. The input frequency to the divider chips is divided by the decimal equivalent of this binary number to produce twice the output frequency which drives the stepper motor driver. The individual bits of this 12-bit binary number are stored individually in the array B(C). The least significant bit (2^0) corresponds to B(11), and the most significant bit (2^11) corresponds to B(0).

Lines 1680 - 1880:

At this point the binary number BN(J) is transformed into two completely different binary numbers, a process which may seem rather confusing at first. The 12-bit binary number BN(J) must be sent to stepper motor control circuit via the Dascon-1 12-bit digital I/O, so it seems that this would be a straightforward process. However, the 12-bit digital I/O output on the Dascon-1 board actually consists of one 8-bit channel (channel PB Lower) and one 4-bit channel (channel PC Lower). The 12-bit number BN(J) must be broken into two parts: one part which is sent through channel PB Lower and another part which is sent through channel PC Lower. The combined output of channel PB Lower and channel PC Lower must, to the stepper motor control circuit, look exactly like the binary number BN(J). In other words, if the string of ones and zeros that comprise the output on channel PB Lower were set beside the string of ones and zeros that comprise the output on channel PC Lower, the resulting binary number would be BN(J).

Lines 1710 - 1730 take the least significant 8 bits of BN(J) and transform it into its corresponding decimal number called PBDEC. This decimal number is sent to channel PB Lower via a call statement later in the software. The software then outputs the binary equivalent. The process is somewhat wasteful in that it transforms the binary number PB into decimal and then back to binary, but the digital I/O requires a decimal input for a binary output. Lines 1780 - 1810 take the 4 most significant digits of the binary number BN(J) and transform them into their corresponding 4-bit decimal number PCDEC. This decimal number is sent to channel PC Lower via a call statement, and the output of channel PC Lower consists of the rest of the binary number BN(J).

Lines 1890 - 2010:

Lines 1890 - 1950 set the relay in the stepper motor control circuit to pass the 1-MHZ frequency if the required test RPM is above 50 RPM. Lines 1980 - 2010 utilize a call statement to output PBDEC to channel PB Lower and PCDEC to channel PC Lower. At this point the stepper motor control circuit receives the most significant 4 bits of BN(J) from channel PC Lower along with the least significant 8 bits from channel PB Lower. The stepper motor control circuit now outputs the frequency to the stepper motor driver corresponding to the required test RPM. The driver is still disabled so no motion ensues.

Lines 2020 - 2240:

Lines 2020 - 2240 ramp the DC motor and attached stepper motor up to the required test RPM. Initially, the Kepco programmable power supply is set to output zero volts. Lines 2050 - 2070 command D/A channel 1 to supply an incremental voltage to the Kepco's voltage programming input. This causes the Kepco supply to output a voltage to the DC motor, causing motion. Lines 2080 - 2100 check A/D channel 0 to see if a driver overvoltage message is being sent from the overvoltage protection circuit. If the driver is experiencing an overvoltage condition, lines 2110 - 2190 stop the test and deliver an error message to the screen. If the driver is not experiencing an overvoltage, line 2220 checks the previous A/D channel 0 output, which measures the tach voltage, to see if the DC motor has reached the required test speed yet. The tach reading is compared to the previously calculated variable TACH(J). If the DC motor has not yet reached the desired speed, the loop is repeated until the DC motor reaches the test speed within a certain bound.

Lines 2250 - 2300:

The DC motor is now motoring the stepper motor at near the required test speed and the stepper motor control circuit is pulsing the driver at the corresponding frequency. The stepper motor is now enabled, causing it to lock into phase at the required test RPM. Line 2260 enables the driver in full-step mode while line 2270 enables the driver in half-step mode. Lines 2280 -

2300 allow the system to achieve steady state before the DC motor applies any torque to the stepper motor shaft.

Lines 2310 - 2340:

After the stepper motor locks into phase, the system test speed is fixed until phase break. At this point a tachometer reading is taken for future speed reference. Line 2330 commands the Dascon-1 to read A/D channel 0 which indicates the tach voltage.

Lines 2350 - 2540:

This section of software causes the DC motor to begin ramping up its applied load on the stepper motor shaft. Lines 2370 - 2390 check A/D channel 2 for a driver overvoltage during applied load condition. In line 2390, if DIO%(2) is greater than 500, then A/D channel 2 is receiving an overvoltage message from the overvoltage protection circuit. Lines 2400 - 2460 subsequently stop the test and deliver an error message to the screen. If no overvoltage is detected, lines 2470 - 2540 increment the DC motor output torque by incrementing the D/A output to the Kepco power supply voltage programming input. The software saves the highest DC motor current reading after each torque incrementation.

Lines 2550 - 2600:

Lines 2550 - 2600 look at the output of A/D channel 0 which is the DC motor tachometer output. If this output deviates significantly from the tach reading taken in lines 2320 - 2340, then a phase break has occurred and the test proceeds with another data point if required. If no stepper motor phase break has occurred, the software goes back to line 2370 and increments the DC motor output torque again until phase break occurs.

Lines 2610 - 2810:

When phase break has been detected, lines 2620 and 2630 command D/A channel 1 to output 0 volts into the voltage programming input of the Kepco supply, thus powering down the DC motor. Lines 2650 and 2660 disable the stepper motor driver thus powering down the stepper motor. Lines 2680 - 2700 contain the curve fit for the DC motor friction torque. Lines 2720 - 2770 correct the DC motor current reading to torque and then add or subtract the DC motor friction torque depending on the test mode. Torque data is written to the screen and disk or to the screen only. Line 2790 repeats the test at another speed if required.

```
10 '*************************************************************************
20 '*                                                                       *
30 '*                    STEPPER MOTOR TEST PROGRAM                         *
40 '* Chris Moscone                     Revised:  10/1/90                   *
50 '*************************************************************************
60 '
70 '
80 '----------------- LOAD UP DASCON1.BIN ---------------------------------
90 'Contract BASIC working space to 32K
100 CLEAR,32768!
110 DEF SEG =0
120 'Find start of BASIC's segment
130 SG=256*PEEK(&H511)+PEEK(&H510)
140 'Initialize offset variable (DASCON1) into CALL routine to zero
150 DASCON1=0
160 'Work out segment to load DASCON1.BIN at end of working space
170 SG=(32768!/16)+SG
180 'Load DASCON1.BIN
190 DEF SEG =SG
200 BLOAD "DASCON1.BIN",0
210 'Initialize call parameters and declare DIO% array
220 DIM DIO%(8)
230 'Fetch base address from DASCON1.ADR file
240 OPEN "I", #1,"DASCON1.ADR":INPUT#1,BASADR%:CLOSE #1
250 REM -------------DIMENSION ALL ARRAYS---------------------------------
260 DIM BN(1500): DIM B(16): DIM TACH(1500)
270 DIM PB(16): DIM PC(16)
280 REM -------------DISABLE STEPPER MOTOR DRIVER--------------------------
290      OUT &H3BC,10 ' Disables and sets to full step mode.
300 REM ---------SET POWER SUPPLY TO OUTPUT 0 VOLTS--------------------
310    MD%=7: CH%=1: DIO%(0)=2048
320    CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
330 REM ---------------SET RELAY TO TRANSMIT 100000 hz FREQUENCY----------
340 MD%=7: CH%=0
350 DIO%(0)=2048
360 CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
370 '  This statement outputs 0 volts to channel 0 of the Dascon1 d/a,
375 '  setting the relay to transmit the 100000 hz frequency.
380 REM ------------------DISK DATA--------------------------------------
390    CLS
400    PRINT "The stepper motor driver should be unplugged at this point"
410    PRINT "to ensure proper mode selection later."
420    PRINT "     "
430    INPUT "Unplug driver and hit any key to continue "; DR$
440    CLS
450    INPUT "DO YOU WANT DATA READ TO THE A:DRIVE DISK? (Y/N) "; D$
460     IF (D$="N") THEN GOTO 500 ELSE GOTO 470
470     IF (D$="Y") THEN GOTO 480 ELSE GOTO 450
480    INPUT "INSERT DISK INTO DRIVE A AND HIT A KEY ";DD$
490    OPEN "O",1,"A:TORQUE.PRN"
500 REM -----------INPUT DC MOTOR RAMP VARIABLE--------------------------
510  CLS
520  PRINT "The DC motor ramp variable controls the rate of change of"
530  PRINT "torque applied to the stepper motor shaft. The DC motor  "
540  PRINT "does not apply a perfectly linear ramp torque to the stepper"
550  PRINT "motor shaft; rather, it increments the torque up in a series "
560  PRINT "of steps. This step size is set by the DC motor ramp variable."
570  PRINT "                  "
580  PRINT "A numerically small ramp variable results in a small step"
590  PRINT "increment of applied torque. This results in greater accuracy"
600  PRINT "of the test results but the test will take a longer time to"
610  PRINT "complete. A numerically high ramp variable results in reduced"
620  PRINT "accuracy and increased speed. See the instructions for a table"
```

```
630  PRINT "of recommended ramp values  "
640  PRINT "          "
650  PRINT "A ramp variable of 5 usually produces an acceptable"
660  PRINT "combination of speed and accuracy"
670  PRINT "          "
680  INPUT "ENTER THE DC MOTOR RAMP VARIABLE (INTEGER) ";DCRAMP
690         DCRAMP=INT(DCRAMP)
700 REM ---------------DO STEPPER MOTOR HOLDING TORQUE TEST------------------
710   CLS
720   INPUT "IS A HOLDING TORQUE TEST REQUIRED? (Y/N)";A$
730     IF (A$="N") THEN GOTO 1090  ELSE GOTO 740
740     IF (A$="Y") THEN GOTO 750  ELSE GOTO 720
750     PRINT "         "
760     SPEED=0
770     CLS
780     PRINT "RECONNECT POWER TO THE STEPPER MOTOR DRIVER"
790     PRINT "     "
800     INPUT "HIT ANY KEY TO CONTINUE "; DR$
810     CLS
820     PRINT "DISCONNECT THE `STEP CLOCK' INPUT TO THE STEPPER DRIVER--"
830     INPUT "AFTER STEP CLOCK DISCONNECT, HIT ANY KEY TO CONTINUE";B$
840        OUT &H3BC,0    ' Enables stepper motor driver.
850        PSV=2048    ' Sets power supply variable to 0 volts.
860        TORQ=0: TORQUE=0
870        MD%=7: CH%=1 ' Next 3 lines increment power supply voltage.
880        DIO%(0)=PSV
890        CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
900          MD%=0: CH%=0    ' Checks to see if phase break has ocurred.
910          CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
920          TORQ=DIO%(1)   ' A/D Converter torque reading.
930            IF ( ABS(DIO%(0)) ) > 10 THEN GOTO 970  ELSE GOTO 940
940            PSV=PSV+DCRAMP ' Decrements power supply voltage.
950            IF ( ABS(TORQ) > ABS(TORQUE) ) THEN TORQUE=TORQ ' Saves highest.
960             GOTO 870
970          MD%=7: CH%=1 'After phase break, powers down dc motor.
980          DIO%(0)=2048
990          CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
1000          OUT &H3BC,10    ' Disables stepper motor driver/ full step.
1010        TORQUE=ABS(TORQUE*.1872545)-8.2 ' Output data to screen or disk
1020        CLS
1030        PRINT "HOLDING TORQUE= "TORQUE" OZ-IN"
1040        PRINT "    "
1050        IF (D$="Y") THEN GOTO 1060 ELSE GOTO 1070
1060         PRINT #1,TORQUE,SPEED
1070        INPUT "RECONNECT STEP CLOCK INPUT ON DRIVER, DISCONNECT DRIVER POWER
 AGAIN AND PRESS ANY KEY TO CONTINUE  "; BB$
1080        CLS
1090 REM -----------------DETERMINE STEPPER MOTOR TEST SPEEDS---------------
1100 CLS
1110 FREQ1=50000!  ' Half of 1-MEG chip after divide-by-10 chip.
1120 FREQ2=500000! '  Half of 1-MEG chip frequency. (Half because of flip-flop)
1130 PRINT "RECONNECT DRIVER POWER AT THIS TIME TO ENSURE PROPER"
1145 PRINT "DRIVER INTERNAL MODE SELECTION. "
1150 PRINT "     "
1160 INPUT "HIT ANY KEY TO CONTINUE "; DR$
1170 CLS
1180 PRINT "In acceleration mode the dc motor simulates a load which "
1190 PRINT "the stepper motor tries to accelerate. As a result, the dc"
1200 PRINT "motor applies a torque to the stepper motor shaft in a "
1210 PRINT "direction opposite rotation."
1220 PRINT "      "
1230 PRINT "In braking mode the dc motor simulates a load that the"
1240 PRINT "stepper motor tries to decelerate or slow down. As a "
1250 PRINT "result, the dc motor applies a torque to the stepper motor"
1260 PRINT "shaft in the direction of rotation."
1270 PRINT "     "
```

```
1280 INPUT" ENTER 1 FOR ACCELERATION MODE; ENTER 2 FOR BRAKING MODE ",ABMOD
1290      IF (ABMOD=1 OR ABMOD=2) THEN GOTO 1300 ELSE GOTO 1280
1300 INPUT" ENTER 1 FOR FULL-STEP MODE OR 2 FOR HALF-STEP MODE:",MODE
1310      IF (MODE=1 OR MODE=2) THEN GOTO 1320 ELSE GOTO 1300
1320 INPUT" ENTER STARTING RPM (INTEGER 3 RPM OR GREATER) ",SRPM
1330 INPUT" ENTER FINISHING RPM (INTEGER 1500 RPM OR LESS) ",FRPM
1340 INPUT" ENTER STEPPER MOTOR STEPS PER REVOLUTION ",SREV
1350 INPUT" ENTER TEST RPM INCREMENT (INTEGER 2 OR GREATER) ",TIN
1360  FOR J=SRPM TO FRPM STEP TIN
1370      IF (J <= 50) THEN BN(J)=INT(FREQ1/(MODE*J*SREV/60))
1380      IF (J > 50)  THEN BN(J)=INT(FREQ2/(MODE*J*SREV/60))
1390  '   BN is the decimal equivalent of the number going into the frequency
      '  divider from the dascon1 digital output. The frequency of the 1-MEG
      '  chip is divided by this number at and above 50 rpm.
1400  '  Below 50 rpm the 1-MEG freq. goes through the divide-by-10 first.
1410  NEXT J
1420 REM -----------------DETERMINE D/A OUTPUT FOR DC MOTOR SPEEDS------------
1430   C1=-6.878102E-05: C2=-1.198917E-03: C3=-7.21001E-08: C4=1.273918E-10
1440   C5=-1.016015E-13: C6=2.77025E-17
1450   FOR J=SRPM TO FRPM STEP TIN
1460     TACH(J)=(C1+C2*J+C3*J^2+C4*J^3+C5*J^4+C6*J^5) ' TACH(J) is the tach
        voltage corresponding to the required dc motor speed.
1470   NEXT J
1480 REM -----------BEGIN TEST: TRANSLATE BN TO BINARY, BREAK INTO 8 AND 4 BITS.

1490 REM -----------A TORQUE TEST IS DONE FROM SRPM TO FRPM IN STEPS OF ( TIN ).

1500 REM
1510 Z=50   'Z is a count variable that determines the relay switch point.
1520 FOR J=SRPM TO FRPM STEP TIN
1530      ' Translate BN to binary, store in B array.
1540      '
1550      DEC=BN(J)
1560      C=0
1570      FOR I=11 TO 0 STEP -1
1580        IF ((2^I) > DEC) THEN GOTO 1630
1590        B(C)=1
1600        DIFF=DEC-2^I
1610        DEC=DIFF
1620        GOTO 1640
1630        B(C)=0
1640        C=C+1
1650      NEXT I
1660      ' B(C) array is the binary version of BN. The least significant digit
1670      ' corresponds to B(11). Again, this goes into the freq. divider.
1680   REM -----THIS SECTION CHOPS THE BINARY NUMBER B(C) INTO ONE 8-BIT NUMBER
1690   REM -----AND ONE FOUR-BIT NUMBER FOR OUTPUT TO THE DASCON1 CHANNELS
1700   REM -----PB AND PClower.
1710      FOR X=11 TO 4 STEP -1
1720        PB(X)=B(X)
1730      NEXT X
1740      PBDEC=PB(11)*1+PB(10)*2+PB(9)*4+PB(8)*8+PB(7)*16+PB(6)*32+PB(5)*64+
                PB(4)*128
1750      'PB corresponds to the least sig. 8 bits of the 12 bit number BN.
1760      'PBDEC is the decimal value of PB.
1770      'This output goes to channel PB of the 12bit Dascon1 digital I/O.
1780      FOR Y=3 TO 0 STEP -1
1790        PC(Y)=B(Y)
1800      NEXT Y
1810      PCDEC=PC(0)*8+PC(1)*4+PC(2)*2+PC(3)*1
1820      'PC corresponds to the most sig. 4 bits of the binary number BN.
1830      'PCDEC is the decimal equivalent of PC.
1840      'This output goes to channel PClower of the 12 bit digital I/O.
1850   REM -------------SEND PBDEC AND PCDEC TO DASCON1 DIGITAL I/O. THIS
1860   REM -------------WILL CAUSE V/F CIRCUIT TO OUTPUT A FREQUENCY TO
1870   REM -------------THE STEPPER DRIVER CORRESPONDING TO THE REQUIRED
```

```
1880   REM -------------TEST SPEED.
1890      IF ((Z-J) < 0) THEN GOTO 1900 ELSE GOTO 1960
1900        '***************************************************
1910        'Set relay to pass 1-MEG frequency.
1920        MD%=7: CH%=0: DIO%(0)=4095
1930        CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
1940        Z=10000  ' So relay will only trigger once.
1950        'End of relay call routine.
1960        ' **************************************************
1970      ' Call routine for digital output.
1980      MD%=9
1990      CH%=1
2000      DIO%(0)=PBDEC: DIO%(1)=PCDEC
2010      CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
2020  REM ---------BRING DC MOTOR TO TEST SPEED----------------
2030     PRINT "TEST SPEED IS "J" RPM"
2040      PSV=2048
2050      DIO%(0)=PSV
2060      MD%=7: CH%=1 ' increments programmable power supply.
2070      CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
2080       MD%=0: CH%=0 ' Checks stepper driver voltage
2090       CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
2100          IF DIO%(2) > 500 THEN GOTO 2110 ELSE GOTO 2200
2110           MD%=7: CH%=1: DIO%(0)=2048 ' Stops dc motor.
2120           CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
2130           OUT &H3BC,2  ' Disables stepper driver.
2140          CLS
2150          PRINT "TEST TERMINATED DUE TO STEPPER MOTOR DRIVER"
2160          PRINT "OVERVOLTAGE CONDITION DURING DC MOTOR RAMP-UP."
2170          PRINT "DRIVER UNABLE TO HANDLE STEPPER MOTOR BACK EMF"
2180          PRINT "AT THIS SPEED."
2190          GOTO 2800
2200        MD%=0: CH%=0  ' checks to see if at test speed yet.
2210        CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
2220          IF ((DIO%(0)*2/4000-.012) < TACH(J)) THEN GOTO 2250  ELSE
                                                      GOTO 2230
2230           PSV=PSV+10
2240           GOTO 2050
2250  REM ---------------------ENABLE STEPPER DRIVER----------------
2260      IF ( MODE=1 ) THEN    OUT &H3BC,8   ' Full-step mode
2270      IF ( MODE=2 ) THEN    OUT &H3BC,0   ' Half-step mode
2280      FOR I=1 TO 40   ' Allows system to come to steady-state.
2290          DUMMY=DUMMY+I
2300      NEXT I
2310  REM ------------------READ TACH VOLTAGE-----------------------------
2320      MD%=0: CH%=0
2330      CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
2340      SPEED=DIO%(0)
2350  REM -----------------BEGIN DC MOTOR BRAKING---------------
2360      TORQ=0: TORQUE=0
2370       MD%=0: CH%=2 ' Checks driver voltage during applied load.
2380       CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
2390       IF DIO%(2) > 500 THEN GOTO 2400 ELSE GOTO 2470
2400         MD%=7: CH%=1: DIO%(0)=2048 ' Stops motor if driver overvoltage
2410         CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
2420         OUT &H3BC,2 ' Disables stepper driver.
2430         CLS
2440         PRINT "TEST TERMINATED DUE TO STEPPER DRIVER OVERVOLTAGE"
2450         PRINT "OCCURRING DURING APPLIED LOAD. "
2460       GOTO 2800
2470      IF ( ABS(TORQ) > ABS(TORQUE) ) THEN TORQUE=TORQ
2480      MD%=7: CH%=1
2490      IF ( ABMOD=1 ) THEN GOTO 2500 ELSE GOTO 2520
2500        PSV=PSV-DCRAMP  ' Acceleration mode.
2510        GOTO 2530
2520        PSV=PSV+DCRAMP  ' Braking mode.
```

```
2530       DIO%(0)=PSV ' Decrements power supply voltage.
2540       CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
2550   REM --------------READ IN NEW TORQUE VALUE AND--------------------
2560   REM  -------------CHECK TACH VOLTAGE FOR STEPPER PHASE BREAK-----
2570             MD%=0: CH%=0
2580             CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
2590               TORQ=DIO%(1)    ' A/D converter torque reading
2600               IF ABS(DIO%(0)-SPEED) > 30  THEN GOTO 2620 ELSE GOTO 2370
2610   REM -------------POWER DOWN DC MOTOR-----------------------------
2620                  MD%=7: CH%=1: DIO%(0)=2048
2630                  CALL DASCON1 (MD%, CH%, DIO%(0), DIO%(1), BASADR%)
2640   REM --------------DISABLE STEPPER DRIVER-------------------------
2650       IF ( MODE=1 ) THEN    OUT &H3BC,10   ' Full-step mode
2660       IF ( MODE=2 ) THEN    OUT &H3BC,2    ' Half-step mode
2670   REM --------CORRECT TORQUE VALUES AND PRINT-----------------------
2680        C1=8.204233: C2=9.995369E-05: C3=-3.360963E-06
2690        C4=2.228447E-08: C5=-2.410426E-11: C6=7.737551E-15
2700         FRTORQ=C1+C2*J+C3*J^2+C4*J^3+C5*J^4+C6*J^5
2710         ' DC Motor friction torque vs. rpm
2720         TORQUE=ABS(TORQUE*.1872545)  'Corrected from bits to oz-in
2730       IF ABMOD=1 THEN TORQUE=TORQUE+FRTORQ  ' Acceleration mode.
2740       IF ABMOD=2 THEN TORQUE=TORQUE-FRTORQ  ' Braking mode
2750                PRINT "          TORQUE= "TORQUE " OZ-IN
2760       IF (D$="Y") THEN GOTO 2770 ELSE GOTO 2780
2770         PRINT #1,TORQUE,J
2780   REM --------------GOTO NEXT SPEED POINT--------------------------
2790 NEXT J
2800 CLOSE 1
2810 END
```

APPENDIX E

OPERATION OF STEPPER MOTOR CONTROLLER

The stepper motor controller circuit described in this section is the device that permits the PC to operate a stepper motor during a torque test. This circuit is responsible for producing the frequency used to control the pulse rate of the stepper motor driver. The driver, when pulsed at a given frequency, steps the stepper motor at the same frequency. The PC determines the desired stepper motor speed and step frequency, then outputs a signal to the stepper motor control circuit to produce this frequency.

A simplified method of operation of the stepper motor controller is as follows: The PC, after determining the required stepper motor step frequency, outputs a corresponding 12 bit binary number through the Dascon-1 data acquisition board. This 12-bit number is sent directly into the stepper motor control circuit, where an internal frequency is divided by the decimal equivalent of this binary number to produce the output frequency going into the stepper motor driver.

The Binary-to-Frequency stepper motor control circuit contains the following parts:

3	CD4526B Binary Frequency Dividers
1	1.000 MHZ Crystal
1	CD4017BCN Divide-By-10 Chip
1	Reed Relay
1	CD4013BF Flip-Flop
1	P3055E Field Effect Transistor
12	10K Resistors

A detailed method of operation is now presented for the stepper motor control circuit.

The internal frequency that is divided by the input binary number and sent to the stepper motor driver is produced by a 1.000 MHZ crystal. This frequency is divided by 10 in the CD4017B chip to produce a 100000 Hz frequency. These two frequencies are used as the input frequencies to the CD4526 frequency dividers. Both the 1 MHz frequency and the 100000 Hz frequency are then routed through a reed relay that switches between the two frequencies. The reed relay is switched by a FET which is controlled by a 0-5 volt signal from the Dascon-1 board. As discussed in Section 3.5, the 100000 Hz frequency is used at the start of a torque test and up to stepper motor speeds at and below 50 RPM. The 100000 Hz frequency is selected by the Dascon-1 board by outputting 0 volts to the FET. Above 50 RPM the PC signals the Dascon-1 board to output 5 volts to the FET and switch the relay. This operation allows the relay to pass the 1.000 MHz frequency used above 50 RPM. As explained in Section 3.5, the 1.000 MHz frequency allows better resolution of the stepper motor speeds above 50 RPM.

The input frequency (either 1 MHz or 100000 Hz) passes through the relay and enters the CD4526B frequency dividers. These three dividers have 4-bit capability apiece, and are all cascaded together to provide 12-bit capability. As shown in Figure E.1, the 16 pin connector carries the binary output from the Dascon-1 board. The CD4526 chips divide the input frequency (1 MHz or 0.1 MHz) by the decimal equivalent of the Dascon-1 binary number output to produce a lower frequency. This lower frequency is not suitable to drive the stepper motor driver, however. Since this frequency started as a 1.000 MHz frequency, it has a pulse width of approximately 1/2 of a microsecond. The stepper motor driver requires a minimum pulse width of 3 microseconds to operate properly. Therefore, this frequency is passed through the CD4013 flip-flop which divides the frequency by two and, more importantly, recharacterizes the frequency to a 50% duty cycle so that the pulse width will always be one-half of the period after division. After passing through the flip-flop the frequency is sent directly to the stepper motor driver. As shown in Figure E.1, this output frequency is equal to half of the 1 MHz or 100000 Hz frequency divided by the decimal equivalent of the input binary number.

The sequence of input binary digits is shown on the 16 pin connector in Figure E.1. Generation of this number is detailed in Appendix D: Software. The external wiring for the stepper motor control circuit is given in Appendix I: Wiring Diagram.

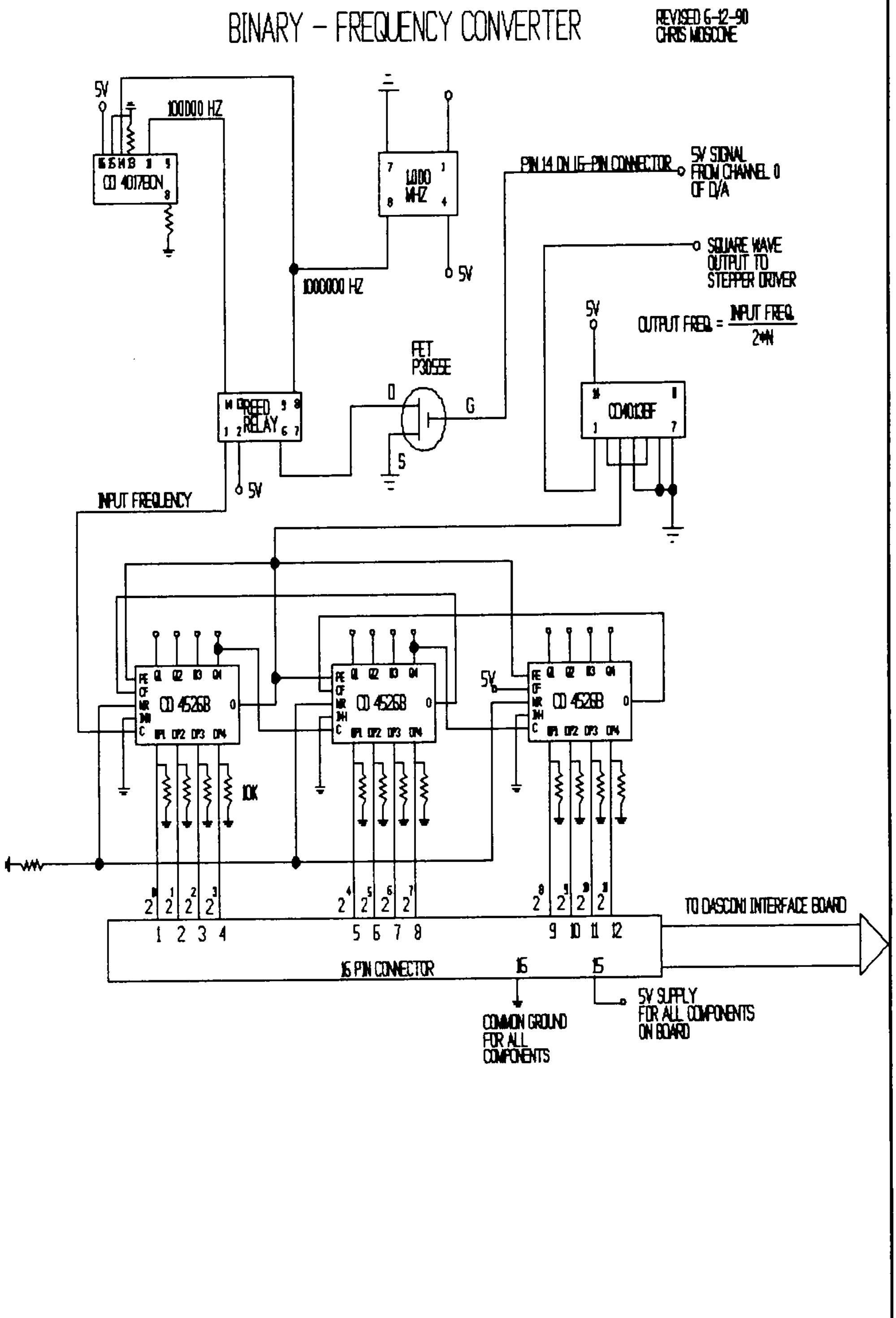


FIGURE E.1 Binary-Frequency Stepper Motor Control Circuit.

APPENDIX F

CIRCUIT DIAGRAM AND OPERATION: TACH FILTER

The DC motor tachometer low-pass filter filters out noise from the tach signal caused by low speed stepper motor operation. As explained in Section 3.7, the uneven step motion of the stepper motor at low speeds (below about 40 RPM) causes the DC motor tachometer to output an oscillating voltage of the same frequency as the stepper motor pulse rate. This voltage oscillation is of sufficient magnitude to cause the data acquisition system to behave as if a stepper motor phase break has occurred. In order to remedy this problem, a low-pass RC filter has been incorporated between the tach and the Dascon-1 interface input. Figure F.1 shows a circuit diagram for the tach filter.

The tach filter serves as a low-pass filter and also as a voltage divider. The voltage division is incorporated to scale the tach output voltage to a level acceptable to the Dascon-1 analog input.

The low-pass filter design is a compromise between filtering capability and system response to a tachometer input. The low-pass filter must have a breakpoint low enough so that most noise above the break frequency is filtered out. If the breakpoint is too low, however, the filtered signal will lag behind the actual tach signal as explained in Section 3.7.

Referring to Figure F.1, the relation between the filter input voltage and the filter output voltage is given by

$$\frac{V\ \text{output}}{V\ \text{input}} = \frac{1/(1 + R_1/R_2)}{1 + s(\ CR_1 + CR_3 + CR_1R_3/R_2)\ /\ (1 + R_1/R_2)}$$

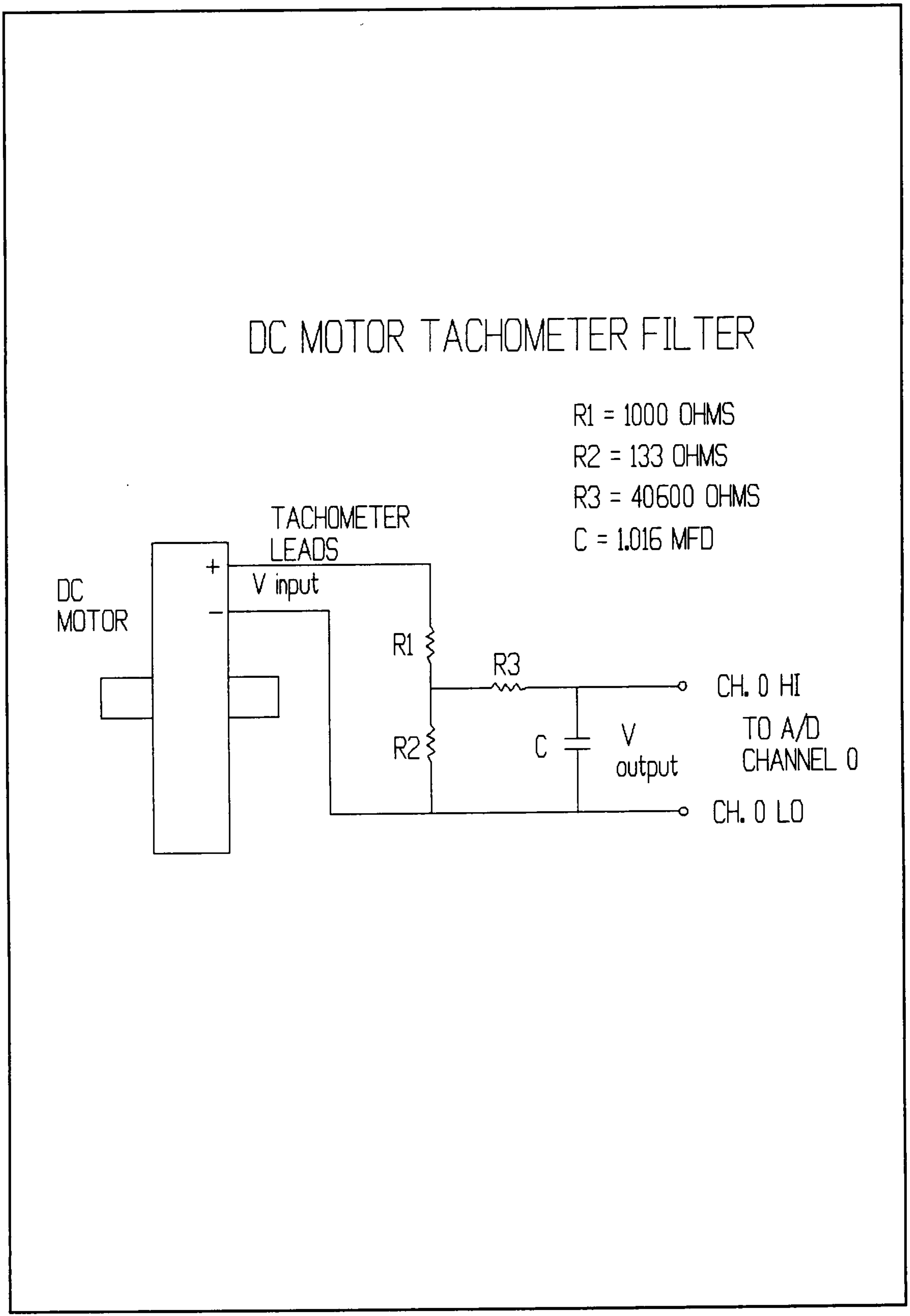


FIGURE F.1 Tachometer Filter Circuit Diagram.

where V output is the DC motor tach output voltage and V input is the Dascon-1 analog input voltage. The steady state gain for this circuit is

$$\text{Gain} = 1/(1 + R_1/R_2)$$

and the time constant is given by

$$\text{Tau} = (CR_1 + CR_3 + CR_1R_3/R_2) \ / \ (1 + R_1/R_2).$$

From the values of the resistors and capacitor used, the steady state gain has a value of 0.11738 while the time constant has a value of 0.036 seconds. The break frequency, given by 1/tau, has a value of 27.778 radians per second or 4.42 hertz. This corresponds to a stepper motor speed of 1.326 RPM assuming a 200 step-per-revolution motor is used. These values have been found to provide satisfactory filtering capabilities while at the same time having good dynamic response.

The software ramps the DC motor up to speed at approximately 200 RPM per second by incrementing the D/A output by 5 bits at a time. The steady state error introduced by the tachometer filter is given by tau*ramp , where ramp is the 200 RPM per second DC motor ramp value. This product is numerically equal to 7.2 RPM, which means that, during ramp up, the DC motor is actually turning approximately 7.2 RPM faster than what the tach filter output indicates. This value is within the bounds needed to ensure proper stepper motor enabling after ramp-up.

The tachometer output, after passing through the filter and the voltage divider, goes into the A/D converter in the Dascon-1 main board. An input of

2.0475 volts to the A/D converter corresponds to a digital output of 4095 bits. The software reads the number of bits to determine the DC motor speed.

APPENDIX G

CIRCUIT DIAGRAM / OPERATION: DRIVER OVERVOLTAGE PROTECTION

The following text describes the operation of the stepper motor driver overvoltage protection circuit. As described in Section 3.8, this circuit is responsible for detecting and stopping dangerous overvoltage levels that may appear across the driver power supply terminals during the course of a torque test.

Section 3.8 described the three conditions under which a driver overvoltage may occur. The driver overvoltage protection circuit can not and does not differentiate between the particular causes of a driver overvoltage condition. Rather, its function is to sense when the driver voltage rises over a prescribed limit, and then prevent the voltage from rising any further.

The DC motor is the direct cause of any overvoltage condition occurring on the driver during a torque test. The DC motor induces generator-like behavior in the stepper motor, resulting in a back emf across the driver power supply terminals. The driver overvoltage circuit eliminates this back emf by abruptly shutting off the DC motor power as soon as a higher-than-normal voltage is sensed across the driver power supply terminals.

The driver overvoltage protection circuit contains the following parts:

1 LM393 Dual Comparator
1 EAC Reed Relay
1 P3055E Field Effect Transistor
1 0.93 Microfarad Capacitor
10 Resistors: 93.1K, 2870, 2.2K, 2.3K, 3.24K (2),
1 MEG (2), 2.4 MEG, 10K.

A detailed method of operation is now presented for the stepper motor driver overvoltage protection circuit. A circuit diagram is presented in Figure G.1.

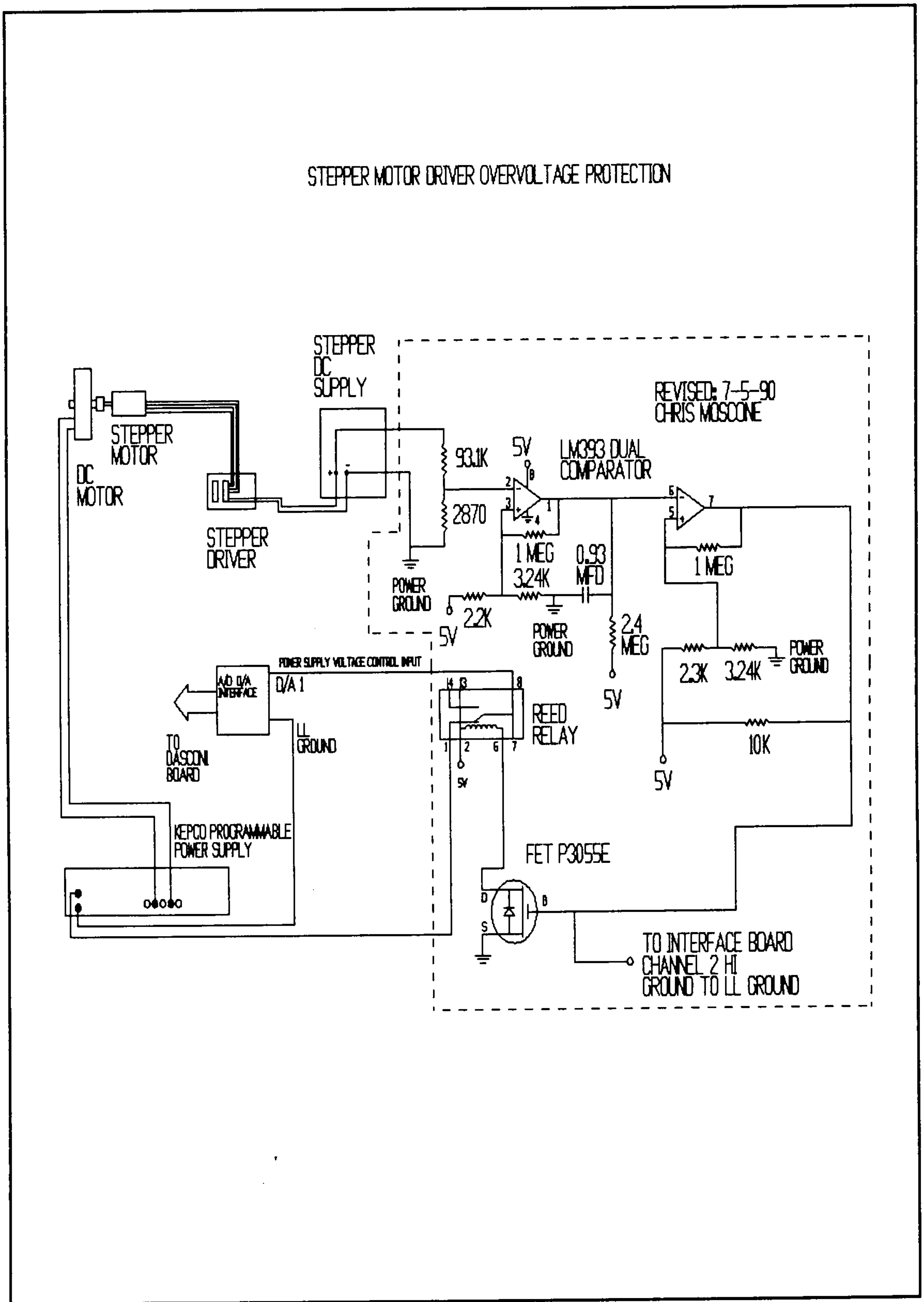


FIGURE G.1 Stepper Driver Overvoltage Protection Circuit.

The following discussion is intended to lead the reader through a torque test in which an overvoltage condition suddenly occurs. The operation of the driver overvoltage protection circuit is explained in the order of its sequence of operation.

1. Initially, the test system is performing a dynamic torque test on a stepper motor and no overvoltage condition across the driver power supply terminals is present. The driver terminals and the driver DC supply terminals are common, as shown in Figure G.1. Any overvoltage condition appears across both the driver terminals and the driver DC power supply terminals. The stepper motor DC unregulated supply operates somewhere between 80 and 88 volts depending on the wall voltage. The driver itself can operate at up to 100 volts. Any voltage appearing across the driver supply terminals in excess of 95 volts is considered an overvoltage condition.

The driver power supply terminals have a voltage divider connected across them. At this point, with the test system running without an overvoltage, the voltage divider outputs a voltage into pin 2 of the comparator that is less than the reference voltage (2.9 V) going into pin 3. This causes the output of the first comparator on pin 1 to go open. Since the comparator open-circuits pin 1, a voltage of approximately 3.23 volts appears across this line due to the incoming 5 volts applied to the 2.4 MEG resistor. The 0.93 MFD capacitor is also charged at this point. The 3.23 volts across pin 1, and correspondingly across pin 6, is higher than the reference voltage (2.9 V) appearing across pin 5 of the second stage comparator. The output of the second stage comparator is therefore at ground level. (The comparators either output open or ground). Pin 7, the output of the second stage comparator, sends 0 volts (ground level) into the gate of the FET. The FET allows no current to pass and thereby a closed circuit exists between pins 1 and 8 of the relay. Connected across pins 1 and 8 of the relay are the Kepco programmable power supply voltage programming inputs. These inputs allow the Kepco supply to control the DC motor via the Dascon-1 data acquisition board and software. When pins 1 and 8 of the relay are closed as just described the Kepco power supply is enabled to control the DC motor.

2. A driver overvoltage occurs at approximately 92 - 95 volts across the driver power supply terminals. Due to the voltage divider, the voltage across pin 2 becomes higher than the voltage across pin 3 of the first stage comparator. The first stage comparator output (pin 1) goes to ground. The 0.93 MFD capacitor discharges in approximately 87 microseconds and the input to the second stage comparator (pin 6) reaches ground level. Since the voltage across pin 6 is now less than that across pin 5, the second stage comparator output goes open and approximately 5 volts appears across pin 7 due to the 5 volt supply and 10K resistor. This is sufficient to power the gate on the FET. The FET now opens the relay, cutting off the voltage control input between the Dascon-1 board and the Kepco power supply. The Kepco power therefore defaults and sends 0 volts into the DC motor, shutting the motor off. This effectively eliminates any overvoltage caused by the DC motor driving the stepper motor. The circuit responds and stops power to the DC motor within 50 microseconds after detecting an overvoltage condition. The Dascon-1 board monitors the gate to the FET and, when the A/D senses a voltage across this line, the software is signaled to stop the test and provide the system user with an error message.

3. The driver overvoltage disappears when the DC motor is powered down. The voltage across pin 2 is now less than that across pin 3 and the first stage comparator output (pin 1) returns to open. This allows the capacitor to slowly charge back up. The capacitor charges through the 2.4 MEG resistor, and reaches a voltage level sufficient to trigger the second stage comparator after about 1.5 seconds. It is important to note that the capacitor charges through a different path than it discharges through due to its location on the first stage comparator output. The capacitor discharges quickly through the comparator internal resistance in about 87 microseconds in order to provide quick response to an overvoltage condition. The capacitor now charges through the 2.4 MEG resistor in about 1.5 seconds so that the overvoltage protection circuit will not turn the DC motor back on before the software has a chance to shut off the Kepco power supply voltage control input. The software takes about 1 second to respond to an overvoltage condition, which is much slower than the overvoltage protection circuit responds. Thus, the capacitor delays the circuit from turning the DC motor back on too soon and thereby prevents any oscillation in the system.

When the capacitor has charged to a level such that the voltage across pin 6 is higher than that across pin 5, the second stage comparator output (pin 7) returns to ground, cutting off power to the FET gate and restoring contact between pins 1 and 8 in the relay. This allows the relay to transmit the DC motor power supply voltage control input and allows the software to restore power to the DC motor if the overvoltage condition was due to case 3 as described in Section 3.8.

The software now either powers down the system and provides the user with an overvoltage message (case 1 and case 2, Section 3.8) or allows further testing (case 3, Section 3.8).

APPENDIX H

DC MOTOR CURRENT MEASUREMENT

As shown in Section 3.6, the DC motor output torque is determined through a direct measurement of the DC motor armature current. The current measurement device used is a current shunt consisting of four parallel resistors. The DC motor armature current flows directly through this current shunt, and the corresponding voltage drop across the shunt is read by the data acquisition system in order to determine the DC motor output torque. Operation and calibration values for the current shunt are provided in this appendix.

Figure H.1 shows a diagram of the DC motor current shunt. The total resistance of the current shunt is 0.07975 ohms. The maximum current output of the Kepco power supply is 13.5 amps, corresponding to 1.076 volts appearing across the current shunt. This voltage is sent to the A/D converter in the Dascon-1 main board. A voltage input of 2.0475 volts into the A/D converter corresponds to a digital output of 4095 bits. Therefore, a DC motor output torque equation can be shown as follows:

$$\text{TORQUE} = \text{BITS}*(0.0005)*K_t/R \text{ +- FRICTION TORQUE}$$

where bits is the A/D digital output, K_t is the DC motor torque constant, and R is the current shunt resistance. The DC motor friction torque is either added or subtracted depending on whether the test is being run in acceleration or braking mode.

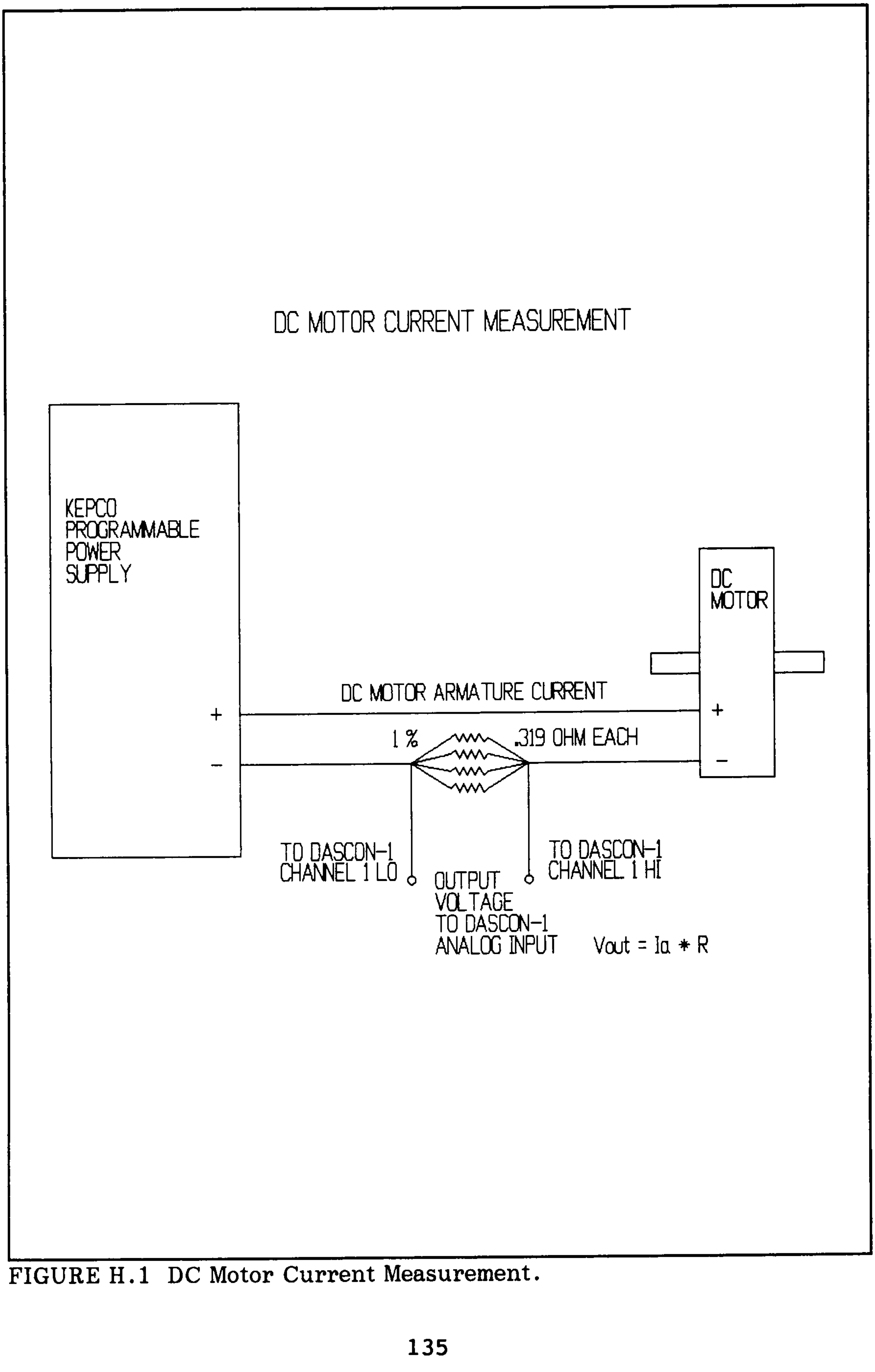


FIGURE H.1 DC Motor Current Measurement.

APPENDIX I

SYSTEM EXTERNAL WIRING

This appendix contains the external wiring diagrams for all components in the stepper motor pull-out torque testing system. In reading this appendix it should be kept in mind that only the main external wiring between components is presented. Details of actual internal circuitry should be referred to the appropriate section or appendix in this writing.

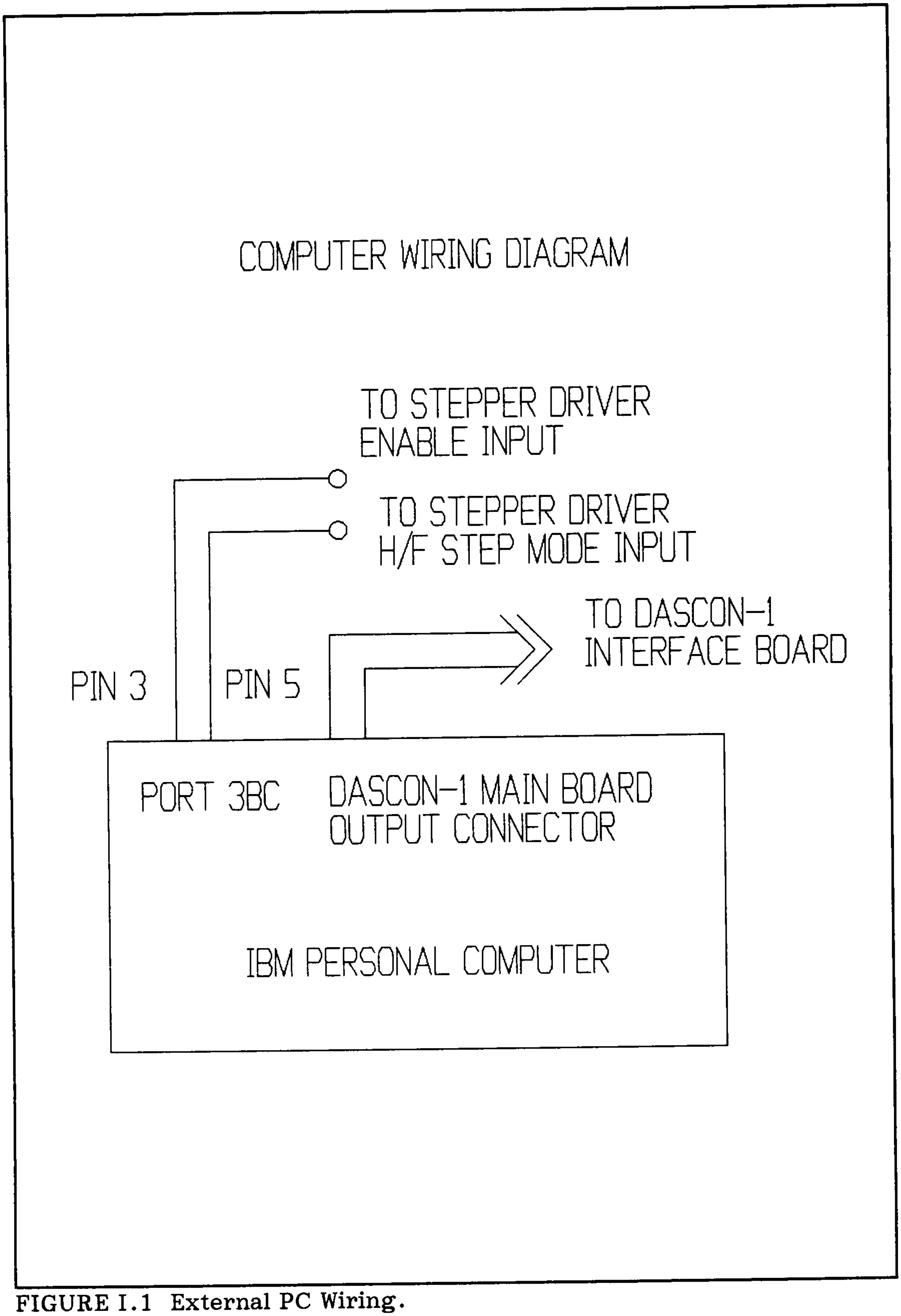


FIGURE I.1 External PC Wiring.

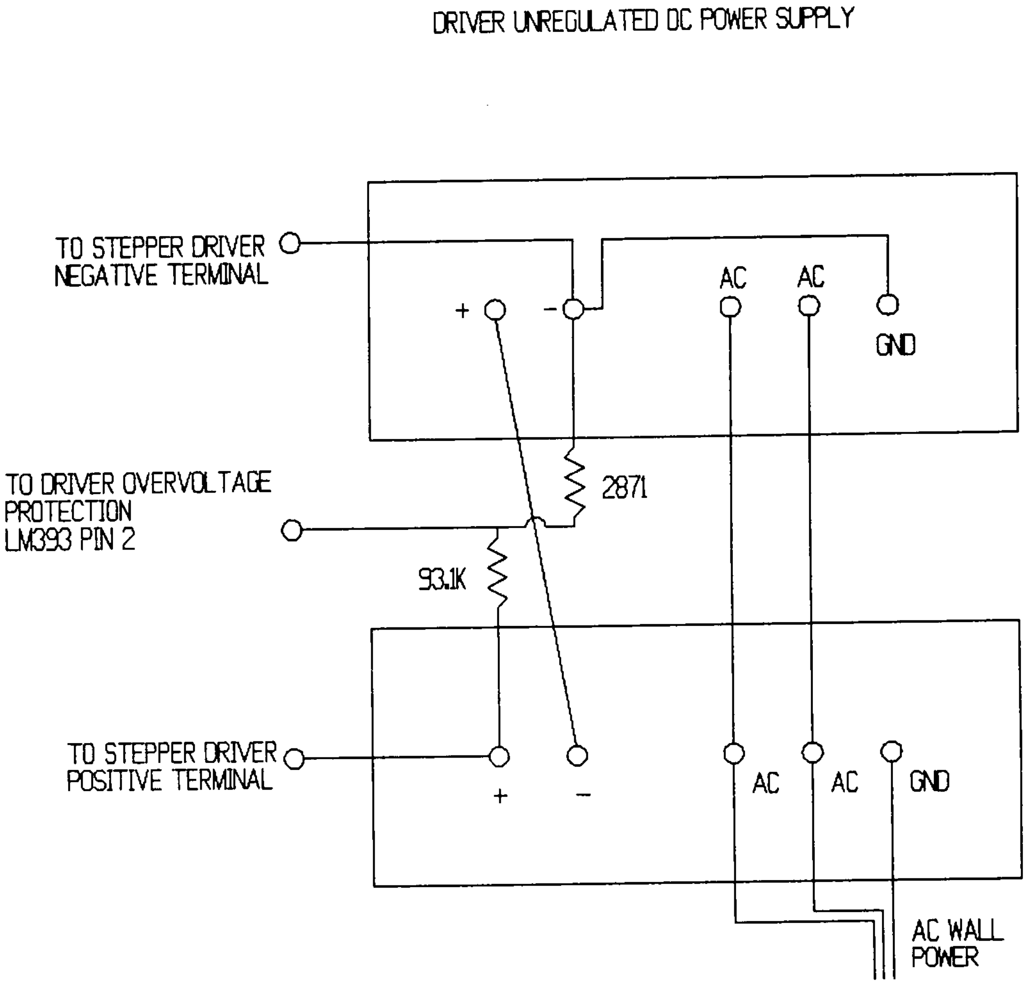


FIGURE I.2 External wiring - Driver DC Supply.

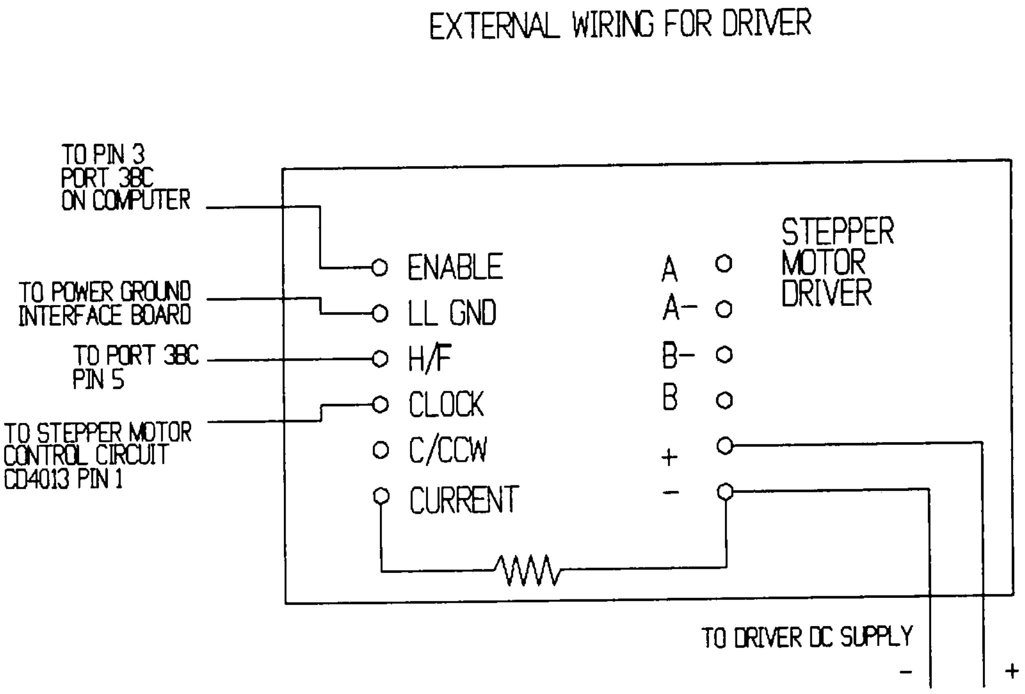


FIGURE I.3 External Wiring - Stepper Motor Driver.

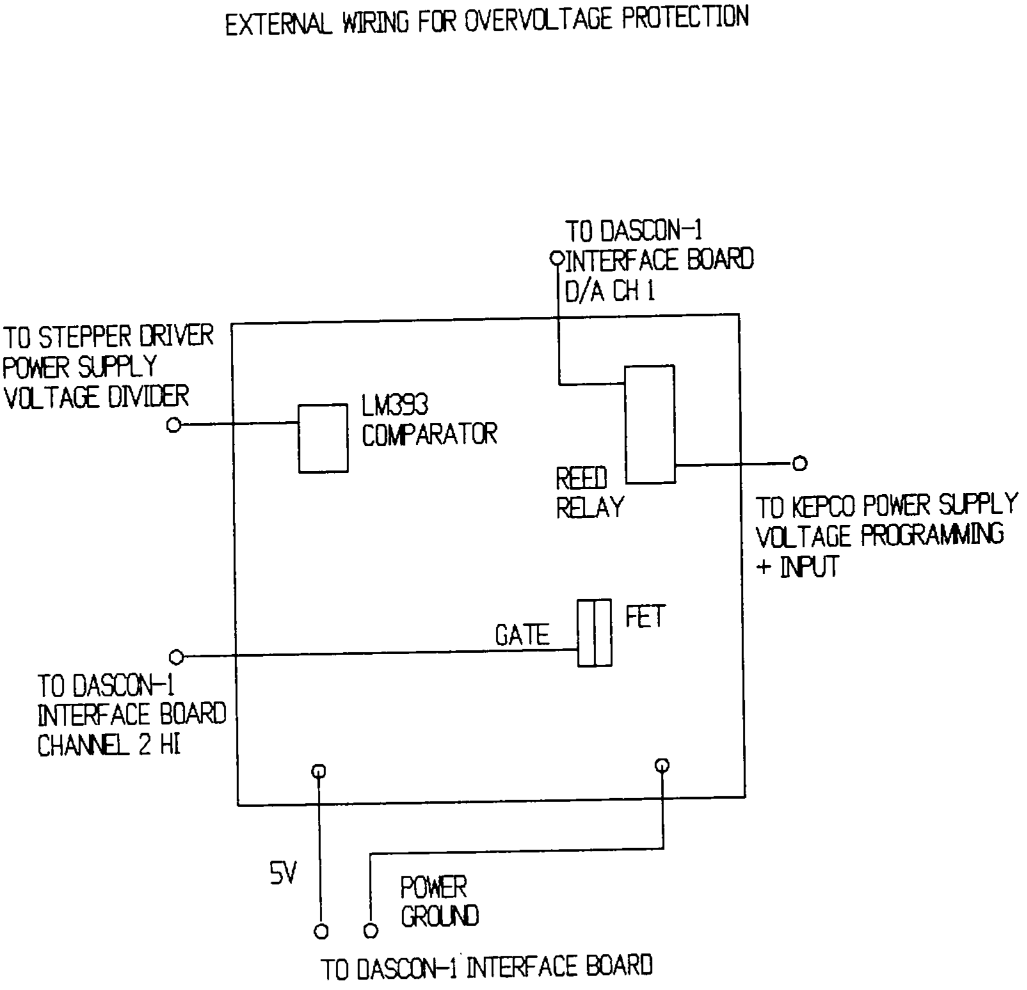


FIGURE I.4 External Wiring - Overvoltage Protection.

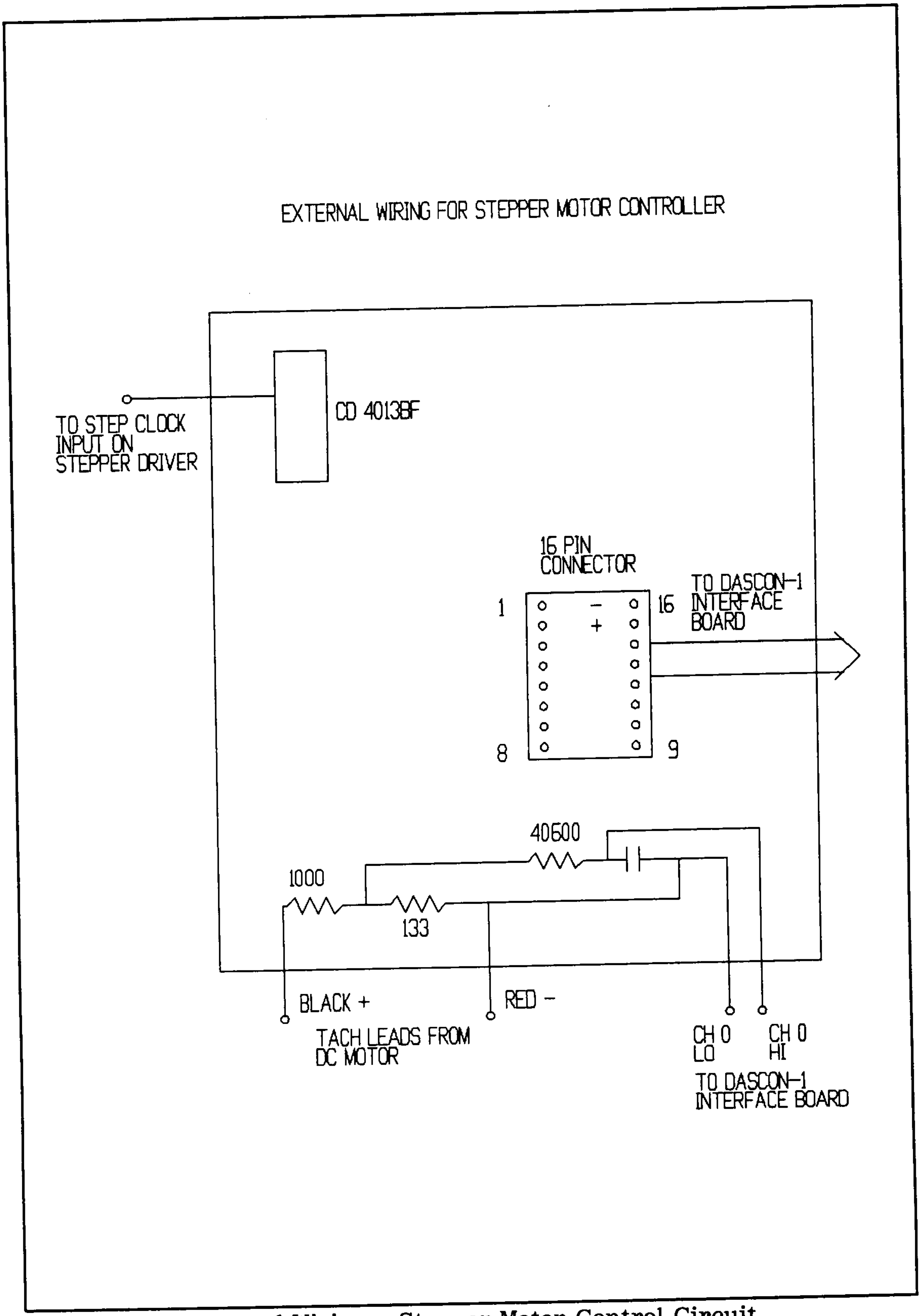


FIGURE I.5 External Wiring - Stepper Motor Control Circuit.

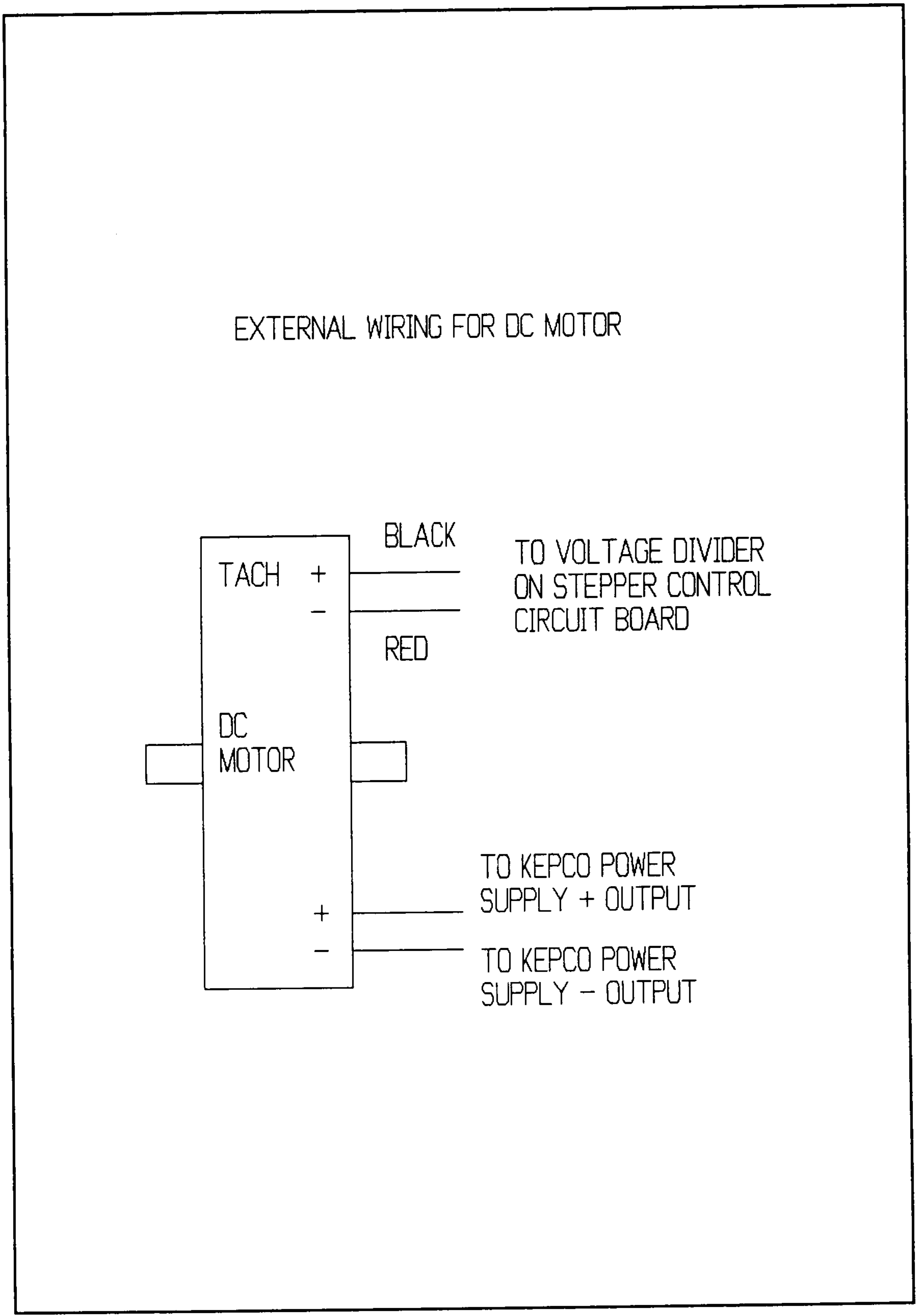


FIGURE I.6 External Wiring - DC Motor.

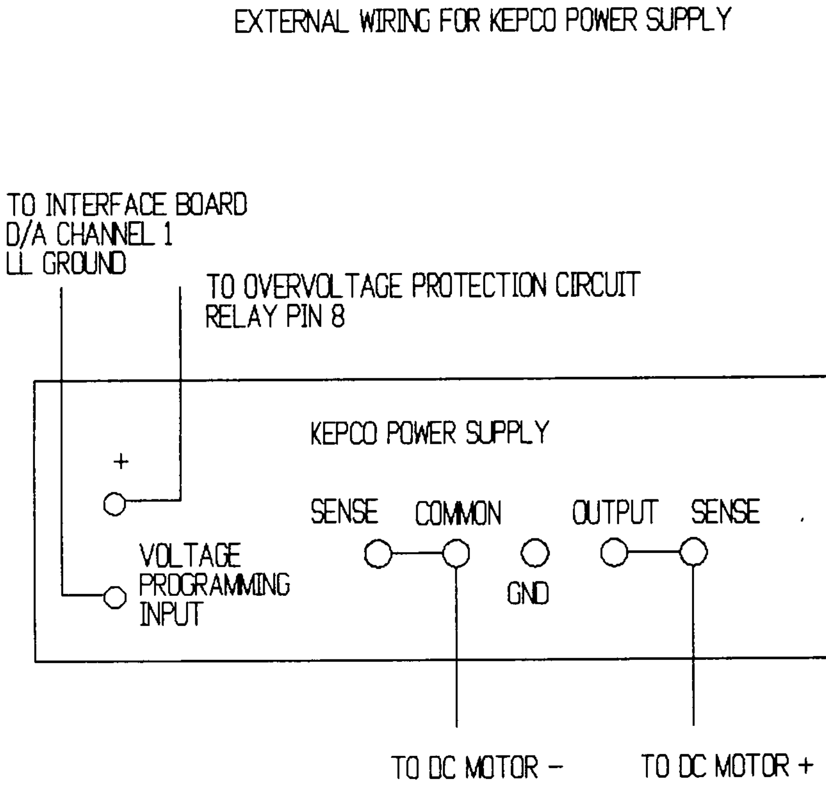


FIGURE I.7 External Wiring - Kepco Programmable Power Supply.

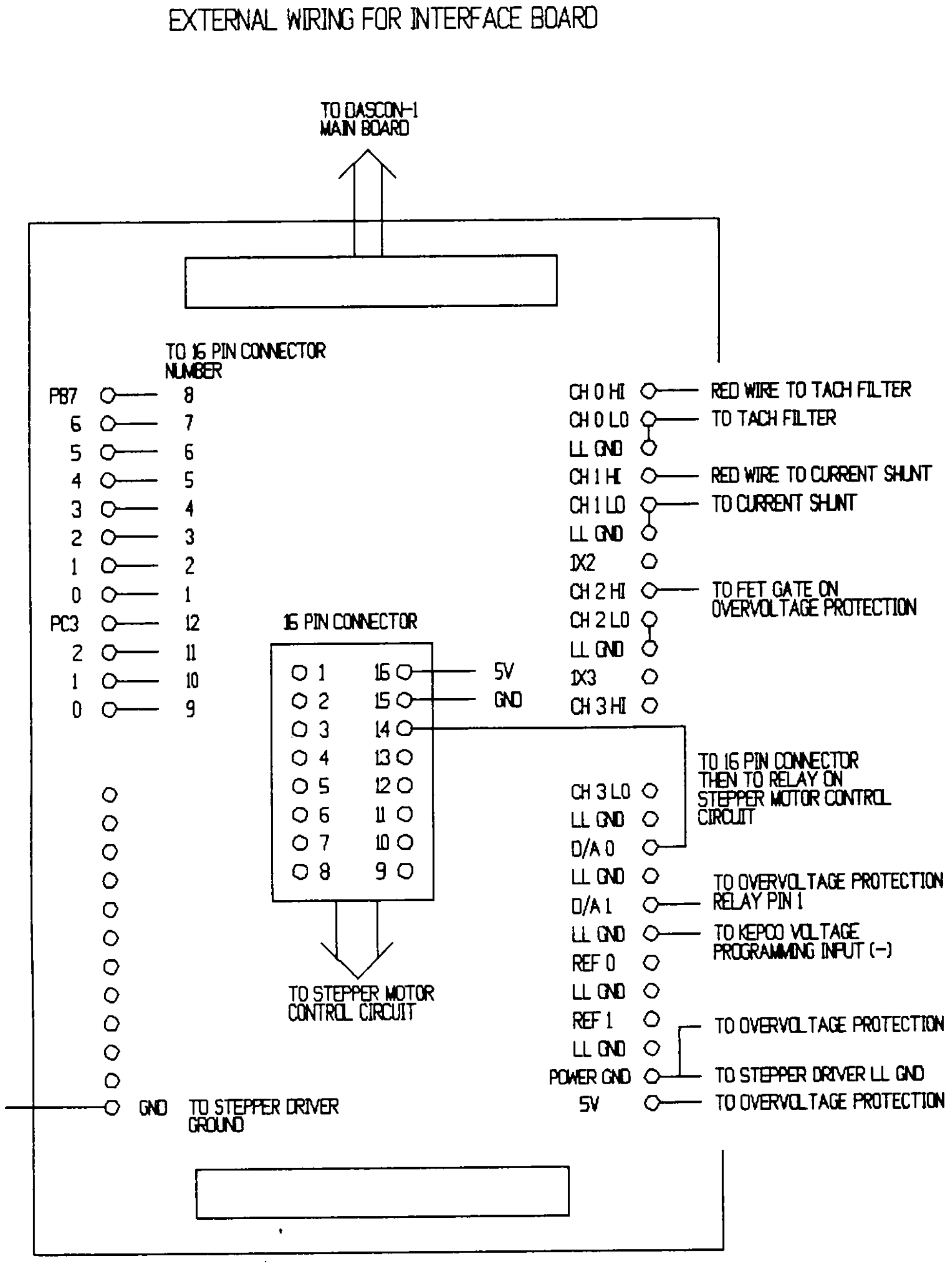


FIGURE I.8 External Wiring - Interface Board.

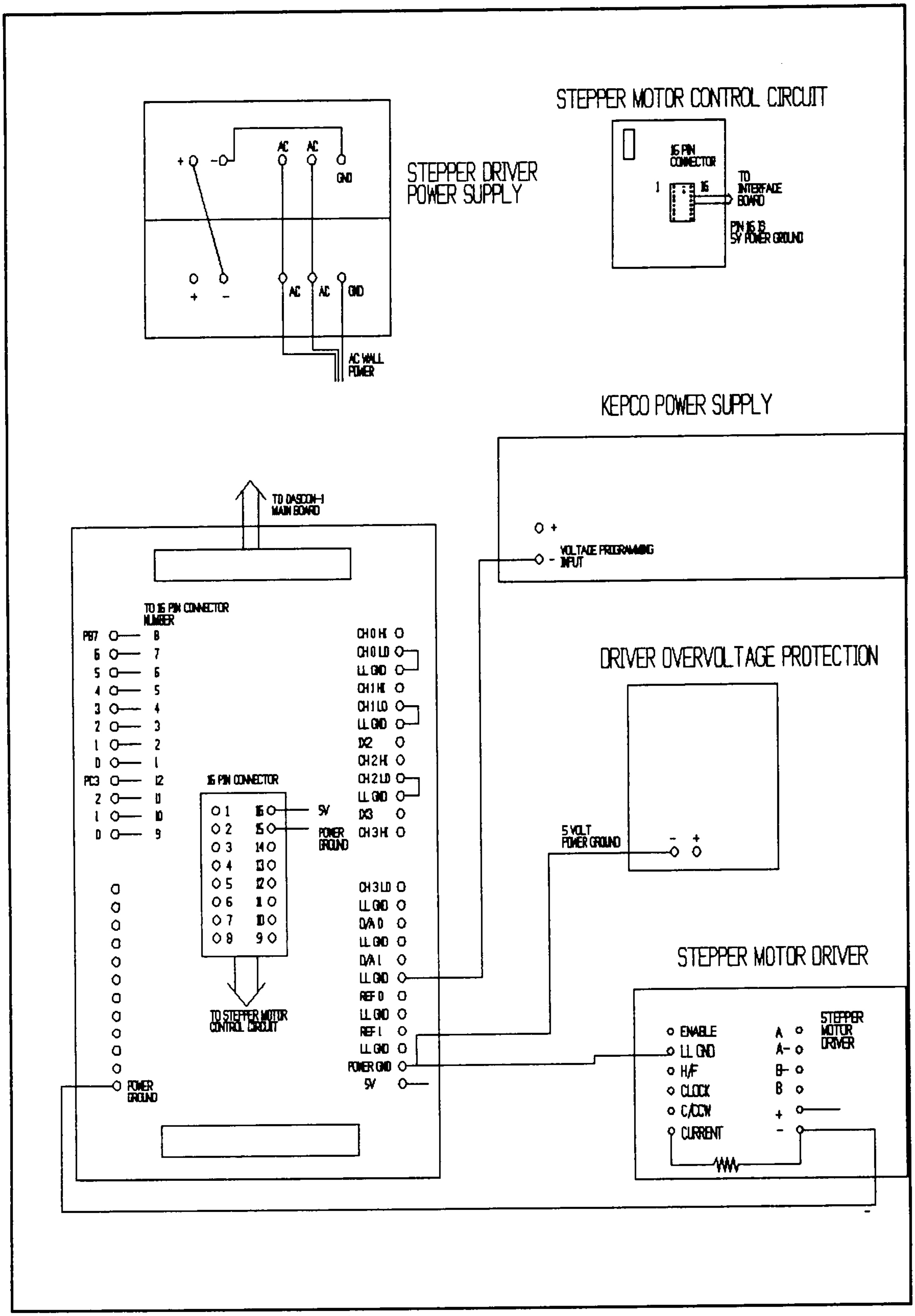


FIGURE I.9 Ground Wire Diagram.

APPENDIX J

FRAME DRAWINGS

This appendix contains drawings for the stepper motor characterization system frame. Figures J.1 through J.6 contain detailed information on each individual frame component.

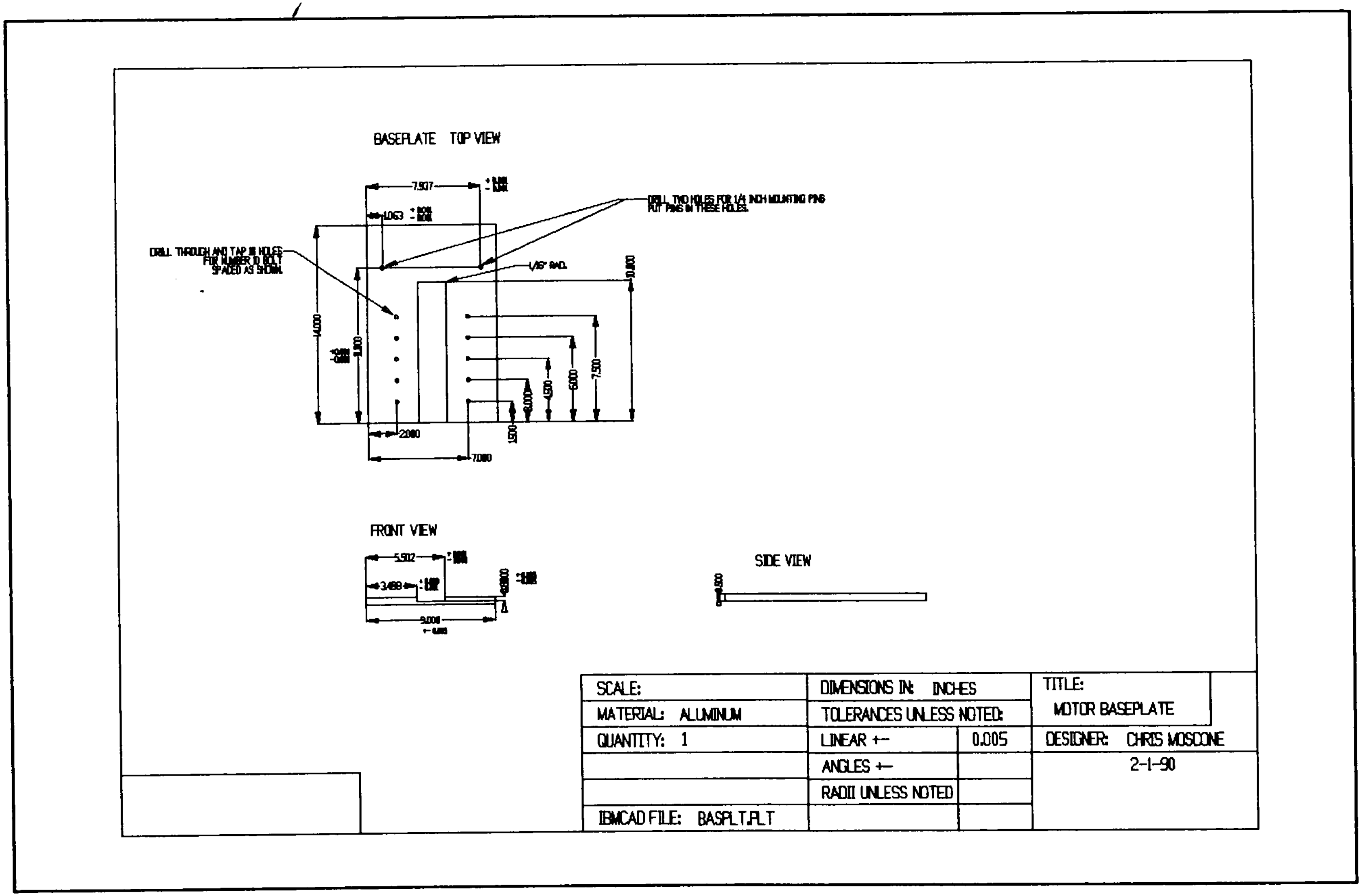
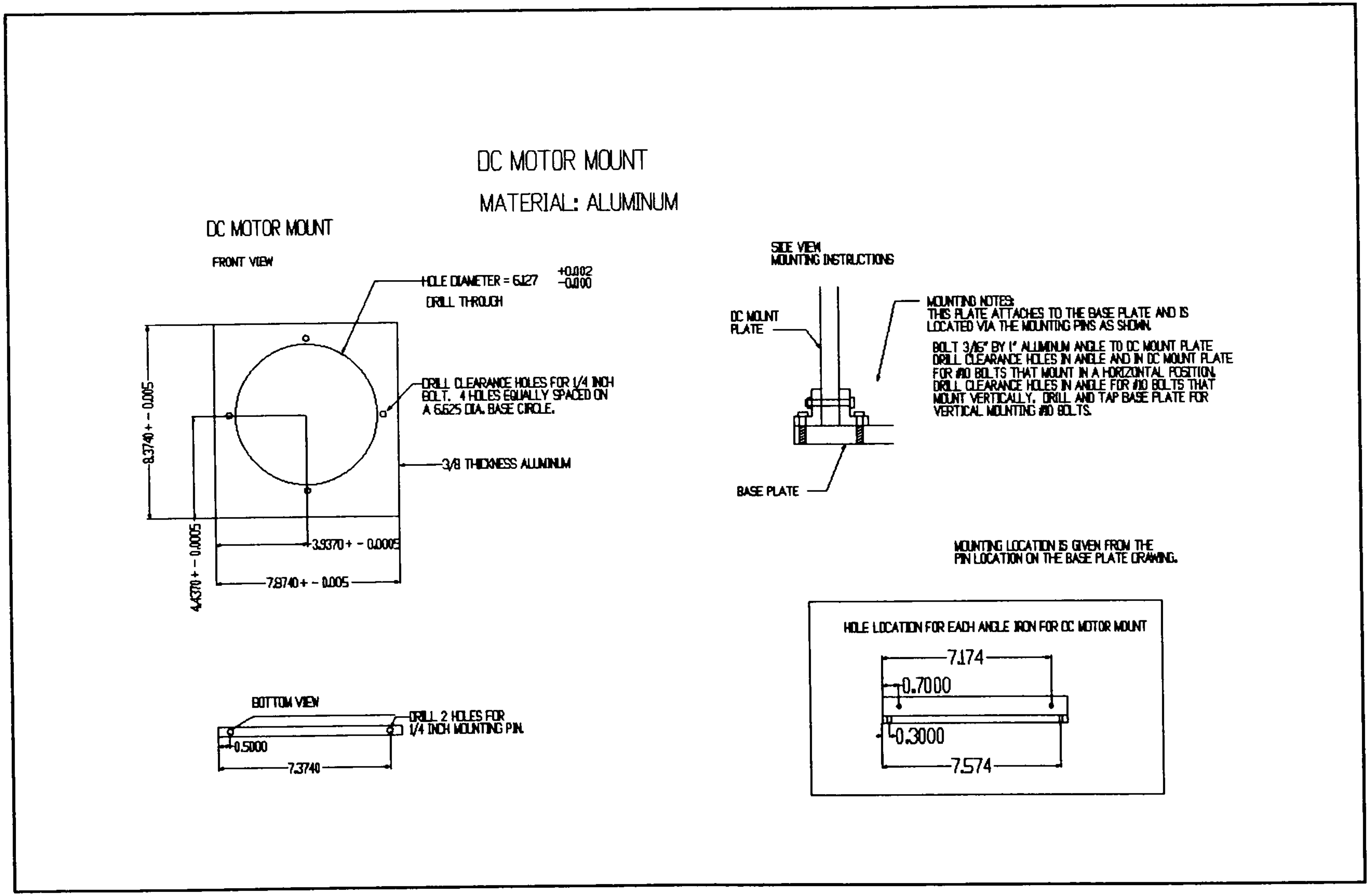


FIGURE J.1 Frame Baseplate.



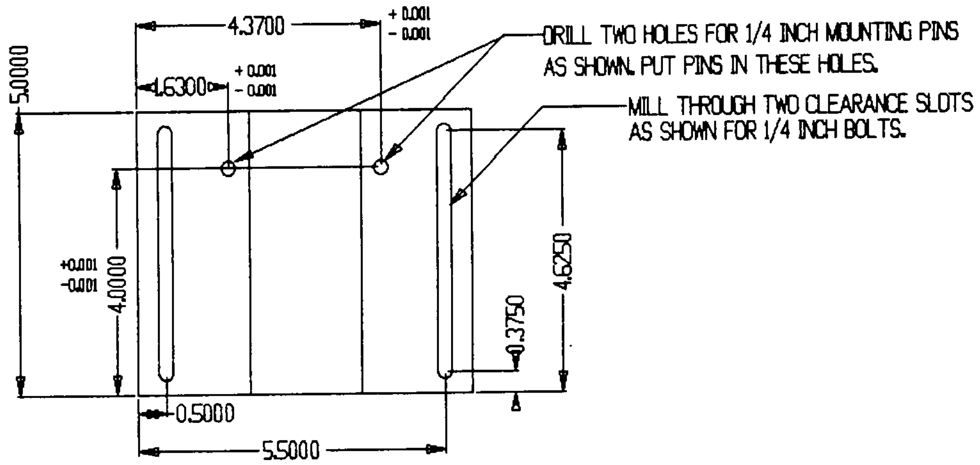
MOUNTING NOTES:
THIS PLATE ATTACHES TO THE BASE PLATE AND IS LOCATED VIA THE MOUNTING PINS AS SHOWN.

BOLT 3/16" BY 1" ALUMINUM ANGLE TO DC MOUNT PLATE DRILL CLEARANCE HOLES IN ANGLE AND IN DC MOUNT PLATE FOR #10 BOLTS THAT MOUNT IN A HORIZONTAL POSITION. DRILL CLEARANCE HOLES IN ANGLE FOR #10 BOLTS THAT MOUNT VERTICALLY. DRILL AND TAP BASE PLATE FOR VERTICAL MOUNTING #10 BOLTS.

MOUNTING LOCATION IS GIVEN FROM THE PIN LOCATION ON THE BASE PLATE DRAWING.

FIGURE J.2 DC Motor Mount.

STEPPER GUIDE PLATE MATERIAL: ALUMINUM
TOP VIEW



STEPPER MOTOR GUIDE PLATE
FRONT VIEW

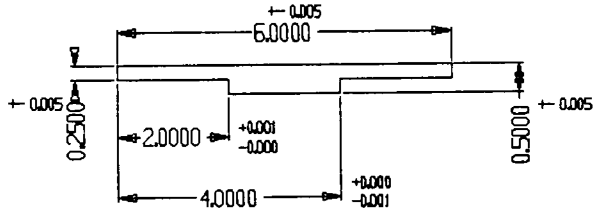
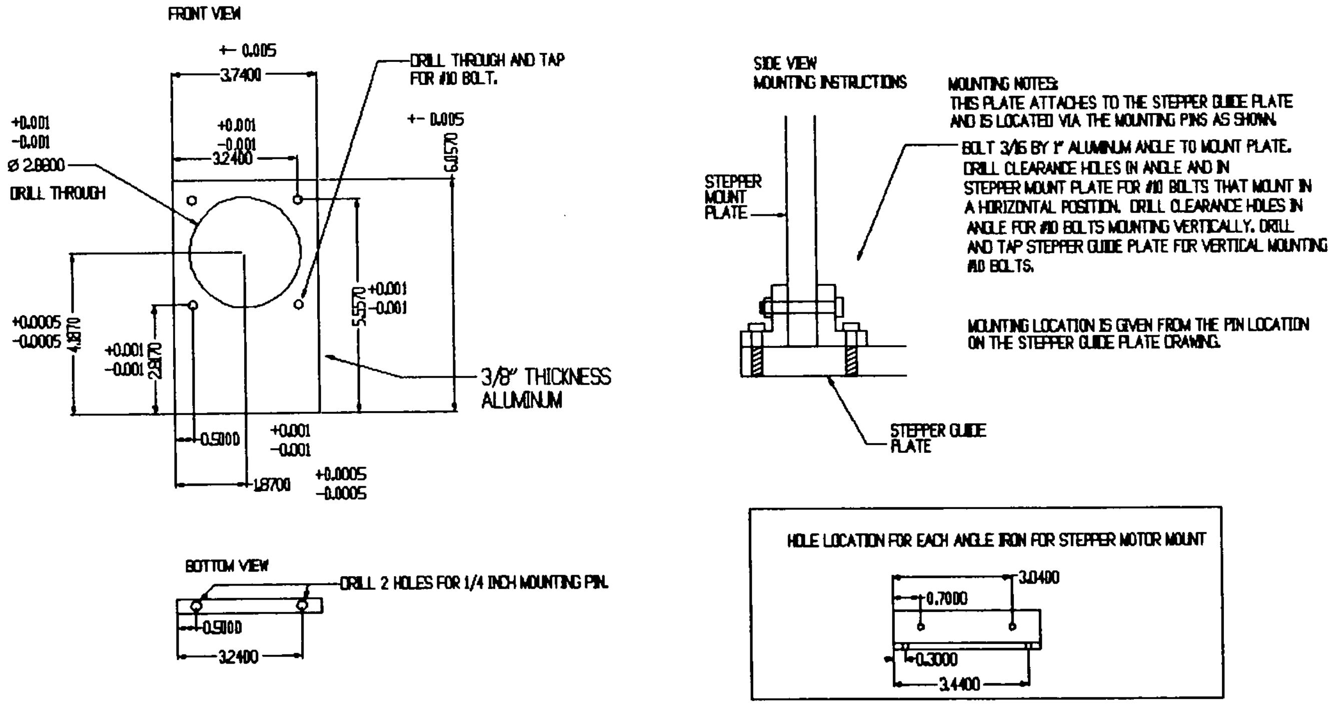


FIGURE J.3 Stepper Motor Guide Plate.



MOUNTING NOTES:

THIS PLATE ATTACHES TO THE STEPPER GUIDE PLATE AND IS LOCATED VIA THE MOUNTING PINS AS SHOWN.

BOLT 3/16 BY 1" ALUMINUM ANGLE TO MOUNT PLATE. DRILL CLEARANCE HOLES IN ANGLE AND IN STEPPER MOUNT PLATE FOR #10 BOLTS THAT MOUNT IN A HORIZONTAL POSITION. DRILL CLEARANCE HOLES IN ANGLE FOR #10 BOLTS MOUNTING VERTICALLY. DRILL AND TAP STEPPER GUIDE PLATE FOR VERTICAL MOUNTING #10 BOLTS.

MOUNTING LOCATION IS GIVEN FROM THE PIN LOCATION ON THE STEPPER GUIDE PLATE DRAWING.

FIGURE J.4 Stepper Motor Mount.

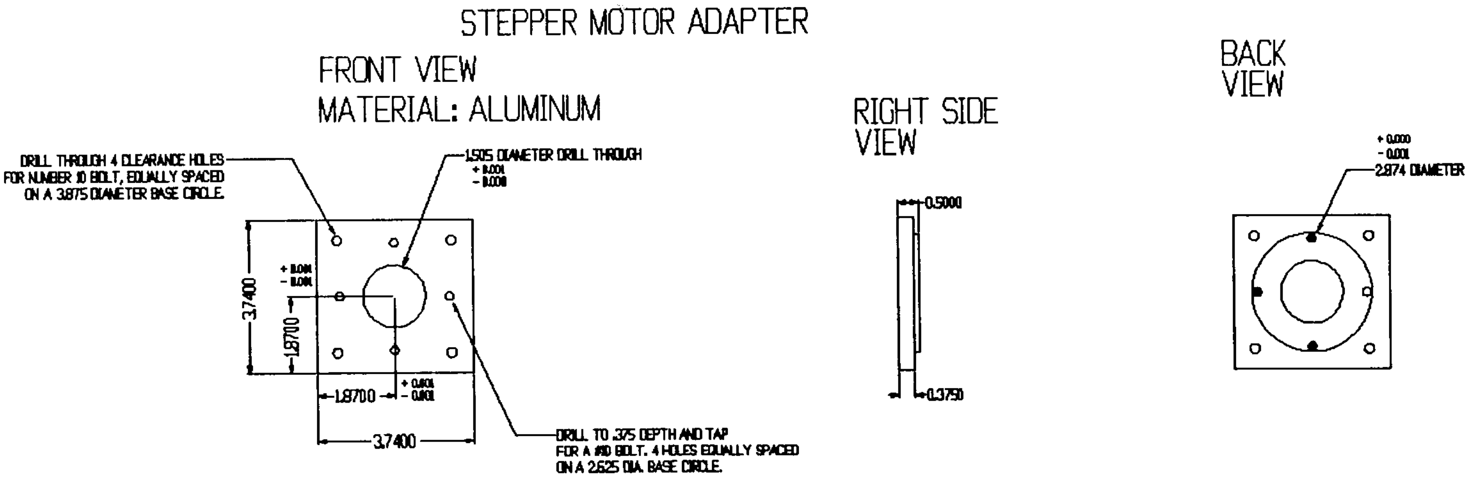


FIGURE J.5 Stepper Motor Adapter.

FIGURE J.5 Stepper Motor Adapter.

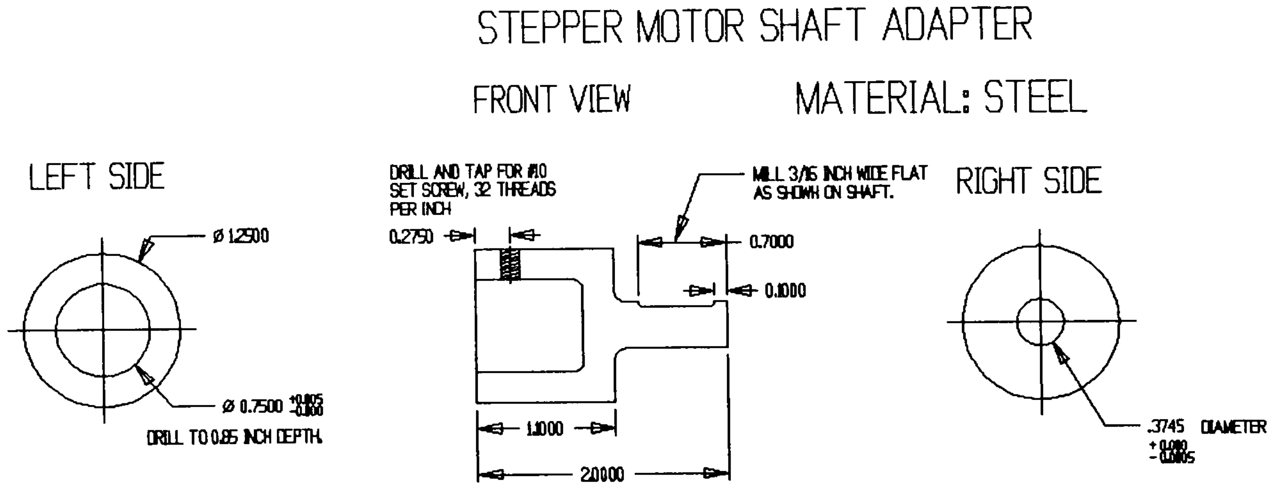


FIGURE J.6 Stepper Motor Shaft Adapter.

VITA

Christopher G. Moscone was born on June 8, 1965 in Boston, Massachusetts. In 1968, he moved to Knoxville, Tennessee. After graduating from South-Young High School in Knoxville in 1983, he entered the University of Tennessee in Fall of 1983, and received his Bachelor of Science degree in Mechanical Engineering in 1988. In Fall 1988 he entered graduate school in Mechanical Engineering at the University of Tennessee, with an emphasis in machine and electromechanical system design. A graduate teaching assistantship and fellowship involved work as a teaching assistant for an undergraduate experimental lab class.

He received his Master of Science in Mechanical Engineering in May 1991. Chris's interests include waterskiing, automobile racing, and automotive engine technology.