COMMON DRIVE UNIT

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ABSTRACT

The Common Drive Unit (CDU) is a high reliability rotary actuator with many versatile applications in mechanism designs. The CDU incorporates a set of redundant motor-brake assemblies driving a single output shaft through differential. Tachometers provide speed information in the AC version. Operation of both motors, as compared to the operation of one motor, will yield the same output torque with twice the output speed.

INTRODUCTION

The CDU drive motors can be (and have been) designed to meet specific program needs. Two designs of the CDU are fully developed, qualified, and space proven by use in the Solar Max Repair Mission. The CDU's were used to drive retention latches for the multi-mission spacecraft (MMS) and also to rotate and tilt the MMS. Future usage of the CDU includes the following:

° Keel Latch Drive for the Space Telescope
° Umbilical Disconnect Mechanism for the Space Telescope
° Deployment and Stowage of Solar Array Wings for the EURECA Free-flying Platform
° Latches for the Upper Atmospheric Research Satellite

Common Drive Unit

The CDU consists of a differential gearhead and a set of two motor-brake assemblies. The motor-brake assembly of the original CDU design consisted of a three-phase AC motor, a three-phase AC brake, and a tachometer. Two configurations, 0001 and 0002, were designed and supplied. (See Figure 1.) Both configurations have output torque of 11 N-m. The output speed of the 0001 configuration is 8 rpm and of the 0002 configuration is 64 rpm. This was accomplished by using a smaller motor with a higher gear ratio for the 0001 unit. The most recent design (currently in qualification testing) incorporates a DC brush-type motor and a DC brake. (See Figures 2 and 11.)

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Any type of motor-brake assembly could conceivably be used. Proposed CDU motor designs have included the following:

A. DC brushless motors, including the drive electronics and additional planetary gearing
B. DC brush motors with a torque limiting hysteresis clutch
C. Stepper motors

DRIVE UNIT MECHANICAL DESIGN

The primary design goal of the CDU was to provide as much redundancy as reasonably possible. There are, therefore, two separate power paths with the only common element being the output shaft, which is also the planet carrier. There are numerous redundant features within each individual power path. A cross-sectioned layout of the unit is shown in Figure 3. The complete unit consists of a differential output driven by two spur gears, dual two stage planetary reductions and dual motors with integral friction brakes. The differential allows either of the two motors to be operated separately or together. If one motor fails, its brake will lock the motor shaft and allow output from the other motor.

The output shaft carries three pairs of planet gears turning on needle bearings, supported by carrier pins. The carrier pins are free to turn and act as bearings in the event the needle bearings seize. The planets alternately engage two internal ring gears. External ring gears mate with two spur gears. The ring gears are also supported by bearings that are free to turn if the bearing should seize. If the entire differential assembly malfunctions, output can still be provided by powering both motors. The differential then turns as a unit, without providing any gear reduction. If only one motor drives the differential, it produces a 2/1 reduction in speed, but a 2/1 increase in torque, so that the torque is the same as when both motors are powered.

Between the differential and each motor are two-stage planetary gear reductions. Each stage has a floating carrier with three posts supporting three planet gears on ball bearings. An internal ring gear is common to both stages. The ring gear was made as a separate part to simplify the design and fabrication of the spacer plate. The ring is trapped against a shoulder when the motor is installed, and an axial dowel pin at the ring O.D. prevents rotation.

All of the gears and bearings in the drive are lubricated with Braycote Micronic 601. This grease has good temperature and vacuum stability and has worked well in many of our space designs. All rubbing surfaces are coated with the grease, but

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the amount is controlled to minimize the effects of high viscosity at extremely low temperatures and reduce any possibility of leakage from the unit.

The overall gear reduction ratio of the 0001 unit is 786.5 to 1. This is accomplished by an 11/1 planetary, a 5.286/1 planetary, a 6.765/1 spur stage, and the 2/1 differential. The unit had to produce a normal torque of 11 N-m and a stall torque of 36.7 N-m maximum. However, it also had to be operated into a hard stop. The mechanical parts were, therefore, designed to have adequate factors of safety at over twice the maximum stall torque, or 80 N-m.

The motor/brakes used on the drive unit are independent assemblies which are pretested and can be replaced if necessary without any adjustment or calibration.

AC MOTOR/BRAKE DESIGN

The AC motor used on this unit was based on a motor that was developed for the Shuttle Cargo Bay pallet latches. Those latches also used a dual motor/brake and differential design. Over 200 of those motors have been fabricated and shipped. Since the brake of a nonoperating motor must hold to allow the other motor to provide output through the differential, every feature of the brake was made redundant to ensure fail-safe operation.

Figure 3 shows a cross section view of the motor/brake. Referring to this figure, the following features should be noted.

A. The motor rotor is a squirrel cage type for ruggedness and high reliability.

B. The bearings are preloaded with a spring washer to 13-22 newtons (3-5 pounds) to provide for differential thermal expansion.

C. The insulation system consists of polyimide coated magnet wire, polyimide impregnation, and polyimide film (all Class 220) for maximum compatibility and temperature resistance.

D. The brake armature has a total of six springs to minimize the effect of failure of one spring.

E. The brake disc is mounted on a splined sleeve which is mounted on a splined shaft to provide redundancy.

F. The brake disc slides on a spline and is captured between the two friction surfaces resulting in no axial loading of the bearings.

G. The armature pins slide in a self-lubricating polyimide bushing which can also slide in the pilot holes to provide redundancy.

H. The solenoid is composed of six poles, each phase having two poles spaced 180° for balance.

I. The bearings are sealed to minimize lubricant migration. Lubricant is Micronic 601 grease.

J. The friction surfaces are separated from all lubricated surfaces by a five stage labyrinth seal.

K. The friction surfaces and their bonding interface are slotted to create a "key" to prevent rotation in case of a bond failure.

L. The back nut and internal screws are secured with a mechanical lock and a secondary adhesive lock.

M. All materials are selected to minimize differential thermal expansion.

N. The brake disc is aluminum to minimize rotating inertia.

O. Connections between motor and brake wiring are made using terminals.

P. All wiring and terminals are conformal coated.

Q. The brake friction surfaces are composed of brake lining on brake lining to minimize wear and provide maximum stability of friction torque at ground ambient or space vacuum and temperature conditions.

R. The brake has dual friction surfaces to provide required holding torque even if one surface is completely inoperative.

THERMAL DESIGN

The unit motor/brake has been designed and tested for operating temperatures from -71°C to +176°C. Mechanical stresses due to thermal effects have been minimized by using 15-5PH stainless steel for motor housings, gears, and shafts. The inherent thermal stability permits nonoperational temperature exposure of -129°C without damage or performance degradation.

TACHOMETERS

The tachometer consists of a wound two-phase stator and a permanent magnet rotor. Both the output voltage and frequency varies linearly with rotational speed.

MOTOR/BRAKE MAGNETIC DESIGN

The motor size and design are controlled by the required torque output and the required brake operation. The final design required close coordination and integration of the motor and brake designs to ensure proper operation. Curves of the motor performance are shown for reference in Figures 4 through 7.

The shape of the speed-torque curve is dictated primarily by the ratio of rotor resistance to the motor reactance. To obtain good low slip (high speed) operation, low rotor resistance is required. Increasing the rotor resistance will result in increased stall torque until the peak torque is at stall. Further increases will cause reduced stall torque. The temperature sensitivity of the motor is also affected by the resistance/reactance ratio. With very low rotor resistance, the stall torque will increase at high temperature, since the rotor resistance increases with temperature. At high rotor resistance, the torque will reduce as the temperature increases. In addition, the high speed torque always reduces as the rotor resistance is increased. The rotor resistance was selected to minimize the stall torque temperature sensitivity as illustrated by Figures 5 and 6.

The stall torque for two phase operation is approximately two thirds the three phase torque. The torques at other speeds are also reduced; the amount depends on the final design parameter. For this design, the two-phase torque is greater than two thirds the three-phase torque at all speeds above stall.

The power factor of an AC induction motor is low at stall and increases to a peak at some speed, then reduces again as the speed increases further. Figure 4 shows the nominal performance at rated input, room ambient. The power factor peaks at approximately 68%. It is above 60% for all torque loads greater than 14 N-m and above 50% for all torque loads greater than 85 N-m. The efficiency peaks at 65% and is greater than 60% for loads between 4.3 N-m and 2 N-m. It is greater than 50% for loads between 0.2 N-m and 2.7 N-m. The current ranges from 2.18 amps to 0.46 amp.

Figure 5 shows the speed-torque output at -71°C for the voltage and frequency extremes. Both the stall torque and the maximum torque vary approximately 35% over these extremes.

Figure 6 shows the speed-torque output at +121°C for the specified voltage and frequency extremes. At this high temperature, the stall torque is also the peak torque and varies approximately 35%.

Figure 7 shows the speed-torque output at the conditions of minimum and maximum peak torque. The minimum peak torque occurs at minimum voltage, maximum frequency, and maximum temperature. Note that the stall torques are very nearly the same.

The design for the 0001 configuration is basically the same except scaled down for the reduced output.

The motor size required for either configuration, depends primarily on the required output duty cycle. The limiting constraint on the 0002 configuration is the heat dissipation in the rotor during stall or near stall operation. By designing the motor to have the maximum rotor temperature rise that can be safely handled during the specified 30 second stall condition, the size is minimized.

The brake must be designed so that the solenoid force is great enough to pull in at the low voltage, high temperature (i.e., minimum current) condition with two phases excited and also drop out with two phase removed at the other extreme (i.e., maximum current). For a conventional design, the force will vary as the square of the applied current and directly with the number of phases.

The general relation between the solenoid force and current in an unsaturated design is shown in Figure 8. This figure shows the force versus current for six conditions.

    1. Three phase input, minimum gap (brake engaged).
    2. Three phase input, maximum gap (brake released).
    3. Two phase input, minimum gap.
    4. Two phase input, maximum gap.
    5. One phase input, minimum gap.
    6. One phase input, maximum gap.

The minimum running current and the minimum and maximum stall current are drawn in and the following points are pertinent.

A.   TWO PHASE INPUT, MINIMUM GAP, AT MINIMUM RUNNING CURRENT

The generated solenoid force must be great enough to hold the armature (i.e., must exceed the spring force).

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B. ONE PHASE INPUT, MINIMUM GAP, AT MINIMUM RUNNING CURRENT

    The generated solenoid force must be small enough for
the spring to overcome to allow the armature to release
and engage the brake.

C. TWO PHASE INPUT, MAXIMUM GAP, AT MINIMUM STALL CURRENT

    The generated solenoid force must be great enough to
overcome the springs and allow the armature to pull in.

D. ONE PHASE INPUT, MAXIMUM GAP, AT MINIMUM STALL CURRENT

    The generated solenoid force must be low enough for the
spring to prevent the armature from pulling in.

E. TWO PHASE INPUT, MAXIMUM GAP, AT MAXIMUM STALL CURRENT

    The generated solenoid force must be great enough to
overcome the spring and allow the armature to pull in.

F. ONE PHASE INPUT, MAXIMUM GAP, AT MAXIMUM STALL CURRENT

    The generated solenoid force must be low enough for the
spring to prevent the armature from pulling in.

    By referring to the figure, it can be seen that the maximum
force which the spring must overcome occurs at point "F". This
establishes the minimum spring force. The minimum force which
must overcome the spring force occurs at point "A" and estab-
lishes the maximum spring force. From the figure, the minimum
spring force is more than 3 times the maximum spring force, an
obvious impossibility.

    Figure 9 shows the same conditions for a brake designed
with a square saturation curve. The force variations are mini-
mized by operating the solenoid in saturation at the stall cur-
rent levels. With this type design, the maximum spring force is
more than 40% greater than the minimum spring force, which is
possible.

    This allows the following brake operation:

3 Phase Operation

    The brake will release when excitation is applied and engage
when power is removed for all conditions of voltage,
frequency, and temperature.

2 Phases Operation

The brake will release when excitation is applied and engage when power is removed for all conditions of voltage, frequency, and temperature.

1 Phase Operational

The brake will engage. Brake torque will be less than one-half the unexcited torque until excitation is removed.

DC MOTOR DESIGN

The motor assembly for the DC CDU is shown in Figure 10. Performance of the complete drive unit is shown in Figure 11.

The rotor incorporates a lamination stack, windings, commutator, and shaft. The insulation system is rated at 220°C. Labyrinth seals are used to avoid bearing contamination from brush wear particles.

The stator contains samarium cobalt permanent magnets; their extreme resistance to demagnetization assures consistent motor performance over the unit life. A band is bonded to the I.D. to protect the magnets during assembly, and prevent a potential magnet chip from entering the air gap, and possibly jamming the motor.

Brush holders are cartridge type, making the brushes easily replaceable without motor disassembly. This is important when determining wear rates in development and life testing.

Bearings are deep groove, double shielded, and lubricated with Braycote Micronic 601 grease.

MOTOR BRUSH COMPATIBILITY

The most important factors in a vacuum-rated motor design are the characteristics of the brush material. Sperry's preferred brush material has a low metallic content with molybdenum di-sulfide for vacuum lubrication. It was selected for low wear in a vacuum, but it's most important characteristic is the relatively high resistance of the wear debris. End-of-life insulation resistance is typically in the one megohm range. Other brush types with a high metallic content can cause significant current leakage paths to ground. In the extreme case, the brush debris can bridge between commutator bars, shorting out the motor.

Brushes wear due to two factors; mechanical friction and electrical arcing. The selected material has a low wear rate due

to friction but will wear very rapidly if arcing is significant. To maximize life, the motor is a very slow speed design (600 rpm). This minimizes wear due to friction and reduces arcing. To further reduce arcing, the motor was designed with 49 winding coils and 49 commutator bars, many more than normally used for a motor of this size. The result is a substantial reduction in inductance for each coil and lower voltages generated between adjacent commutator bars as the motor is commutated.

Motor testing confirmed the soundness of this design. Brush arcing was not visible in a dark room and wear in a vacuum was low. Motor life in a vacuum is approximately 400 hours. Another benefit is the long life under atmospheric pressure. From measured wear rates, the life was projected to be 40,000 hours. Thus, special precautions, such as nitrogen back-fill are not necessary or desirable.

DC BRAKE DESIGN

The brake is a fail-safe design which will disengage when power is applied. (Refer to Figure 11.) The brake has two friction material interfaces and is engaged by four compression springs. The brake armature slides approximately 0.015 cm on four pins. The pin sliding surfaces are redundant. The rotating disc is attached to the shaft by redundant splines. The brake has no mechanical single-point failure modes and could be electrically redundant with the addition of another energizing coil.

The friction material was developed by Sperry for the Shuttle Remote Manipulator Arm. It provides consistent torque (approximately +25%) under environmental extremes of pressure, temperature and humidity.

EMI FILTER

A DC motor produces conducted and radiated emissions due to current ripple in commutation, and brush arcing. This motor design has low current ripple and arcing due to the use of many coils and commutator bars. A relatively small EMI filter can be used effectively since the basic motor design is very quiet. Figure 10 shows the EMI schematic. Since the motor polarity must be reversed to change direction of rotation; the filter has been designed to be effective for either polarity.

TESTING EXPERIENCE

The AC drive units had one significant test problem. The original design included a three-phase thermal protector which was sensitive to motor temperature as well as input current.

During vacuum stall testing, the motor and brake windings over-heated before the thermal protector tripped. To correct this, three small thermostats were placed in good contact with the motor windings. Selective screening was used to match thermostats since all three phases should be opened at approximately the same time.

The first DC drive units experienced a problem during random vibration testing as part of the qualification. The amplification at the brake pins was higher than expected, and the pins sheared. The pin was redesigned to have an enlarged diameter and to eliminate the shoulder. This design modification provided a safety factor of four at the qualification vibration level.

CONCLUSIONS

The CDU is a high reliability rotary actuator with many versatile applications in mechanism designs.
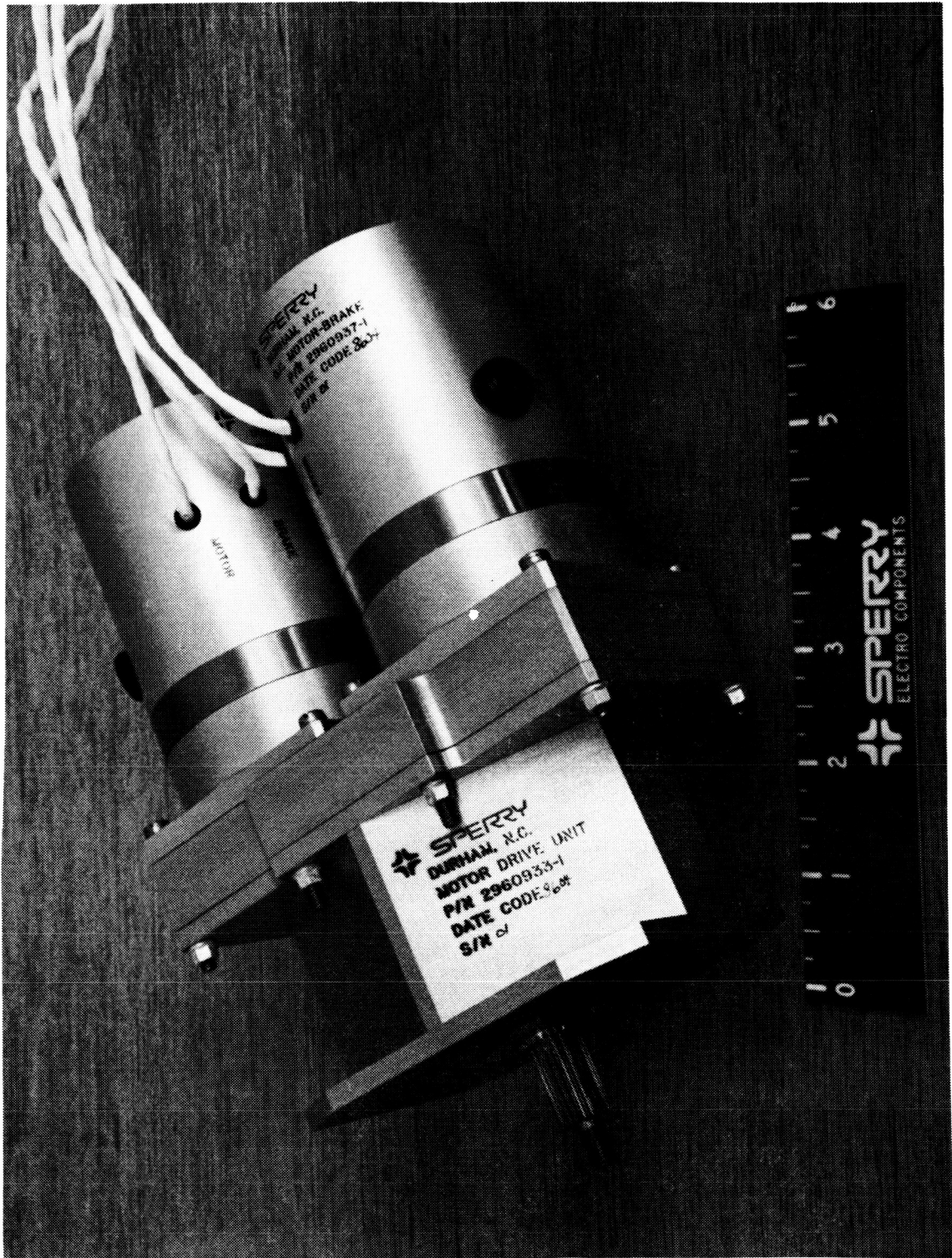
FIGURE 1

FIGURE 2

DIFFERENTIAL

DUAL PLANETARY

TACHOMETER

MOTOR

BRAKE

COMMON DRIVE UNIT

FIGURE 3

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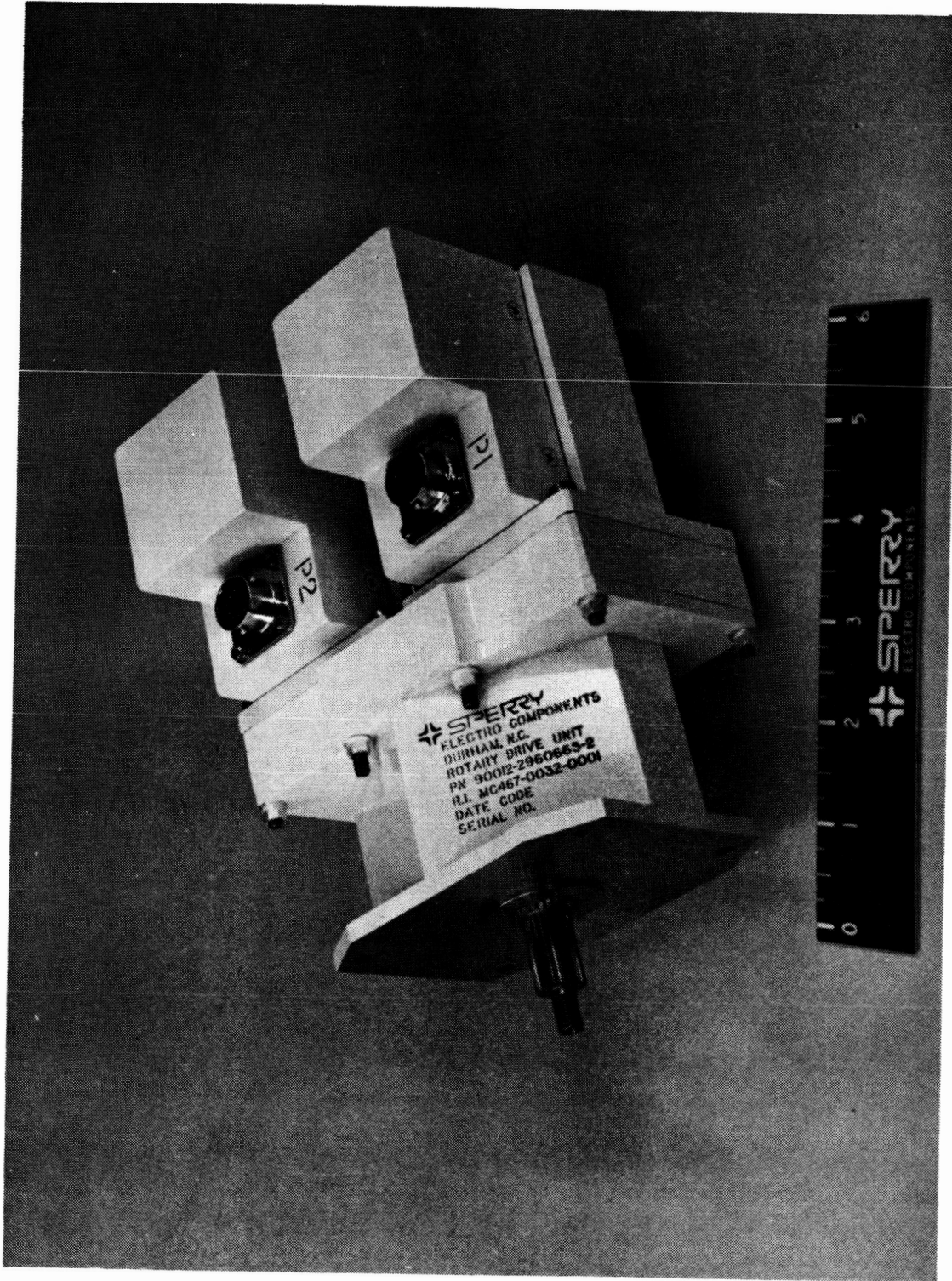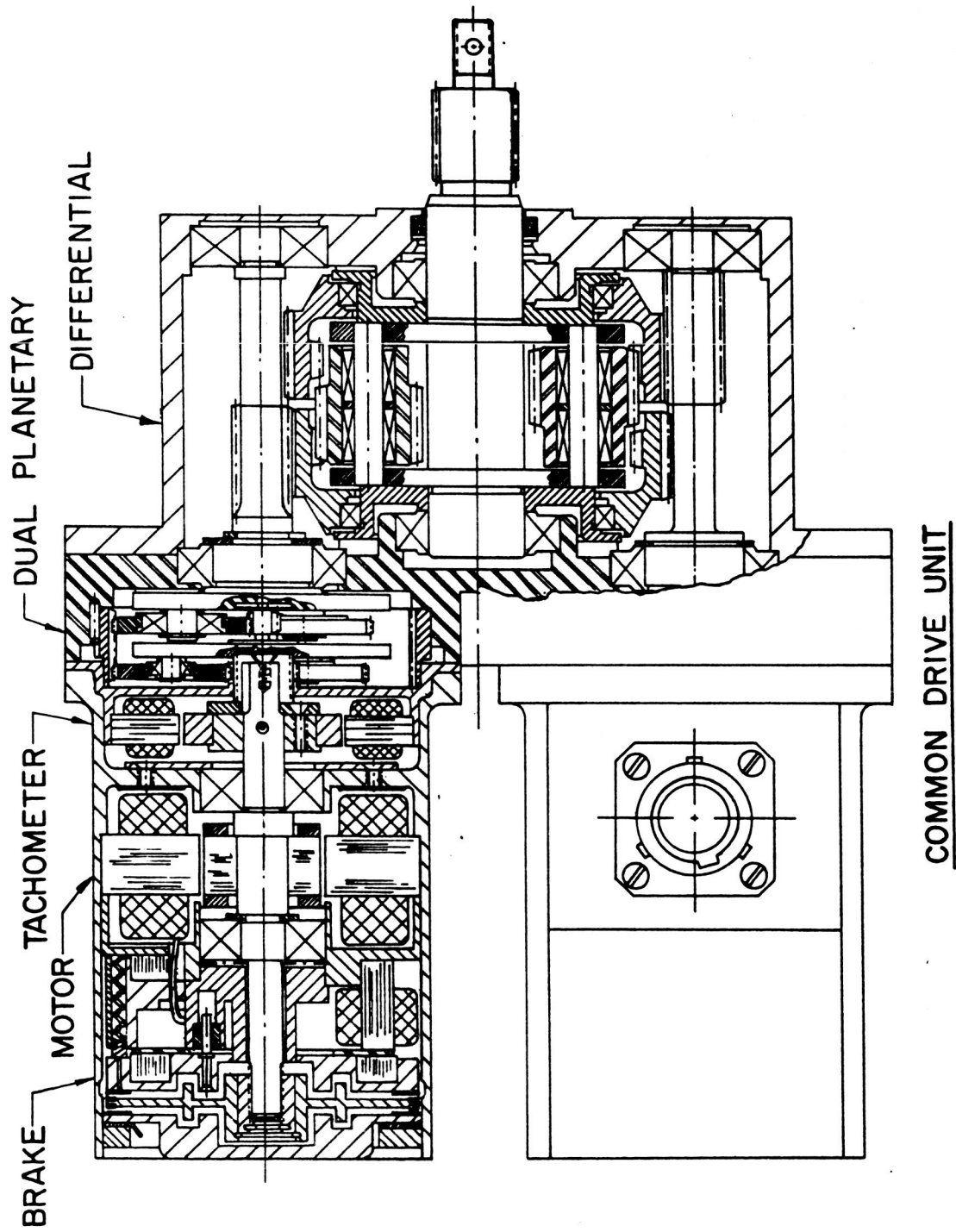
−0002 A.C. DRIVE UNIT
PERFORMANCE AT ROOM AMBIENT

SPEED–RPM

POWER FACTOR–%

EFFICIENCY–%

10°CURRENT–AMPS
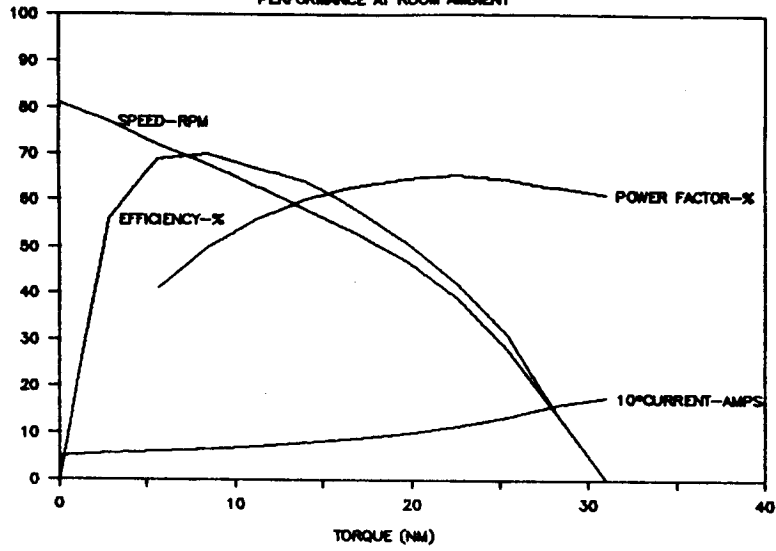
TORQUE (NM)

FIGURE 4

−0002 A.C. DRIVE UNIT
SPEED TORQUE AT −71 C

SPEED (RPM)

108V,407HZ

120V,407HZ

<120V,393HZ

<108V,393HZ

TORQUE (NM)

FIGURE 5

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−0002 A.C. DRIVE UNIT
SPEED TORQUE AT 121 C

Speed (RPM) vs Torque (NM). Curves labeled: 108V,407HZ; 120V,407HZ; <120V,393HZ; <108V,393HZ.

FIGURE 6

−0002 A.C. DRIVE UNIT
PERFORMANCE AT TORQUE EXTREMES

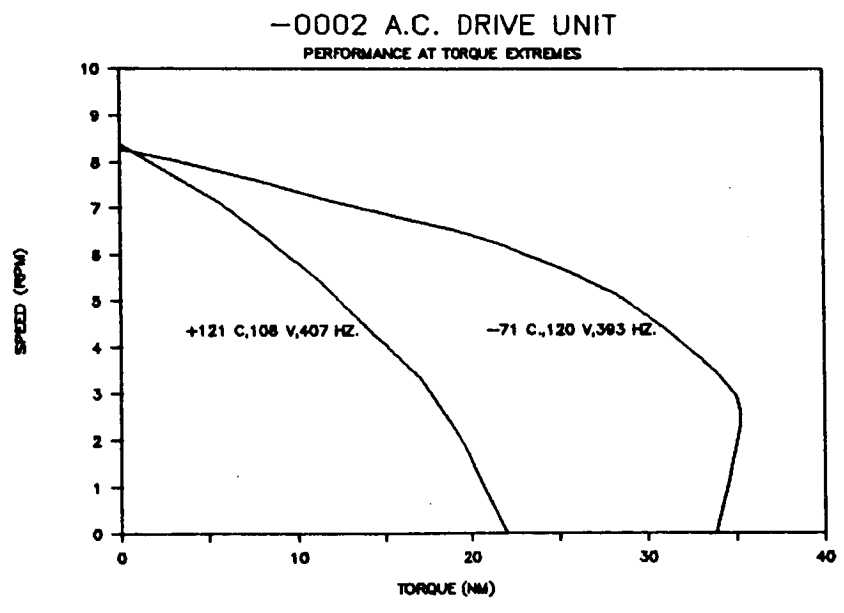Speed (RPM) vs Torque (NM). Curves labeled: +121 C,108 V,407 HZ.; −71 C.,120 V,393 HZ.

FIGURE 7

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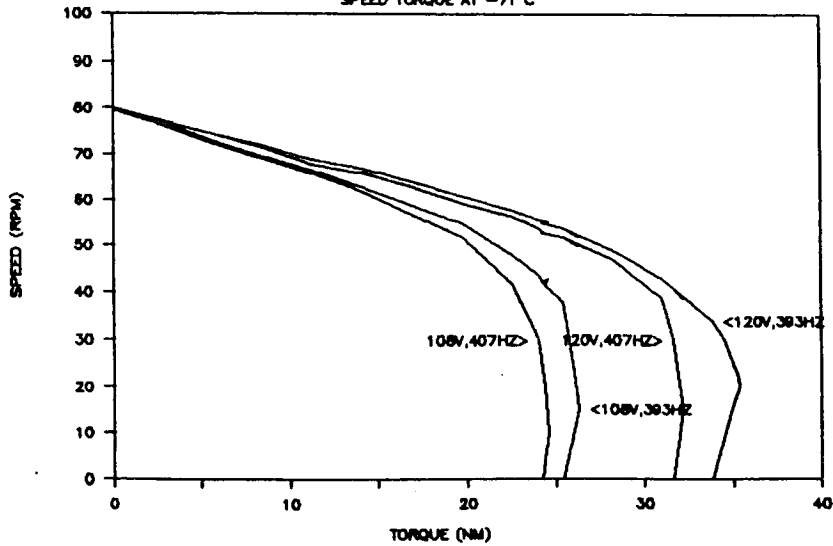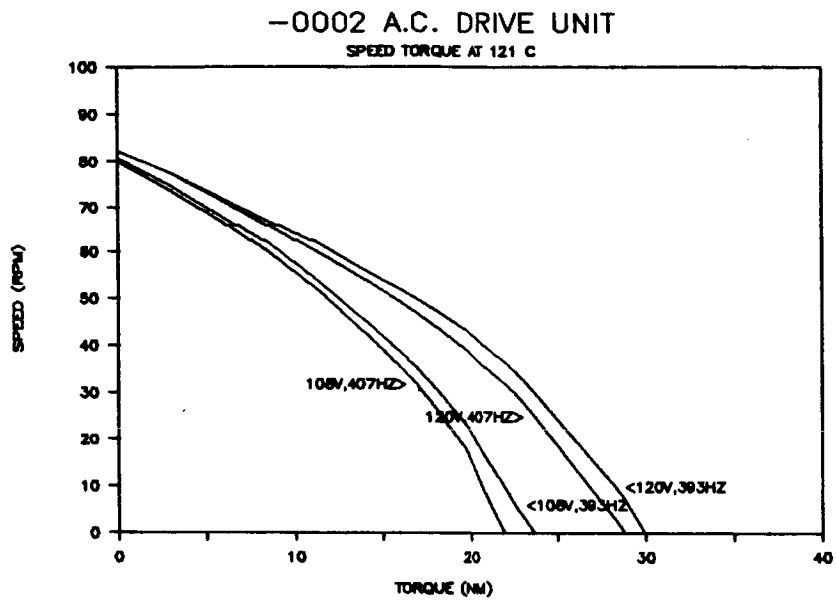
SOLENOID FORCE
FOR UNSATURATED CORE

FIGURE 8

SOLENOID FORCE
FOR SATURATED CORE

FIGURE 9

BRAKE CORE
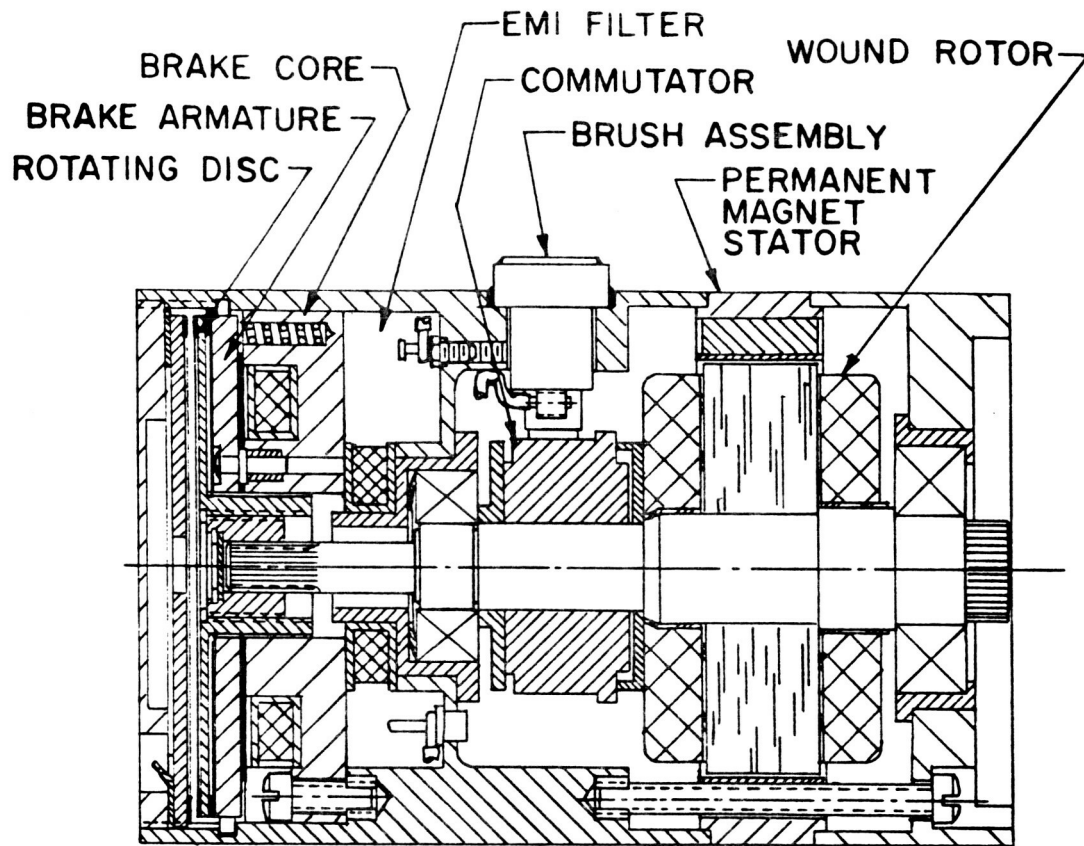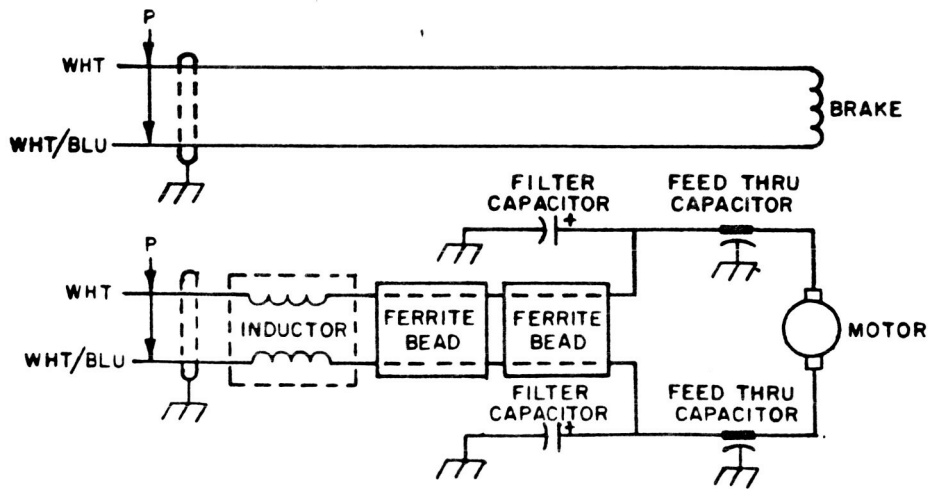BRAKE ARMATURE
ROTATING DISC
EMI FILTER
COMMUTATOR
BRUSH ASSEMBLY
PERMANENT MAGNET STATOR
WOUND ROTOR

DC MOTOR/BRAKE

WHT

WHT/BLU

BRAKE

FILTER CAPACITOR

FEED THRU CAPACITOR

WHT

INDUCTOR

FERRITE BEAD

FERRITE BEAD

MOTOR

WHT/BLU

FILTER CAPACITOR

FEED THRU CAPACITOR
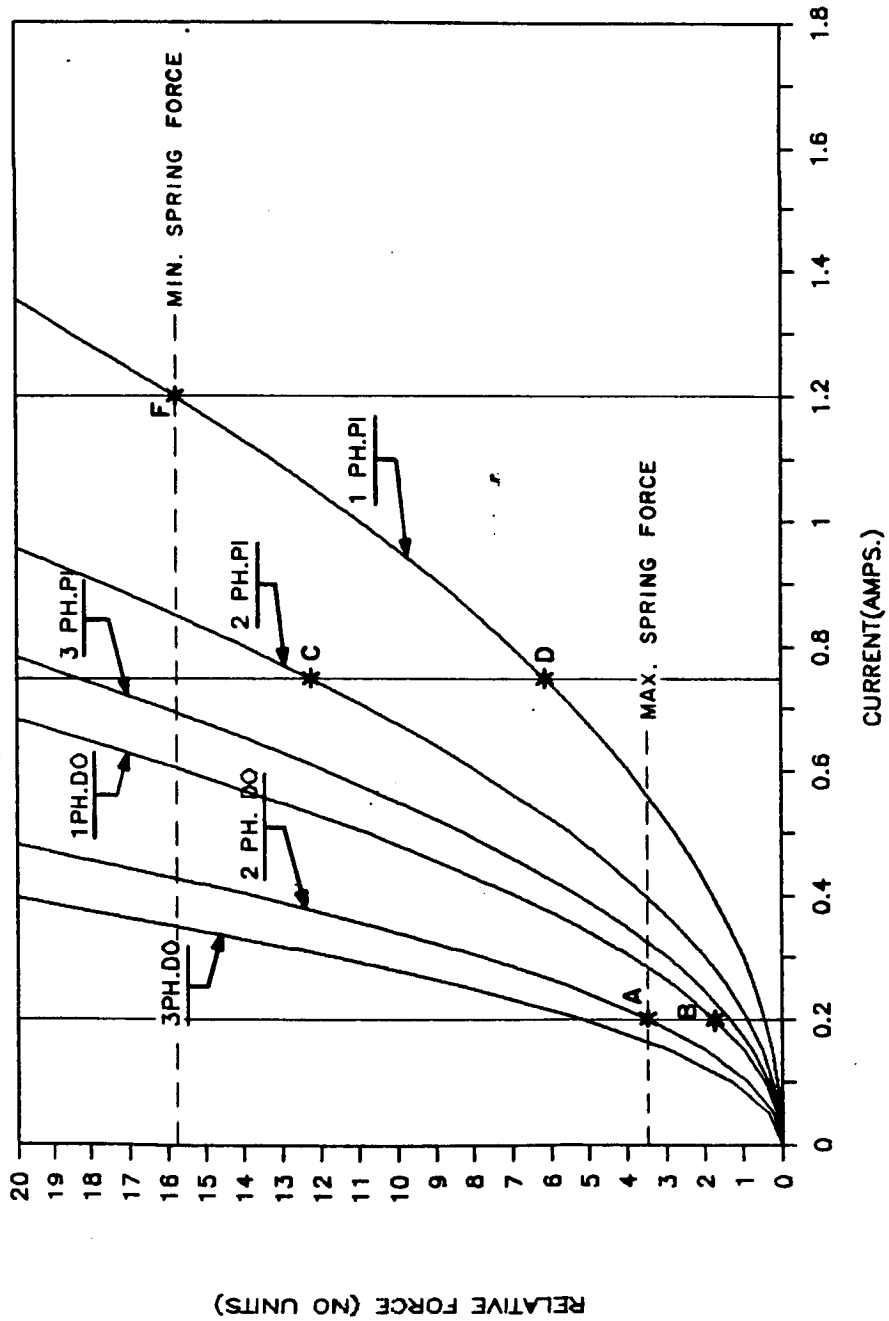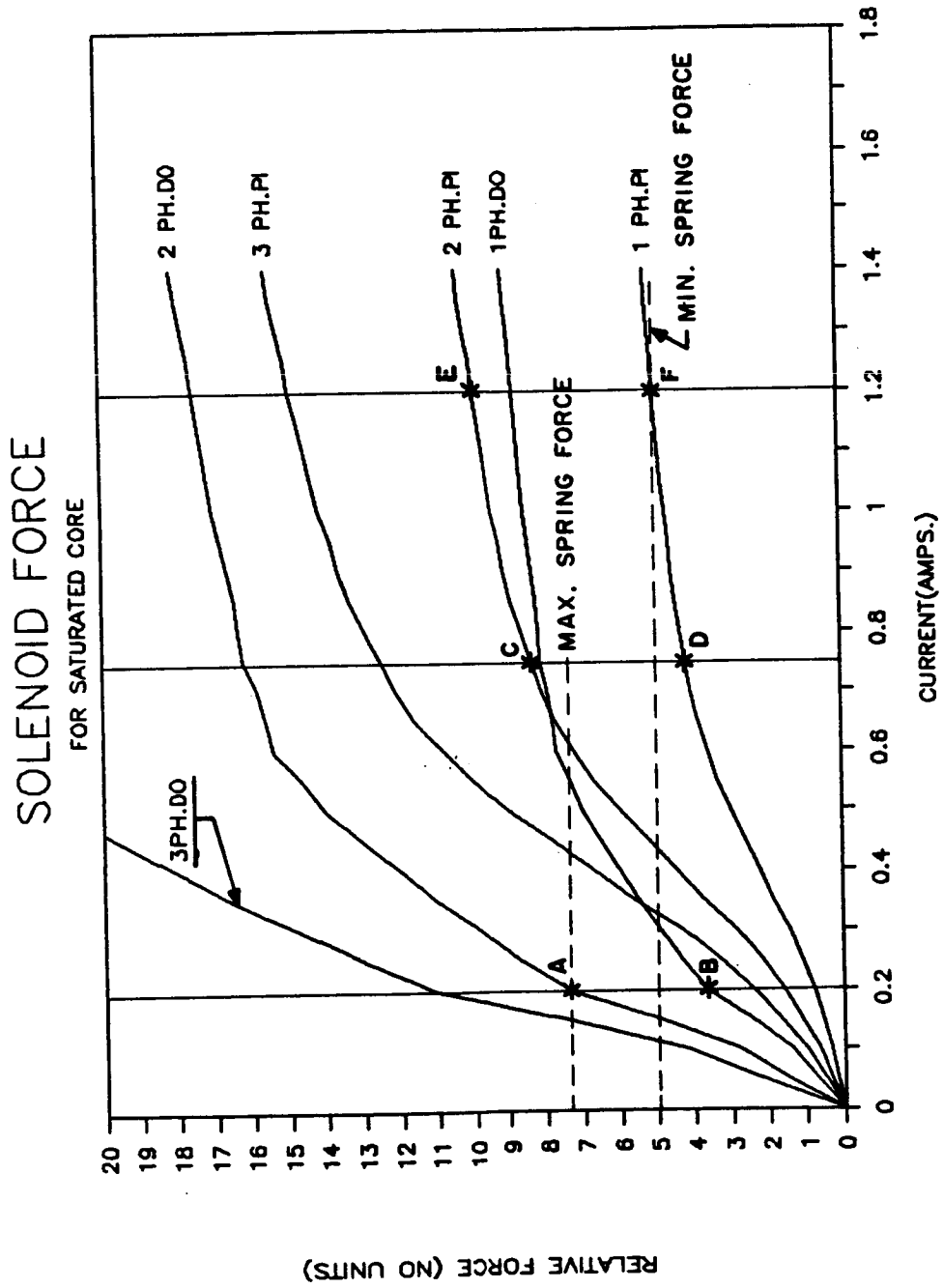
MOTOR/BRAKE SCHEMATIC

FIGURE 10

********* DC MOTOR PERFORMANCE *********

********* COMMON DRIVE UNIT *********

INPUT:

VOLTAGE:	24 MIN.	28 NOMINAL	32 MAX.
TEMP (C):	-68 MIN.	35 MAX.	
RESISTANCE:	108 OHMS @25C	5 TOL.(+,-)	
TORQ. SENS.:	0.52 NM/A	0.028 TOL.(+,-)	
DRAG TORQ.:	0.01 NM		
BRUSH DROP:	0.5 VOLTS		
GEAR RATIO:	786.		
GHD. EFF.:	0.87 PER UNIT		

OUTPUT:

	24V,35C	28V,25C	32V,-68C
VOLTAGE:	24	28	32
TEMPERATURE (C):	35	25	-68
NO-LOAD SPEED (RPM):	0.433	0.552	0.714
NO-LOAD CURR. (AMPS):	0.032	0.034	0.036
STALL TORQUE (NM):	55.15	78.72	166.5
STALL CURRENT (AMPS):	0.199	0.254	0.474
RESISTANCE (OHMS):	117.8	108	66.34

DC MOTOR PERFORMANCE

COMMON DRIVE UNIT

FIGURE II