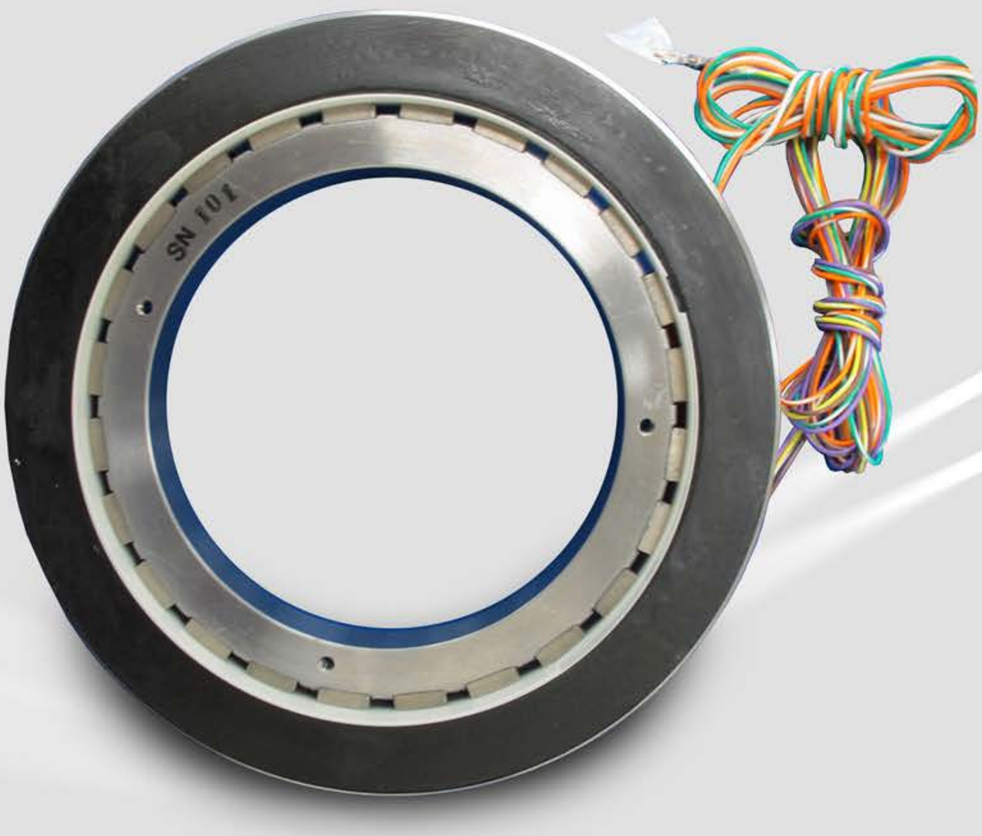
GENERAL DYNAMICS
Ordnance and Tactical Systems



BRUSHLESS DC MOTORS | HANDBOOK

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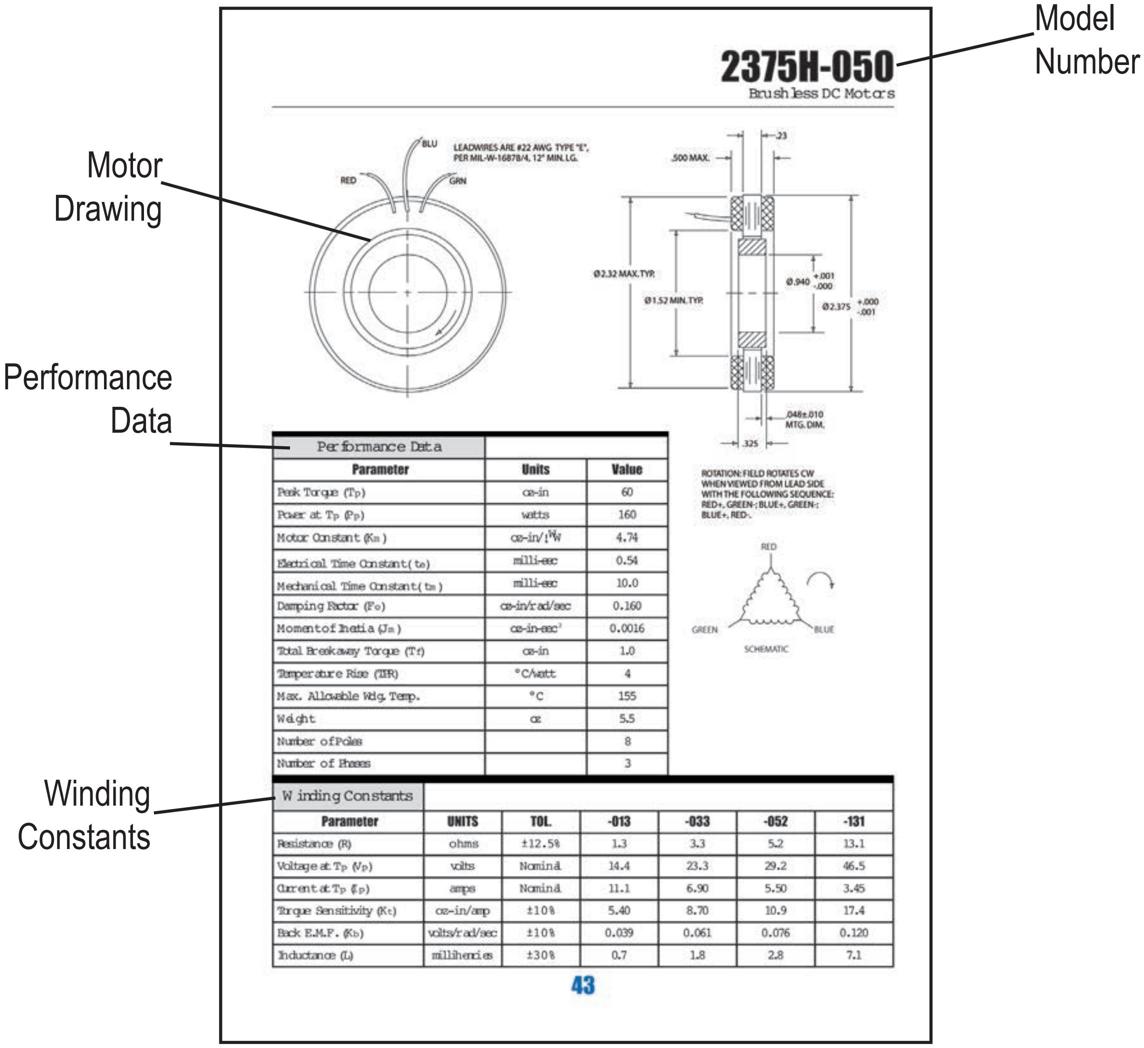
ALPHA-NUMERIC INDEX

USER'S GUIDE

The General Dynamics Ordnance and Tactical Systems Brushless DC Motor Manual is organized in a manner which makes it easy to access the product performance information. Starting with the Design Guides, you should be able to locate the specific brushless motor which best suits your needs.

SAMPLE DATAPAGE

The Selection Guide is the first page in each brushless motor section. The Selection Guide lists the products featured, basic parameters, and the page where the data page can be found. Immediately following the Selection Guide are the individual data pages. On each data page are end and cutaway views of the product, as well as winding and performance data.



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	60
Power at Tp (Pp)	watts	160
Motor Constant (Km)	oz-in/√W	4.74
Electrical Time Constant (te)	milli-sec	0.54
Mechanical Time Constant (tm)	milli-sec	10.0
Damping Factor (Fo)	oz-in/rad/sec	0.160
Moment of Inertia (Jm)	oz-in-sec²	0.0016
Total Breakaway Torque (Tf)	oz-in	1.0
Temperature Rise (TPR)	°C/watt	4
Max. Allowable Wdg. Temp.	°C	155
Weight	oz	5.5
Number of Poles		8
Number of Phases		3

Winding Constants						
Parameter	UNITS	TOL.	-013	-033	-052	-131
Resistance (R)	ohms	±12.5%	1.3	3.3	5.2	13.1
Voltage at Tp (Vp)	volts	Nominal	14.4	23.3	29.2	46.5
Current at Tp (Ip)	amps	Nominal	11.1	6.90	5.50	3.45
Torque Sensitivity (Kt)	oz-in/amp	±10%	5.40	8.70	10.9	17.4
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.039	0.061	0.076	0.120
Inductance (L)	millihenries	±30%	0.7	1.8	2.8	7.1

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MOTION CONTROL PACKAGES

For decades, General Dynamics Ordnance and Tactical Systems has provided solutions for complex applications such as ultrasonic imaging systems, semiconductor process, mechanisms, aircraft actuation and missile guidance systems. The mechanism section of the General Dynamics Ordnance and Tactical Systems Brushless DC Motor Manual gives a brief overview.

DESIGN GUIDES

At the end of this catalog, you will find a DC Motor Design Guide, which prompts you to answer the necessary questions about your current motor requirements. The Design Guide is especially useful when your project calls for a custom solution. We recommend you make copies of it to use as worksheets when deciding on your brushless motor requirements.

GENERAL DYNAMICS ORDNANCE AND TACTICAL SYSTEMS MOTION CONTROL PRODUCTS INTRODUCTION

HERITAGE

General Dynamics Ordnance and Tactical Systems has been serving the commercial, industrial and defense motion control industries for 40 years, supplying high performance components and systems that stand up to the most rigorous environments. We supply high performance products that withstand high shock, 15,000 lbs of pressure, and temperature ranges from -55˚C to +200˚C, for applications from aerospace to medical, textile to robotics.

From our inception, General Dynamics Ordnance and Tactical Systems has continuously challenged technological limitations, developing state-of-the-art motors, position feedback devices, and electromechanical assemblies for the rapidly evolving commercial, industrial, defense, aerospace, and medical industries. Equipped for innovation, with a world-class team of engineers and a global support network, General Dynamics Ordnance and Tactical Systems is uniquely able to apply this high performance technology to your system needs, at a competitive cost.

DESIGN AND MANUFACTURING

Your General Dynamics Ordnance and Tactical Systems design begins with a detailed review of your specifications by our engineers. If you have not established formal specifications, our engineers will help develop them with you. We use computer aided design programs, design, and process control specifications to assure the product will meet your specifications. General Dynamics Ordnance and Tactical Systems manufacturing cycle begins with the establishment of a Materials Requirements Plan (MRP).With the aid of an integrated computer planning/scheduling system, detailed production schedules are generated to ensure on-time material delivery, optimal output, and inventory levels.

CUSTOMER SERVICE

At General Dynamics Ordnance and Tactical Systems, service does not end with the delivery of your products. Service and support are our most important responsibilities, and we meet them with our network of technical support staff that stretches around the world. Our engineering, manufacturing and quality experts - in fact, all employees in our entire organization - are ready to serve you from concept, through development, to order delivery, and beyond.

QUALITY ASSURANCE

We have established the internal quality systems required for high-reliability commercial and defense programs. General Dynamics Ordnance and Tactical Systems Quality System is certified to AS9100:D and ISO9001:2015.

MANUFACTURING OPERATION

General Dynamics Ordnance and Tactical Systems MCP has a modern 60,000 square foot facility in San Diego, staffed by dedicated employees. We can easily accommodate contracts from the development phase through full-scale production.

We encourage factory tours. Our operations include an extensive CNC machine shop, automated armature winding station, organized work centers, and environmental and performance testing equipment.

BRUSHLESS DC MOTORS

The mechanical switching of current associated with brush motors is replaced with electronic switching in brushless motors. Brushless DC motors are not simply AC motors powered by an inverter, instead these devices use rotor feedback devices so that the input wave forms are kept in proper timing with the rotor position. Some form of electronic commutation switching is necessary for all motors, except in the limited angle devices. Brushless DC motors with suitable control electronics can be directly substituted for similarly-sized brush DC motors. Brushless DC motors provide several advantages:

1. Brushless units may be operated at much higher speeds and at full torque at these speeds, resulting in a motor with considerable power output for its size. High speed operation is especially difficult for conventional brush DC motors because the high energy that must be switched by the brushes is destructive and shortens motor life. In brushless motors this energy can be handled by the drive circuits.
2. The stator, which contains the motor's windings, may be mounted in a substantial heat sink to minimize temperature rise and prolong bearing life.
3. Where long life is a requirement, the absence of brushes normally increases the motor's life expectancy to that of the bearings.
4. In high-cleanliness applications, unacceptable brush wear particles are eliminated.
5. The EMI (Electromagnetic Interference)normally associated with the arcing of the brush commutator inter-

face is eliminated in the brushless motor. Brushless DC controllers are generally free of major EMI contributors.

6. For explosive environments, a brushless motor can be used without special housing elements necessary to explosion-proof a conventional DC motor.
7. Although brushes have been used extensively in space environments, their preparation is expensive and time consuming. The brushless motor requires much less preparation.

TYPICAL APPLICATIONS

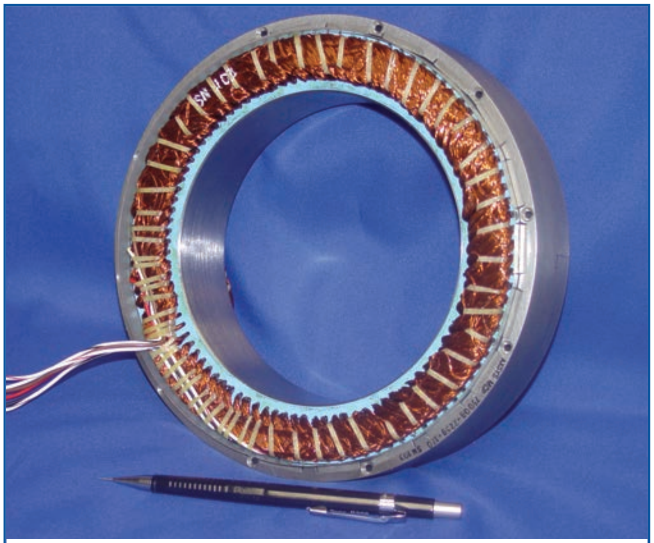
Brushless DC motors have the same electrical performance operating (transfer function) characteristics as brush-commutated DC motors, and can be used in the same applications. They provide high starting torque, variable bi-directional speed operation, and precision position and velocity servo loop capabilities. They can also replace AC motors in spindle and rotary table drives where the higher torque DC motor can drive the spindle directly, eliminating the need for a belt and pulley.

BASIC COMPONENTS

A brushless motor system consists of four basic subassemblies:

1. A stator wound with electromagnetic coils which are connected in single or poly-phase configurations.
2. A rotor consisting of an iron core and permanent magnet poles.
3. A rotor position sensor assembly providing rotor position to the required resolution.
4. Commutation logic and switching electronics to convert rotor position information to the proper stator phase exctation.

Applications	Equipment	Brushless DC Advantage
Velocity Servos		
	Silicon Water Spinner	High Speed, Long Life
	CAT Scanner	Low-EMI, Low Audible Noise
	Infrared Imager	High Speed, Low-EMI
	Cryogenic Compressor	No Brush Debris
	Fuel Pump	No Arching No Brush Debris
	Air Bearing Spindle	No Brush Debris High Speed
Position Servos	Space Vehicle	Vacuum Operation Low-EMI
	Optical System	No Brush Debris
	Stable Platform	Low-EMI
High Power Density	Robot	Low Thermal Resistance
	Airborne Actuator	Low Thermal Resistance Vacuum Operation



The gearless DC motor drive is ideally suited to high acceleration applications requiring improved response for rapid start/stop actions.

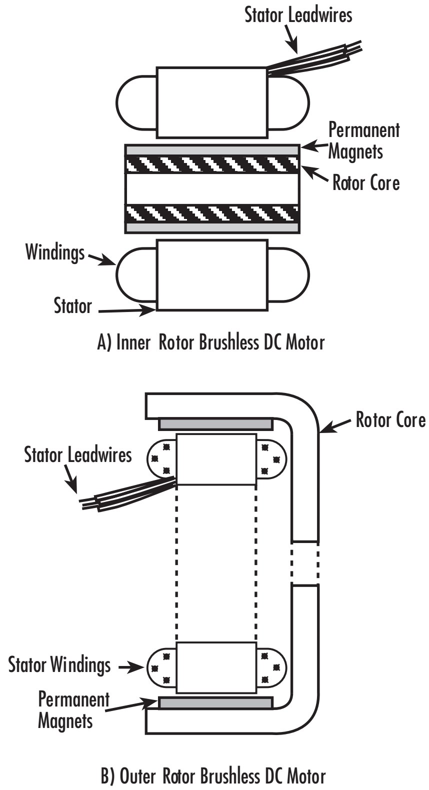


Fig. 1 Brushless Motor Configurations

STATOR

The stator for a brushless DC motor is a laminated steel core with coils of magnet wire embedded and connected in one, two or more phases so that by sequentially exciting these phase winding, a rotating electromagnetic field can be generated.

Since both iron and copper losses in the brushless DC motor take place in the stator, generated heat is easily transferred to the surroundings. A motor with an inner rotor is better in this regard due to the larger stator area in contact with the mounting surfaces.

ROTORS

In all continuous rotation brushless DC motors, the permanent magnetic field is on the rotor. The windings supplying the rotating electromagnetic field are in the stator. The rotor can be designed inside of the stator, as in a conventional motor, or outside of the stator. See Figure 1A and 1B. The inner rotor design is generally used in incremental motion application where low inertia and fast response are required. The outer rotor configuration provides a more rigid structure for the permanent magnets and has higher inertia. It is used in high speed applications where a stiff structure is required to counter the centrifugal forces acting on the permanent magnets, in velocity loop applications where the additional rotor inertia is desired for velocity stabilization, or when the additional inertia is insignificant relative to the total inertia as in a memory disk drive.

POSITION SENSORS

There are several ways to sense brushless rotor position. Rotor position sensing is necessary so the stator winding excitation can be controlled to keep the electro-magnetic field in leading quadrature with respect to the rotor field. These methods fall into three categories: photo-electronic, electromagnetic, and magnetic.

PHOTO ELECTRONIC

A set of photo-transistors and LEDs are coupled across a shutter which is keyed to the rotor and has windows in the proper pattern to control the phase excitation. If a shaft angle encoder is required in the system for normal shaft position sensing, a separate pattern track can be included on the disk for motor commutation. The out-put of an absolute encoder can also be used in a sine cosine ROM or as input to a digital comparator to develop the commutation waveform.

ELECTROMAGNETIC

Electromagnetic sensors use a soft iron target and a set of wound coils. Changes in the coil inductance are sensed and decoded to verify rotor position. Eddy current devices using metallic targets can also be used in the same manner. Brushless resolver are commonly used in sine cosine systems as the source of the phase quadrature waveform.

MAGNETIC

Hall effect sensors, magneto-resistors, or magneto-diodes are used in magnetic sensors. These devices work directly off of the rotor poles so that the alignment of the sensors can be accomplished during the manufacture of the stator. They become a part of the stator assembly so that the user need only install the rotor to have an aligned system.

ELECTRONICS

The electronics module, which can be internal to the motor housing or placed on an external printed circuit board, receives the signals from the position sensors and uses digital logic to develop the wave-forms that are used to control the switches. These switches are usually power MOSFET, IGBT, or bipolar transistor devices. The selection of the type of power switch depends largely on the application and includes factors such as the motor voltage, peak motor current, PWM frequency, and the operating characteristics of the motor.

In general, power MOSFET'S, because of the very low "on" resistance exhibited by this type of device, are the switches of choice while IGBT'S are most common in high voltage brushless motors driver where the motor voltages are on the order of several hundred volts.

Also, for high power applications, most modern three phase brushless drivers are designed to operate directly off of the 230 VAC or 440 VAC power line, eliminating the need for separate power supply lines, and the need for a separate power supply to generate the switch bus voltages. These drive systems almost always use IGBT power devices because of the high voltages encountered and the high efficiency achieved with direct line powered operation.

In a sine-cosine system, the electronics module is a two phase bipolar amplifier. The sensor output are first decoded or demodulate (if required), and then amplified by a four quadrant power amplifier. To reduce power dissipation in the amplifier, pulse width modulation is often used. This type of system is more costly than the digitally switched system. For this reason, is used only when the applications needs the smooth, low ripple torque of a sinusoidally-commutated brushless motor.

Brushless DC motor controllers offer many power levels and commutation options. Standard controller products are available providing closed loop control of speed or torque, accepting Hall sensor, optical encoder or resolver position sensor signals. Often in low power applications, the control electronic are an integral part of the motor and range from single commutation and switching circuits to complete speed control systems. Many IC's combining commutation, current sensing, fault detection, and power switch drive functions provide cost effective Brushless DC motor control.

COMMUTATING BRUSHLESS DC MOTORS

TORQUE AND WINDING CHARACTERISTICS

The basic torque waveform of a brushless DC motor has a sinusoidal or trapezoidal shape. It is the result of the interaction between the rotor and stator magnetic fields, and is defined as the output torque generated relative to rotor position when a constant DC current is applied between two motor leads. This torque waveform is qualitatively equivalent to the voltage generated waveform at the two motor leads when the motor is driven at a constant speed by another motor. The frequency is equal to the number of pole pairs in the motor times the speed in revolutions per second.

The brushless DC motor will exhibit torque speed characteristics similar to a conventional DC motor when the stator excitation is in proper alignment with the rotor's magnetic field. The stator excitation may be square wave or sinusoidal. Ideally, the stator excitation may be square wave or sinusoidal. Ideally, the stator excitation should be applied in a sequence to provide a constant output torque due to the finite commutation angle. The commutation angle is the angle the rotor rotates through before the winding are switched. Ripple torque is typically expressed as a percentage of average to peak torque ratio. It is present whenever the winding are switched by a step function either electrically via solid state switches or mechanically via brushes.

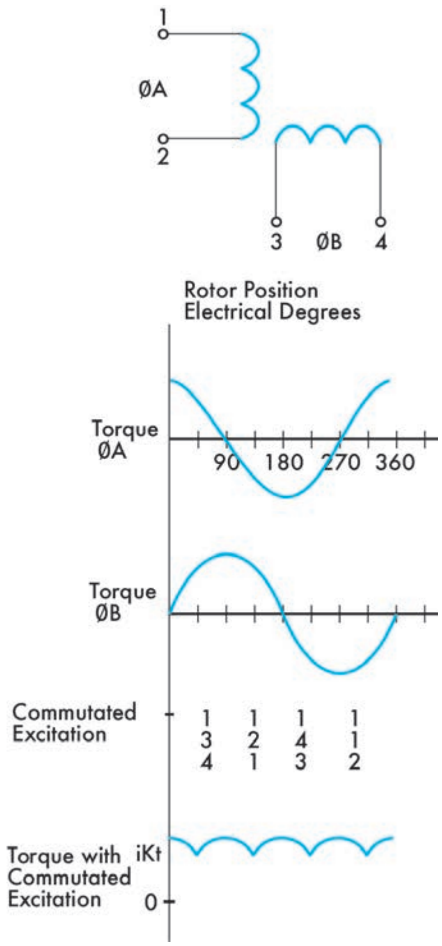


Figure-2. Switch mode commutation of a two phase brushless DC motor.

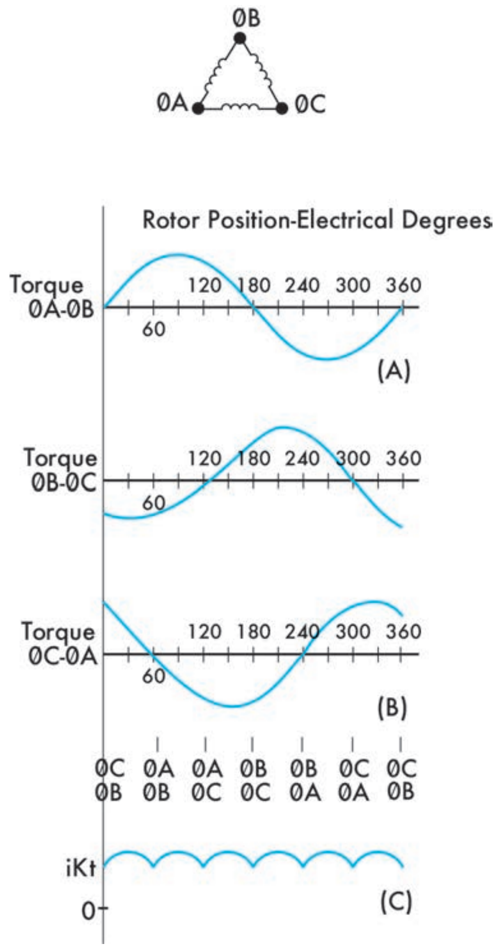


Figure-3. Switch mode commutation of a three phase delta wound brushless DC motor.

In brushless DC motors designed for square wave excitation, the ripple torque can be reduced by reducing the commutation angle by using a higher number of phases, which also improves motor efficiency. Figure 2 shows the commutation points and output torque for a two phase brushless motor. The commutation angle is 90 electrical degrees which yields the largest ripple torque of about 17% average to peak. A three phase delta system is shown in Figure 3.The commutation angle is 60 degrees and the ripple toque is approximately 7% average to peak. Since two-thirds of the available winding are used at any one time, compared to one-half for the two phase system is more efficient.

The torque waveform indicated in Figure 2 and 3 have a sinusoidal shape. A trapezoidal torque waveform can be obtained by using a salient pole structure in conjunction with the necessary lamination/winding configuration. In practice, the trapezoidal torque waveform does not have a perfectly flat top. Manufacturing and other cost considerations result in an imperfect trapezoidal waveform. An example is Figure 4 where the generated voltage waveform across two terminals of a brushless motor designed for trapezoidal torque generation is Shown. Figure 5 is an example of a 12 phase brushless motor with a trapezoidal torque waveform. With the center terminal of the phases connected to the supply voltage, the phases are switched to ground during the indicated commutation angle of 30 electrical degrees. Only three phases are “on” at any one time. This motor was designed to satisfy the requirements of high efficiency and minimum ripple torque for a precision pointing and tracking space gimbal application. In applications requiring smooth operation at low speed, or where the motor is operated in a position loop, a sinusoidal drive system should be considered. Figure 6 is an example of a two phase motor designed for sine wave drive.

The torque output of each phase is:

$T_A = I_A K_T \cos\theta$

$T_B = I_B KT \cos\theta$

Where

I_A = current in phase A

I_B = current in phase B

K_T =torque sensitivity of motor

θ = rotor position in electrical degrees

If the motor currents are supplied in the following relation-

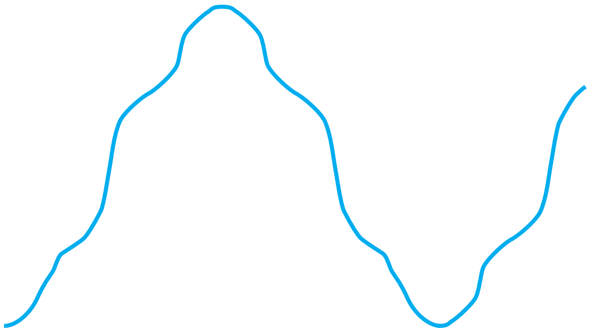


Figure-4. BEMF Trapezoidal waveform.

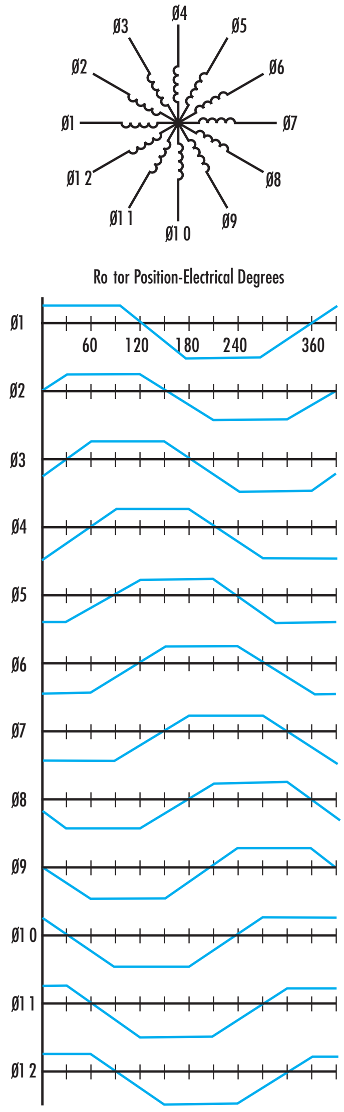


Figure-5.Torque waveform for 12 phase brushless DC motor.

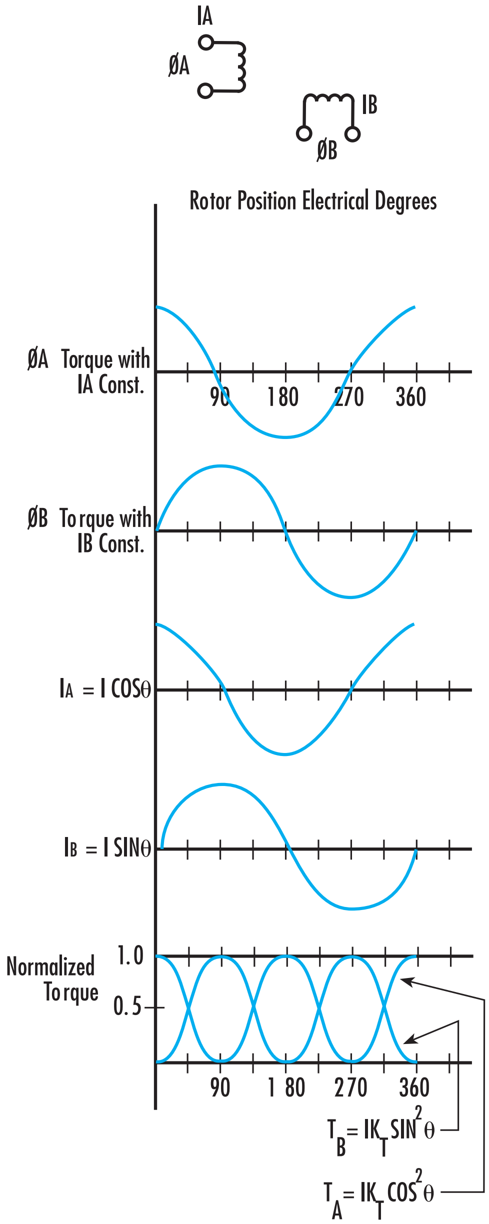


Figure-6.Two phase sinusoidal excitation.

ships:

I_A = I Cosθ
I_B = I Sinθ

The torque output of the motor is:

$T = T_A + T_B$
$T = I\,K_T(\mathrm{Sin}^2\theta + \mathrm{Cos}^2\theta\ )$
$T = I\,K_T$

This analysis indicates that the sinusoidally driven brushless motor has linear characteristics similar to a conventional DC motor and has minimum ripple torque. Three phrase winding can be connected in either wye or delta configuration. Excitation can be switch mode or sinusoidal drive. The switch mode drive is the most commonly used system because it results in the most efficient use of the electronics. Two switches per phase terminal are required for the switch mode drive system. Therefore, only six switches are required for either the wye or delta configuration.

The delta winding form a continuous loop, so current flows through all three winding regardless of which pair of terminals is switched to the power supply. Since the internal resistance of each phase is equal, the current divides unequally, with two-third of the total current from one winding to another as the winding are commutated.

For the wye connection, current flows through the two winding between the switched terminals. The third winding is isolated and carries no current. As the winding are commutated, the full load current must be switched from terminal to terminal. Due to the electrical time constant of the winding, it takes a finite amount of time for the current to reach full value. At high motor speeds, the electrical time constant may limit the switched current from reaching full load value during the commutation interval, and thus limits the generated torque. This is one of the reasons the delta configuration is preferred for applications requiring high operating speed. Other considerations are manufacturing factors which permits the delta configuration to be fabricated with lower BEMF constant, resistance, and inductance. A lower BEMF constant allows the use of more common low voltage power supplies, and the solid state switches will not be required to switch high voltage. For other than high speed applications, the wye connection is preferred because it provides grater motor efficiency when used in conjunction with brushless motors designed to generate a trapezoidal torque waveform.

SENSOR TIMING AND ALIGNMENT

A brushless DC motor duplicates the performance characteristics of a DC motor only when its winding are properly commutated. Proper commutation involves the timing and sequence of stator winding excitation. Winding excitation must be timed to coincide with the rotor position that will produce optimum torque. The excitation sequence controls the polarity of generated torque, and therefore the direction of rotation.

Rotor position sensors provide the information necessary for proper commutation. Sensor output is decoded by the commutation logic electronics. The logic signals are fed to the power drive circuit which activates the solid state switches to commutate the winding.

The commutation points and output torque for a two phase brushless motor were shown in Figure 2.The commutation angle is 90 electrical degrees, and the winding are switched “on” and switched “off” 45 electrical degrees after the peak torque position, the current polarity must be reversed for negative torque peaks. The commutation waveforms for this motor are shown in Figure 7. Sensor output and alignment is shown in figure 7A. The S1 output leads the phase B torque position by 45 electrical degrees.

There are several methods for aligning the S1,2 sensors with respect to the stator winding. As shown in Figure 2, the peak torque position of phase B coincides with the zero torque position of phase A and vice versa. Sensor S1 can be aligned to the phase B winding by applying a constant current to phase A. The rotor will rotate to phase A’s zero torque position. S1 should be positioned so that its output just switches from a low to high logic state at 45 electrical degrees counter-clockwise from phase A’s zero torque position.

Another method is to align the position sensors to the BEMF waveform. Since the BEMF waveform is qualitatively equivalent to the torque waveform, the motor can be driven at a constant speed by another motor, and the position sensors aligned to the generated BEMF waveform. The sensor transition points relative to the BEMF waveform should be as indicated in Figures 2 and 7. For critical applications which require the commutation points to be optimized, the motor should be operated at its rated load point, and then the position sensors should be adjusted until the average winding current is at its minimum value. To facilitate sensor alignment, General Dynamics Ordnance and Tactical Systems can supply stators with reference marks to which the position sensors can be aligned.

The commutation points and output torque for a three phase brushless motor was shown in Figure 3.The commutation angle is 60 electrical degrees, and the winding are switched “on” at 30 electrical degrees before the peak torque position, and switched “off ” at 30 electrical degrees after the peak torque position. The current polarity for each phase during each commutation segment is shown in Figure 3B. The commutated output torque versus motor position(in electrical degrees) is shown in Figure 3C.

To identify each of the 6 commutation terminals, a minimum of three logic signals are required. The commutation waveform are shown in Figure 8. The three sensors are spaced 60 electrical degrees apart, and have a 50% duty cycle.

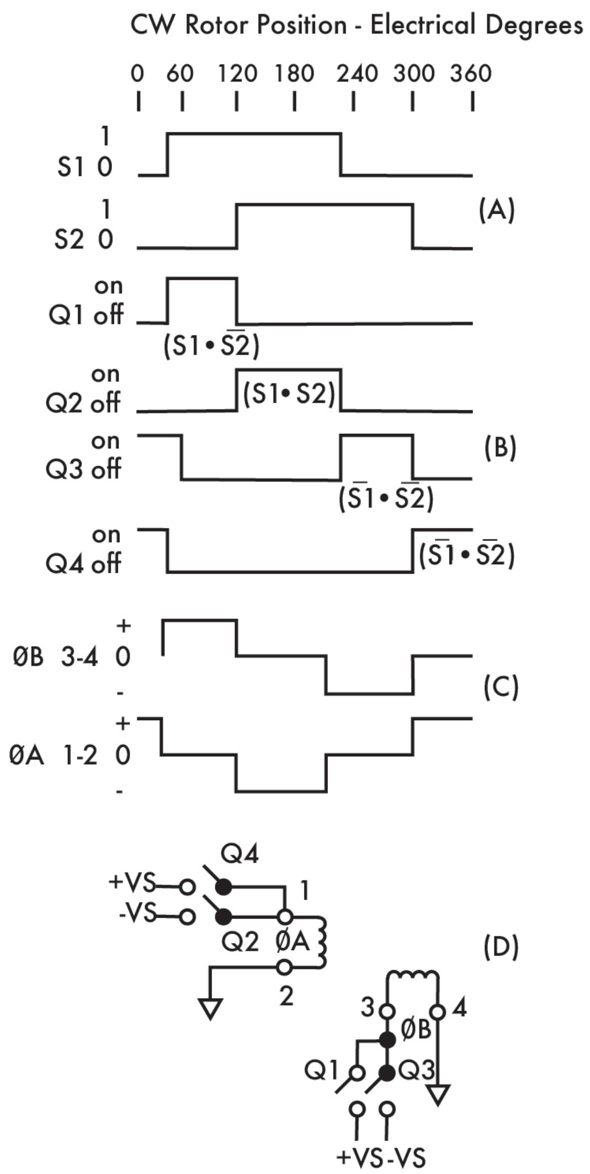


Figure-7. Sensor output, commutation logic, and and winding excitation waveform for a two phase brushless DC motor.

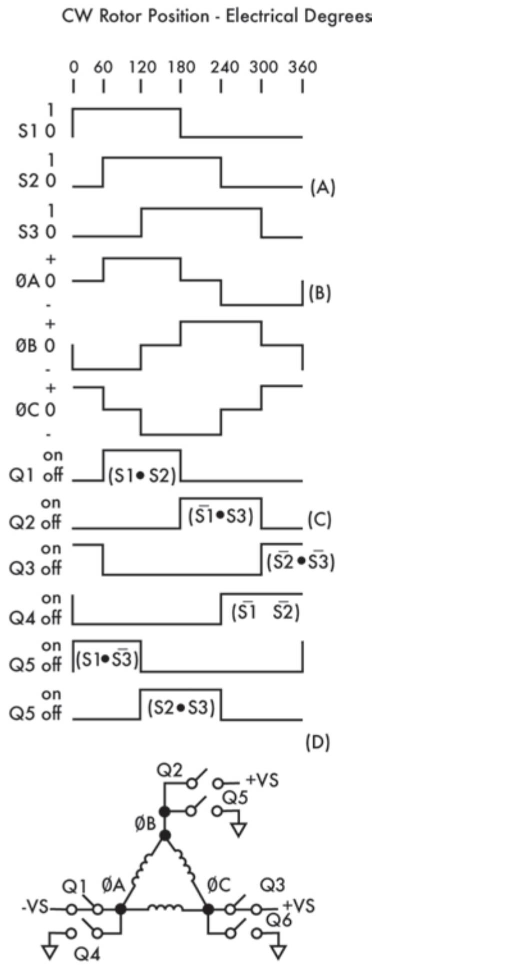


Figure-8. Sensor output, commutation logic and winding excitation waveform for a three phase brushless DC motor.

As indicated in Figure 3 and 8, sensor S1 can be aligned to the [A-[B zero torque position.

This can be accomplished by applying a constant current to the [A-[B terminals. The rotor will rotate to the [A-[B zero torque position. Then S1 should be positioned so that its output just switches from a low to high logic state S2 and S3 should be positioned 60 and 120 electrical degrees respectively from S1. Other alignment considerations are as previously discussed for the two phase motor.

SINE WAVE DRIVE

The sine wave drive control scheme is the best choice when the brushless motor is required to duplicate the performance characteristics of a conventional DC torque motor. Brushless DC torque motors designed to provide sinusoidal torque waveform have the additional advantage of minimum ripple torque and high reliability when compared to the brush-commutated DC torque motor.

The basic equations for controlling motor current and the resulting output torque for a two phase Brushless DC torque motor were shown in Figure 7. The control method consists of developing drive currents that are a sinusoidal function of the rotor position. As mentioned previously, position information can be obtained from a variety of devices. Hall effect elements, sine cosine resolvers, optical encoder, electro-magnetic and electrostatic pickups, magneto-resistors, and magneto-diodes are currently being used as rotor position sensors.

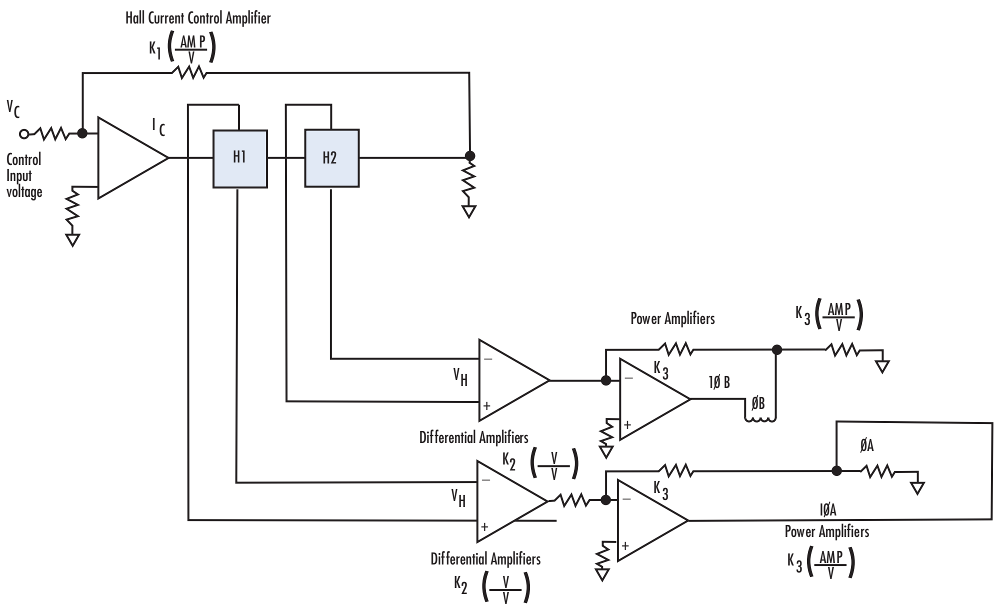


Figure-9. Functional control circuit for a two phase brushless DC torque motor with Hall Effect rotor positioning sensing.

The specific requirements of each application usually dictate the position sensing system selections. The linear Hall effect element is the sensing systems most frequently used because of its small size, low cost, and simplified processing electronics. Figure 9 is a functional control circuit for a two phase brushless DC torque motor with linear Hall effect rotor positions sensing. To obtain Hall device output voltages proportional to the sine and cosine of the rotor's position, the Hall devices are mechanically displaced 90 electrical degrees from each other, and are then align with the stator's BEMF or torque waveform.The magnitude and direction of the motor drive current is regulated by varying the magnitude and polarity of the Hall device control current.

THE CONTROL EQUATIONS ARE AS FOLLOWS:
(Refer to Fig. 9)

$I_C = K_I V_C$
$V_H = K_H I_C B \cos\theta$

Where
Ic = Hall device control current(Amp)
Vc = Input control Voltage (Volt)
K1 = Current amplifier gain (Amp/Volt)
V_H = Hall device output voltage (Volt)
K_H = Hall constant (Volt/Amp-KGauss)
B = Rotor permanent magnet field vector (KGauss)
θ = Angle between the plane of the Hall element and the rotor permanent magnet field vector(degrees)

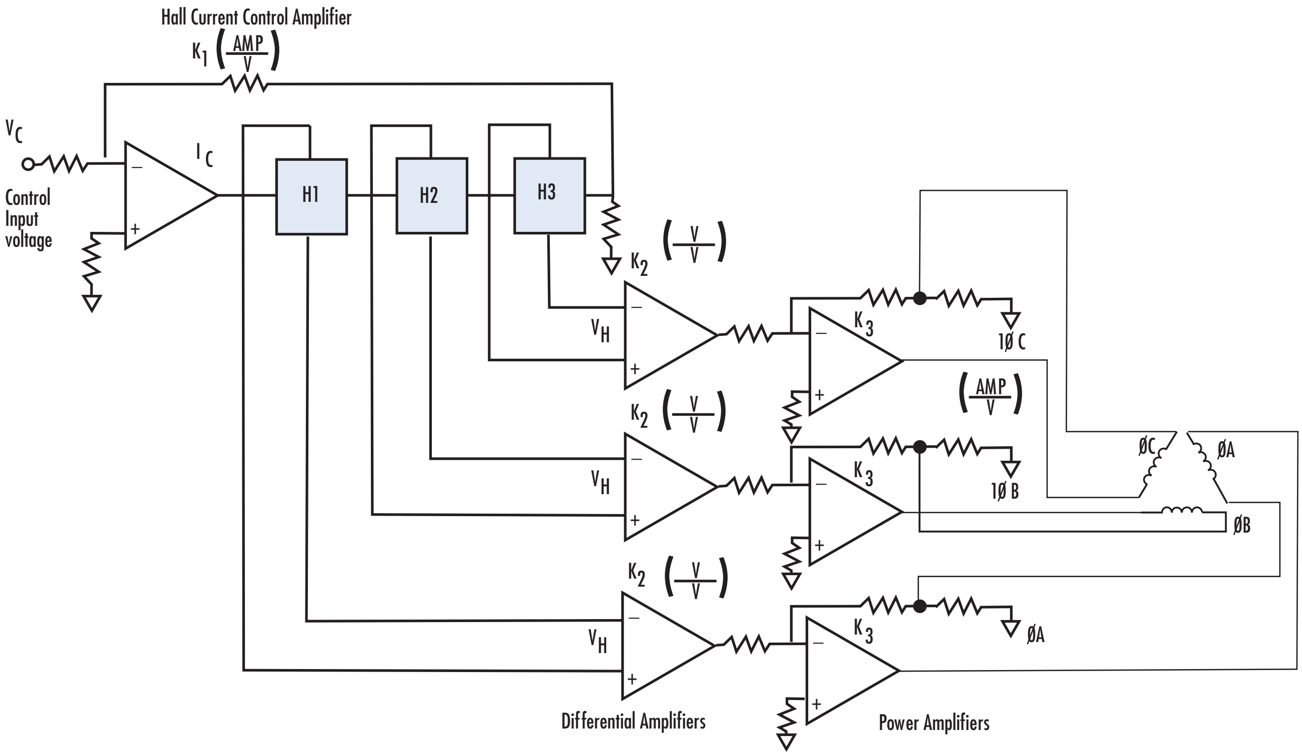


Figure-10. Functional control circuit for a three phase brushless DC torque motor with Hall Effect positioning sensor.

The current in ∅A winding is:

$I_{\varnothing A} = V_H K_2 K_3$

$\quad = K_2 K_3\, K_H I_C B \cos\theta$

$\quad = K_2 K_3\, K_H K_1 B\, V_C \cos\theta$

Similarly, the current in ∅B winding is:

$I_{\varnothing B} = K_2 K_3 K_H I_C B V_C \sin\theta$

The torque output of each phase is:

$T_{\varnothing A} = I_{\varnothing A} K_T \cos\theta$

$T_{\varnothing B} = I_{\varnothing B} K_T \sin\theta$

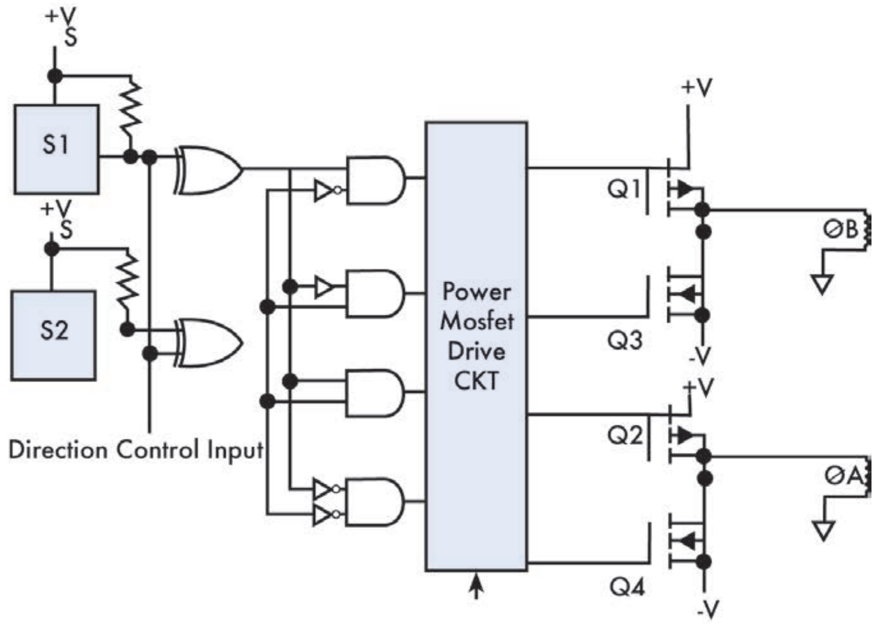


Figure-11. Functional drive circuit for bidirectional control of a two phase brushless DC motor.

Substituting for $I_{\varnothing A}$ and $I_{\varnothing B}$

$T_{\varnothing A} = V_C K_1 K_2 K_3\, K_H K_T B \cos^2\theta$

$T_{\varnothing B} = V_C K_1 K_2 K_3\, K_H K_T B \sin^2\theta$

Let $K_C = K_1 K_2 K_3\, K_H K_T B$

Then the motor's output torque is:

$T = T_{\varnothing A} + T_{\varnothing B} = V_C K_C (\cos^2\theta + \sin^2\theta)$

$T = V_C K_C$

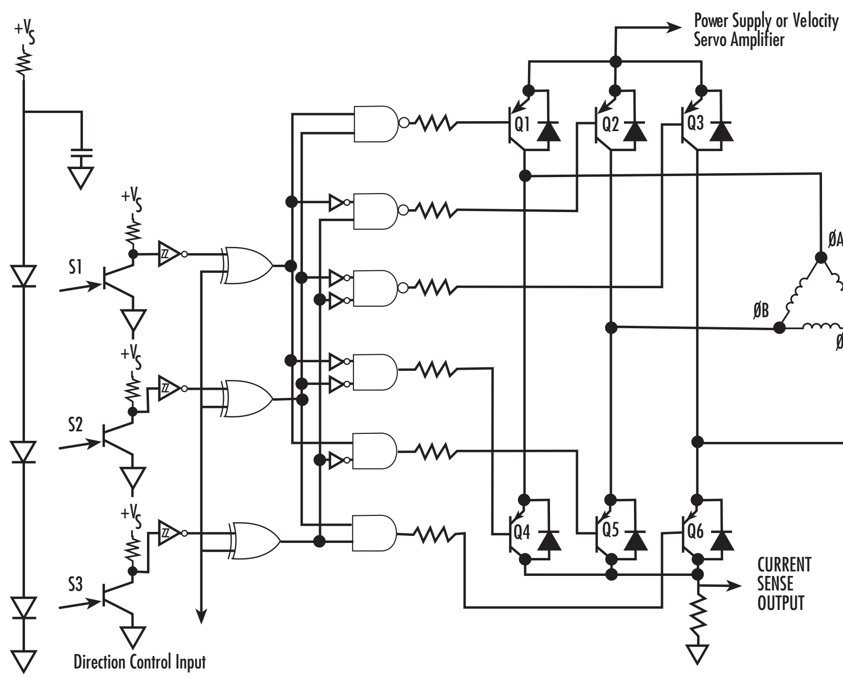


Figure-12. Functional drive circuit for bidirectional control of a three phase brushless DC motor.

Therefore, the output torque is directly proportional to the input control voltage. The same control scheme can be applied to a three phase brushless DC torque motor as shown in Figure 10. The Hall devices are mechanically displaced 120 electrical degrees from each other and are aligned with the BEMF waveform of each phase. The control equations are as previously derived for the two phase system, except the output torque is:

$T = V_C K_C (\sin^2 \theta + \sin^2 (\theta + 120) + \sin^2 (\theta - 240))$
$T = 1.5 V_C K_C$

and, as before, the output torque is directly proportional to the input control voltage.

SQUARE WAVE DRIVE

A square wave drive system provides the most efficient utilization of the control electronics, and yields the lowest system cost. Power dissipation in the output stage is minimized by operating the power switch devices in the complete OFF or fully ON state. The output stage can be interfaced directly with the commutation logic circuit, and the whole system can be digital. This allows the use of lower cost digital integrated circuits to decode the position sensor output and to sequence the drive circuit power semiconductors.

Figure 11 shows a simplified drive circuit for bi-directional control of a two phase brushless DC motor. The timing and excitation waveform for this motor were shown in Figure 7. The rotor position sensors are Hall effect switches and their outputs are processed by Exclusive OR gates. This feature allows the direction of rotation to be reversed. A logic “1” on the direction control input will invert the sense of the position sensor output. Referring back to Figure 7, we note that inverting the sensor polarity will reverse the polarity of excitation on each motor terminal thus making it produce torque in the opposite direction.

The logic statements shown in Figure 7b are implemented with AND and INVERT gates. Power MOSFETS are used to switch the motor winding. Speed control is obtained by pulse width modulating the power MOSFET during its ON commutation period. The MOSFET drive circuit consists of the gate

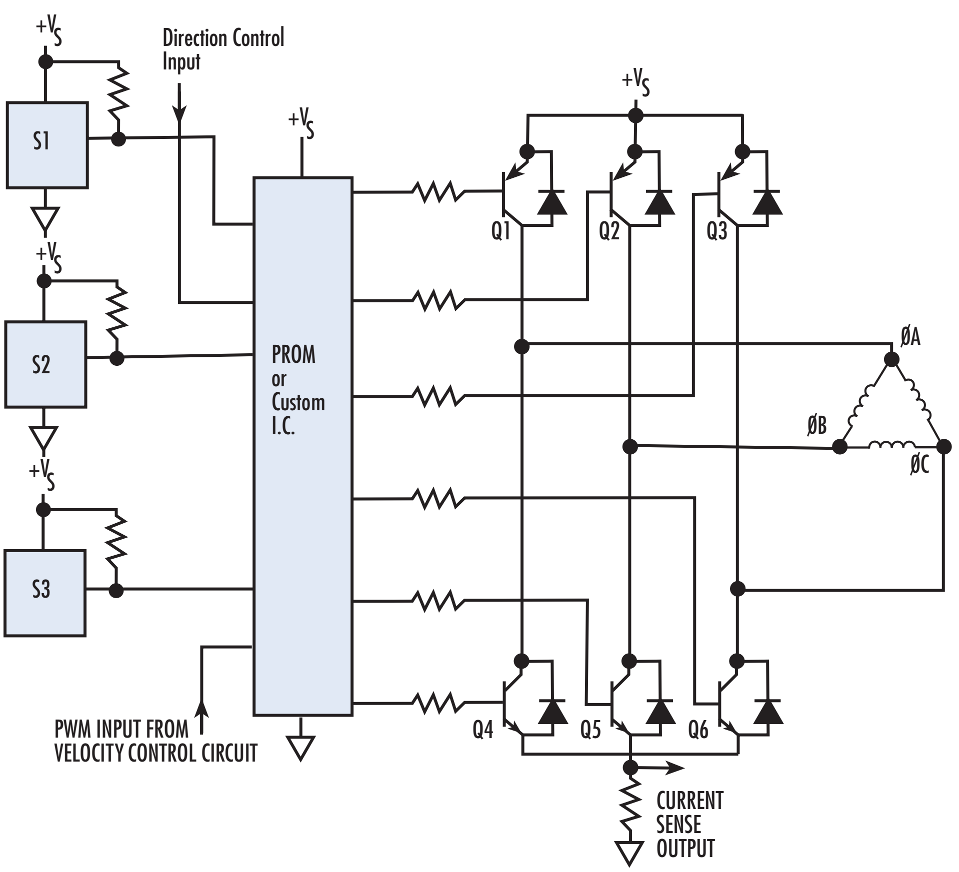


Figure-13. Functional drive circuit for bi-directional control of a three phase brushless DC motor.

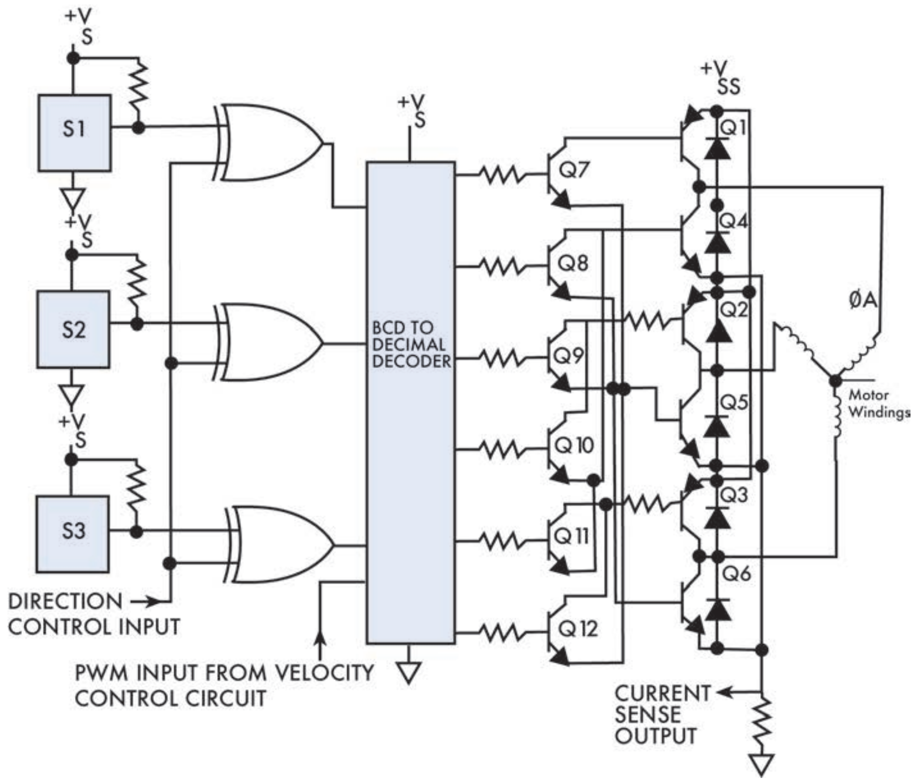


Figure-14. Functional drive circuit for bi-directional control of a three phase brushless DC motor.

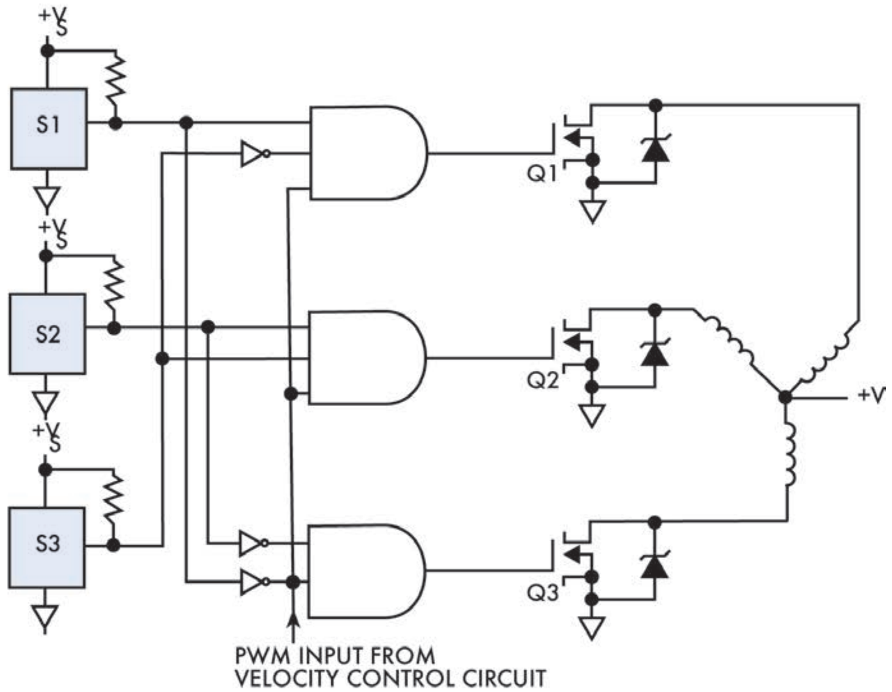


Figure-15. Functional drive circuit for bi-directional control of a three phase brushless DC motor.

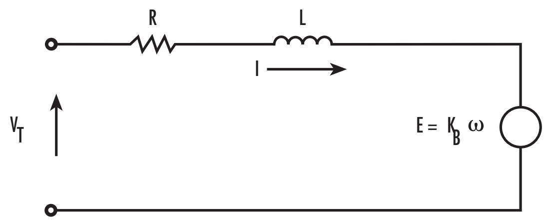


Figure-16. Equivalent electrical circuit of the Brushless DC motor.

drive and appropriate level shifting for the “P” and “N” channel devices.

A functional drive circuit for bi-directional control of a three phase brushless DC motor is shown in Figure 12.The timing and excitation waveform for this motor was shown in Figure 8. The main features of this control scheme are:

1. Rotor position feedback is obtained from three LED-photo-transistors.
2. Schmit-trigger inventers are used to shape the photo transistors output waveform.
3. AND and INVERT gates are used to implement the logic statements of Figure 8B.
4. PNP and NPN power Darlington transistors are used to switch the motor winding.
5. Flyback diodes across each transistors provide a transient path for the commutated winding inductive energy.
6. Speed control is achieved by “servoing” the supply voltage to the transistor bridge.

A single PROM or custom integrated circuit can be used to replace the EXCLUSIVE OR, AND, and INVERT logic ICs. This is shown in Figure 13.

The required logic can also be implemented with a BCD-to-decimal decoder as shown in Figure 14. Since the decoder output has only one unique “high” output state for any combination of logic inputs, both the PNP and NPN power transistors must be switched OFF and ON simultaneously for each commutation point. This control function is performed by driver transistors Q7 through Q12.

A simple low-cost drive used to control the brushless DC spindle motor in a disk drive is shown in Figure 15. Only three power MOSFETS are required to commutate the wye connected winding with the center tap connected to the supply voltage. The winding are switched over 120 electrical degrees. Due to the relatively high inertial load, the increased ripple torque has negligible impact on system performance. Clamping zener diodes are used to protect the power MOSFETS from over-voltage transients produced when the inductive winding are switched OFF.

BRUSHLESS SERVO SYSTEMS

The brushless DC motor, when properly commutated, will exhibit the same performance characteristics as a brush commutated DC motor, and for servo analysis the brushless motor can be represented by the same motor parameters. It can be modeled by the equivalent circuit of Figure 16. This model can be used to develop the electrical and speed-torque characteristics equations for brushless DC motors.

The electrical equation is:

$V_T = I_R + LdI/dt + K_B(\omega)$ (1)

Where

V_T = the terminal voltage across the active commutated phase
I = the sum of the phase currents into the motor
R = the equivalent input resistance of the active commutated phase
L = the equivalent input inductance of the active commutated phase
K_B = the back EMF constant of the active commutated phase
ω = the angular velocity of the rotor

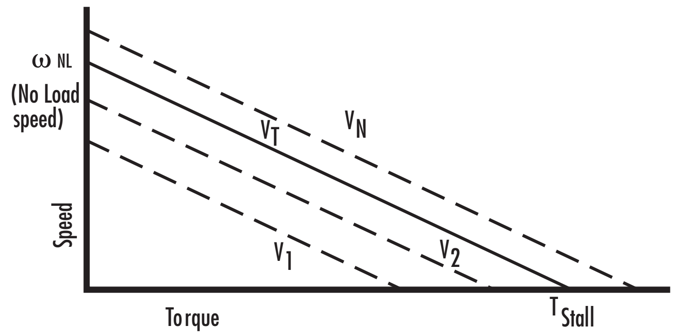


Figure-17 Speed torque characteristic curves.

If the electrical time constant of the brushless DC motor is substantially less than the period of commutation, the steady state equation describing the voltage across the motor is:

$V_T = IR + K_B\omega$ (2)

The torque developed by the brushless DC motor is proportional to the input current.

$T = I\,K_T$

Where K_T = the torque sensitivity (oz-in/amp)

If we solve for (I) and substitute into Equation (2) we obtain:

$V_T = T/K_T R + K_B(\omega)$ (3)

The first term represents the voltage required to produce the desired torque, and the second term represents the voltage required to overcome the back EMF of the winding at the desired speed. If we solve (3) for rotor speed, we obtain:

$\omega = V_T/K_B - TR/K_B K_T$ (4)

which is the speed-torque equation for a permanent magnet DC motor.

A family of speed-torque curves represented by Equation (4) is shown in Figure 17.

The no-load speed can be obtained by substituting T=0 into (4).

$\omega\ NL = V_T/K_B$

Stall torque can be determined by substituting ω=0 in (4)

$T_{STALL} = K_T\ V_T/R = IK_T$

The slopes of the parallel straight line speed torque curves of Figure 17 can be expressed by:

$R/K_B K_T = \omega_{NL}/\ T_{STALL}$

Since the speed-torque curves are linear, their construction is not required; the servo designer can calculate all needed information from the basic motor parameters.

APPLICATION EXAMPLE

A typical constant velocity application such as the spindle in a memory disk drive may have the following requirements:

Operating speed ω = 3600 RPM = 377 rad/sec

Load Torque T_L = 12 oz-in

Available supply Vs = 24V ± 10%

Max Voltage drop across switching transistors $V_{CE(MAX)}$ = 1.5 V

The requirement is to select an appropriate motor and verify that it will meet operating speed torque requirements under worst case parameter conditions.

The motor selected has the following parameters:

K_T = 5.4 ± 10% oz-in/amp
K_B = 0.038 ± 10% Volts/rad/sec
R = 0.90 ± 12.5% ohms

Assume the motor has an internal loss torque. T_{LOSS} = 0.5 oz-in, and the winding will see a maximum temperature rise (ambient plus internal heating) of 25° C.

The minimum voltage available to the motor is:

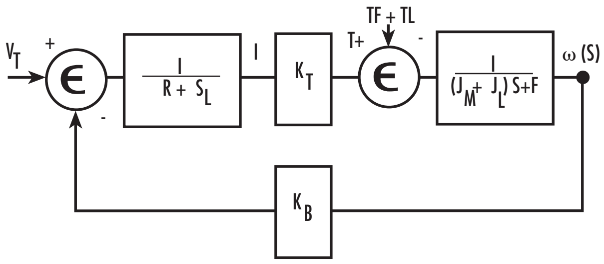


Figure-18 Block diagram of brushless DC motor model.

$V_{T(MIN)} = V_{s(MIN)} - 2V_{CE(MAX)} = 21.6 - 3.0 = 18.6$ V

The maximum resistance of the winding including tolerance and temperature rise is:

$R_{MAX} = R\,(1 + 12.5\%)\{1 + (0.00393)(\Delta T)\}$

$R_{MAX} = 0.9(1.125)\{1 + (0.00393)(25)\}$
$= 1.11$ ohm

The maximum voltage across the motor with worst case parameters is:

$V_{T(MAX)} = (R_{(MAX)}(T_L + T_{LOSS}) / (K_{T(MAX)} + K_{B(MAX)}\omega$
$V_{T(MAX)} = (\ 1.11)(12.5 + 0.5) / (5.94) + (0.0418)(377)$
$V_{T(MAX)} = 18.1$ V

Therefore, the motor selected will meet the requirements under worst case conditions. The block diagram and transfer function for a brushless DC motor when coupled to a load can be constructed from Equation (1) and the following dynamic torque equation:

$T = (J_M + J_L)) d\omega / dt + F\omega + T_F + T_L \quad (5)$

Where
J_M = the motor moment of inertia
J_L = the load moment of inertia
F = the damping factor representing all motor and load viscous friction
T_F = the motor friction torque
T_L = the load friction torque

Taking the Laplace transform of (1) and (5) yields:
$V_T = IR + SL + K_B\ \omega(S) \quad (6)$
$T = (J_M + J_L)S + F\omega(S) + T_F + TL \quad (7)$

Figure 18 is a block diagram representing Equations (6) and (7) and is identical to the model used for the brush commutated DC motor.

SOME COMMON PITFALLS

Motor windings are inductive. This gives rise to two considerations that should not be overlooked. The first is motor speed. Since the winding electrical time constants are in the area of one millisecond, commutating frequencies above several hundred hertz need special treatment. Commutating frequency is equal to the number of pole pairs in the machine times the speed in revolutions per second. For units that must operate at higher speeds some provision for shifting the commutation points must be made. This can be done either mechanically or electronically. Also, the motor inductance causes high voltage spikes to appear across the power transistors as they are switched off. These must be allowed for in the design either by use of high voltage transistors or protective zener diodes or other transient suppressors. Almost all brushless motor systems require current limiting to avoid inadvertent demagnetization of the permanent magnet rotor during starting and fast reversals. The logic system must be examined for possibility of improper outputs during power application. For instance, if the logic states are such that both the transistors at one corner of the three phase delta are turned on, the resulting short circuit will be disastrous. An easy and fruitful test during bread boarding is to step the logic through its sequence and note that the motor steps through its rotation with no reversals or long steps. This assures that the logic is correct and that the motor is connected properly. If this is not done, it is possible that the motor will run, but that during one segment of its rotation its torque will be reversed or non-existent. High current will result, but may be overlooked inadvertently.

A SIMPLE TEST METHOD

Many of our customers have found that an incoming test of the motor torque is expensive to instrument and perform. In these cases we have suggested that the incoming electrical inspection be made on the back EMF constant of the motor (Kb).

This parameter is directly proportional to the torque sensitivity and is more easily measured. The technique involves driving the motor at a constant speed and measuring the generated voltage at the motor terminals. Acceptance limits can be set based on the back EMF constant and assurance of a compliant motor is given by this test.

THERMAL CONSIDERATIONS

On each of the following data pages, the maximum allowable winding temperature is specified. The maximum operating temperature of the winding depends on the load duty cycle and the thermal paths to system heat sinks. The value given for motor resistance and resistance dependent parameters on the data sheets are defined at 25°C winding temperature. If the winding is operated at a different temperature, the temperature coefficient of copper (0.4% per °C) must be taken into consideration.

HANDLING, STORAGE, INSTALLATION

The motors in this Handbook are all designed with rare earth magnets and require careful handling. These magnets have very strong attractions to magnetic materials. Without cautious handling, injury or motor damage could occur.

When motors are stored in their original shipping container, they are well protected for normal storage conditions. Those motors that are housed have permanently lubricated bearings and do not require changing the bearings unless storage packaging has been damaged. The device should be closely inspected to see if damage or contamination has occurred.

Installation of brushless motors has only a handling problem. As the size of the motor increases, not only does the weight affect handling, but the magnetic attraction is a problem. If the motor is shipped with the magnet assembly inside the armature, it should be left this way to keep from damaging the magnets. There is a nonmagnetic shim placed in the air gap to keep the magnet assembly close to the center of the armature. This helps to align the motor to the mating mounting diameters. The mounting diameters of the housing and hub or shaft should have chamfers to help during installation. Once the motor is in place, the shim is removed and the motor should be free to rotate. It is always recommended to inspect the area of the air gap looking for any chips from magnets or other magnetic chips that may have adhered to magnets and removed them before operating the motor.

GLOSSARY

COMMUTATION – Sequenced switching of electrical power so that it is properly distributed in place and time to a motor winding. This function is performed by carbon brushes and a copper commutator in a conventional DC motor.

ELECTRICAL DEGREE – An angular measure dimensioned so that one pole pair contains 360 electrical degrees. In a two pole machine an electrical degree equals a mechanical degree. The number of pole pairs in a machine equals the number of electrical degrees in a mechanical degree.

EXCLUSIVE OR GATE – An electronic logic element in which the output is on when either of the two inputs is on but not when both are on or off. It can be seen that if one input is held off the state of the output is the same as the state of the second input but if the first input is held on the state of the second input is reversed at the output.

HALL EFFECT ELEMENT – Semiconductor which produces an output voltage proportional to the magnetic flux density perpendicular to the surface of the semiconductor and an input control current. It is commonly packaged with signal conditioning electronics to provide a linear or digital output.

LED (LIGHT-EMITTING DIODE) – A two terminal electronic component that emits light from its semiconductor junction when electrical current flows through it.

MOUNTING – The information given on each data page are user requirements for correct axial and concentric orientation of the motor components. It is required to preserve the specified performance characteristics.

PHASE – A motor winding which will set up magnetic poles in a specific position in the motor when a current is flowing in the winding. There is usually more than one phase in a brushless motor. The pole positions for each phase are angularly displaced from one another so that a moving magnetic field may be set up in a stationary component.

PHOTO TRANSISTOR – A semiconductor device in which the electrical current flowing through it is controlled by the amount of light falling in on the junction. When there is no light the current is very small.
A greater amount of light increases the current flow.

PROM – A programmable read only memory is an integrated circuit where data is entered by field programming techniques in which fusible links are blown, or in which some other permanent modification is made to the device structure. They can be employed to eliminate conventional combinational logic circuits.

ROTOR – Rotating element that drives the load.

SOLID STATE SWITCH – A semiconductor device which is used to switch the power to the motor windings. Commonly used devices are transistors and MOSFETS.

STATOR – Stationary element containing lamination stack and windings.

General Dynamics Ordnance and Tactical System's DC torque motors are designed using premium materials that offer unique space and weight savings while generating maximum power output. Limited angle torque motors do not require commutation electronics and have near zero cogging.

CONVERSION TABLE

To Convert:	From	To	Multiply by
Weight	ounces (force) ounces (force) pounds (force) pounds (force)	grams (force) Newtons grams (force) Newtons	28.35 0.278 453.6 4.448
Distance	inches inches feet	centimeters meters meters	2.54 2.54 x 10-2 0.3048
Torque	ounce-inches ounce-inches pound-feet	gram-centimeters Newton-meters Newton-meters	72.01 7.061 x 10-3 1.356
Angular Velocity	RPM degrees/second rev/second	radians/second radians/second radians/second	0.1047 1.745x10-2 6.283
Inertia	ounce-inch-sec^2 pound-feet-sec^2	gram-centimeter^2 Kgram-centimeter^2	7.06 x 104 0.367
Power Rate	ounce-inch/sec2	kilowatts/second	7.061 x 10-3

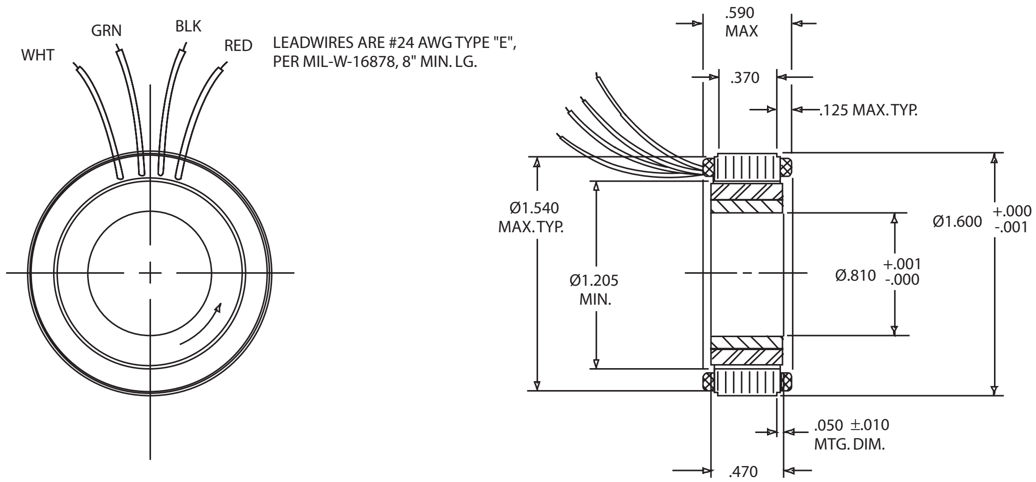
Selection Guide: by Outside Diameter - 2 Phase Brushless Motors								
Model Number	Rotation Inner/Outer	Peak Torque (oz-in.)	Power@TP (watts)	Km (oz-in /√watts)	O.D. (in.)	I.D. (in.)	Axial Length (in.)	Page
1600C-059	I	20	58	2.65	1.600	0.810	0.590	25
4500C-080C	I	384	120	35	4.500	2.770	0.800	26

Selection Guide: by Outside Diameter - 3 Phase Brushless Motors								
Model Number	Rotation Inner/Outer	Peak Torque (oz-in.)	Power@TP (watts)	Km (oz-in /√watts)	O.D. (in.)	I.D. (in.)	Axial Length (in.)	Page
1600C-059J	I	20	60.5	2.57	1.600	0.810	0.590	27
1600M-060	I	20	46.3	2.64	1.600	0.360	0.600	28
2375H-050	I	60	158	4.78	2.375	0.940	0.500	29
2376-057	I	68	68	8.25	2.376	0.800	0.570	30
2376-064	I	68	68	8.25	2.376	0.800	0.640	31
C2813B-047B	I	64	96	6.53	2.813	1.500	0.465	32
3730H-071	I	187	100	18.7	3.730	1.811	0.708	33
4500C-080	I	384	116	35.6	4.500	2.770	0.800	34
4750J-110	I	856	282	51	4.750	3.000	1.100	35
C5125B-100	I	920	240	59.4	5.125	3.500	1.00	36
6000S-146	I	2100	360	110.711	6.000	4.000	1.460	37
6000S-210	I	2100	360	110.7	6.000	4.000	2.100	38
6000S-360	I	5280	384	269.4	6.000	4.000	3.600	39
6000S-400	I	5280	384	269.4	6.000	4.000	4.000	40
8338-157	I	2124 min	106	198 min	8.338	6.417	1.653	41
C8250B-185B	I	4200	240	271.1	8.250	6.230	1.850	42
8860B-330	I	15294	1020	479	8.860	5.000	3.300	43
8860B-475	I	35520	3712	583	8.860	5.000	4.750	44

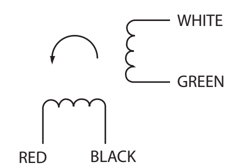
Other sizes are available. Contact General Dynamics Ordnance and Tactical Systems for your specific requirements.

1600C-059

BRUSHLESS DC MOTOR / INSIDE ROTOR



ROTATION: FIELD ROTATES CCW WHEN VIEWED FROM LEAD SIDE WITH THE FOLLOWING EXCITATION SEQUENCE: BLACK & WHITE LEADS COMMON & A POSITIVE VOLTAGE APPLIED TO GREEN LEAD THEN TO RED LEAD.



SCHEMATIC

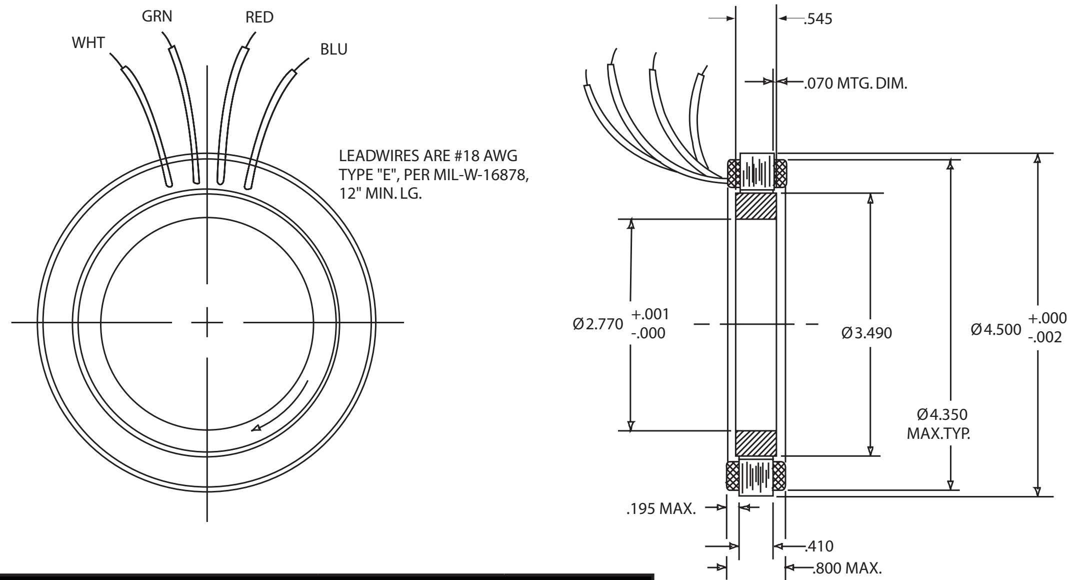
Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	20
Power at Tp (Pp)	watts	58
Motor Constant (Km)	oz-in/$\sqrt{W}$	2.65
Electrical Time Constant (e)	milli-sec	0.43
Mechanical Time Constant (m)	milli-sec	20
Damping Factor (Fo)	oz-in/rad/sec	0.05
Moment of Inertia (Jm)	oz-in-sec2	0.001
Total Breakaway Torque (Tf)	oz-in	1.0
Temperature Rise (TPR)	°C/watt	4
Max. Allowable Wdg. Temp.	°C	155
Weight	oz	2.6
Number of Poles		8
Number of Phases		2

Winding Constants						
Parameter	UNITS	TOL.	-004	-010	-066	-104
Resistance (R)	ohms	±12.5%	0.412	1.16	6.6	10.4
Voltage at Tp (Vp)	volts	Nominal	4.9	8.2	19.6	24.5
Current at Tp (Ip)	amps	Nominal	11.8	7	2.94	2.35
Torque Sensitivity (Kt)	oz-in/amp	±10%	1.70	2.83	6.80	8.50
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.012	0.020	0.049	0.061
Inductance (L)	millihenries	±30%	0.2	0.5	2.9	4.5

All constants, performance data at 25°C ambient temperature.

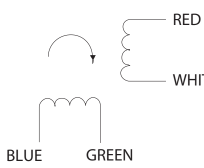
4500C-080C

BRUSHLESS DC MOTORS / INSIDE ROTOR



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	384
Power at Tp (Pp)	watts	120
Motor Constant (Km)	oz-in/$\sqrt{W}$	35
Electrical Time Constant (te)	milli-sec	0.42
Mechanical Time Constant (tm)	milli-sec	5.0
Damping Factor (Fo)	oz-in/rad/sec	8.7
Moment of Inertia (Jm)	oz-in-sec2	0.043
Total Breakaway Torque (Tf)	oz-in	9.6
Temperature Rise (TPR)	°C/watt	5.0
Max. Allowable Wdg. Temp.	°C	155
Weight	oz	22
Number of Poles		20
Number of Phases		2

ROTATION: FIELD ROTATES CW WHEN VIEWED FROM LEAD SIDE WITH THE FOLLOWING EXCITATION SEQUENCE: RED+, WHITE-, BLUE +, GREEN-.



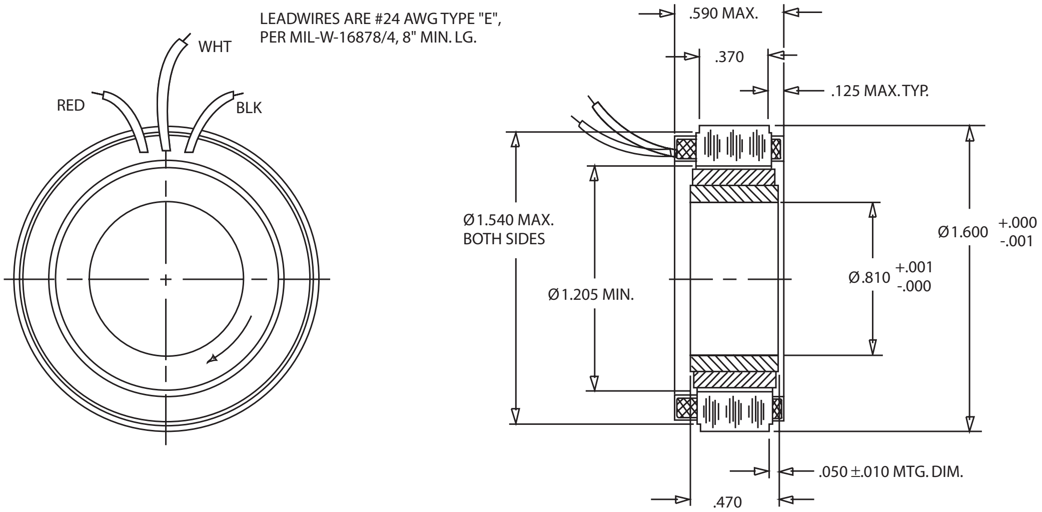
SCHEMATIC

Winding Constants						
Parameter	UNITS	TOL.	-016	-029	-033	-062
Resistance (R)	ohms	±12.5%	1.69	2.9	3.34	6.18
Voltage at Tp (Vp)	volts	Nominal	14.26	18.5	20	27.28
Current at Tp (Ip)	amps	Nominal	8.44	6.5	6	4.41
Torque Sensitivity (Kt)	oz-in/amp	±10%	45.5	59	64	87
Back E.M.F. (Kb)	volts/rad/sec	±10%	.321	0.42	.452	0.614
Inductance (L)	millihenries	±30%	0.69	1.19	1.4	2.59

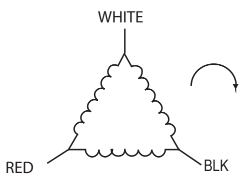
All constants, performance data at 25°C ambient temperature.

1600C-059J

BRUSHLESS DC MOTOR / INSIDE ROTOR



ROTATION: FIELD ROTATES CW WHEN VIEWED FROM LEAD SIDE WITH THE FOLLOWING EXCITATION SEQUENCE: WHT(+)-RED(-), RED(+)-BLK(-), BLK(+)-WHT(-).



SCHEMATIC

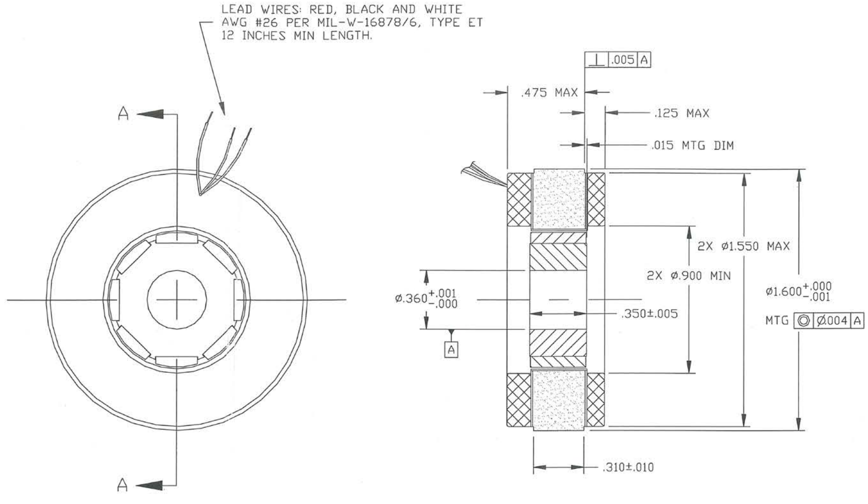
Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	20
Power at Tp (Pp)	watts	60.5
Motor Constant (Km)	oz-in/$\sqrt{W}$	2.57
Electrical Time Constant (e)	milli-sec	0.068
Mechanical Time Constant (m)	milli-sec	21.7
Damping Factor (Fo)	oz-in/rad/sec	0.046
Moment of Inertia (Jm)	oz-in-sec2	0.001
Total Breakaway Torque (Tf)	oz-in	1.0
Temperature Rise (TPR)	°C/watt	23
Max. Allowable Wdg. Temp.	°C	155
Weight	oz	2.6
Number of Poles		8
Number of Phases		3

Winding Constants						
Parameter	UNITS	TOL.	-004	-011	-028	-068
Resistance (R)	ohms	±12.5%	0.42	1.1	2.8	6.8
Voltage at Tp (Vp)	volts	Nominal	5.04	8.15	13	20.4
Current at Tp (Ip)	amps	Nominal	12	7.41	4.65	3
Torque Sensitivity (Kt)	oz-in/amp	±10%	1.67	2.70	4.30	6.70
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.012	.019	.030	.047
Inductance (L)	millihenries	±30%	0.028	.075	.19	.45

All constants, performance data at 25°C ambient temperature.

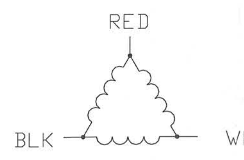
1600M-060-(***)

3 PHASE BRUSHLESS DC MOTOR / INSIDE ROTOR MOTOR ONLY



SECTION A-A

Size Constants	UNITS	SYMBOL	VALUE
Peak Torque, Stalled @ Vp:	oz-in	Tp	20
Power I^2R @ Tp:	watts	P	46.3
Continuous Stall Torque:	oz-in	Tcs	6
Motor Constant:	oz-in/$\sqrt{W}$	Km	2.94
Electrical Time Constant	ms	Te	3.3
Mechanical Time Constant:	ms	Tm	3.3
Damping Factor: (zero impedance)	oz-in/ (rad/sec)	Fo	0.06
Max Breakaway Torque:	oz-in	Tf	0.4
Rotor Inertia:	oz-in-sec^2	Jm	0.0002
Number of Poles:		p	8
Weight:	OZ	WT	2.4
Rated Winding Temperature	°C	Temp	155
Thermal Resistance:	°C/W	tpr	22



SCHEMATIC

Notes:

1) Direction of rotation CW when viewed from lead exit with excitation sequence of: RED(+)/WHT(-), WHT(+)/BLK(-) and BLK(+)/RED(-)

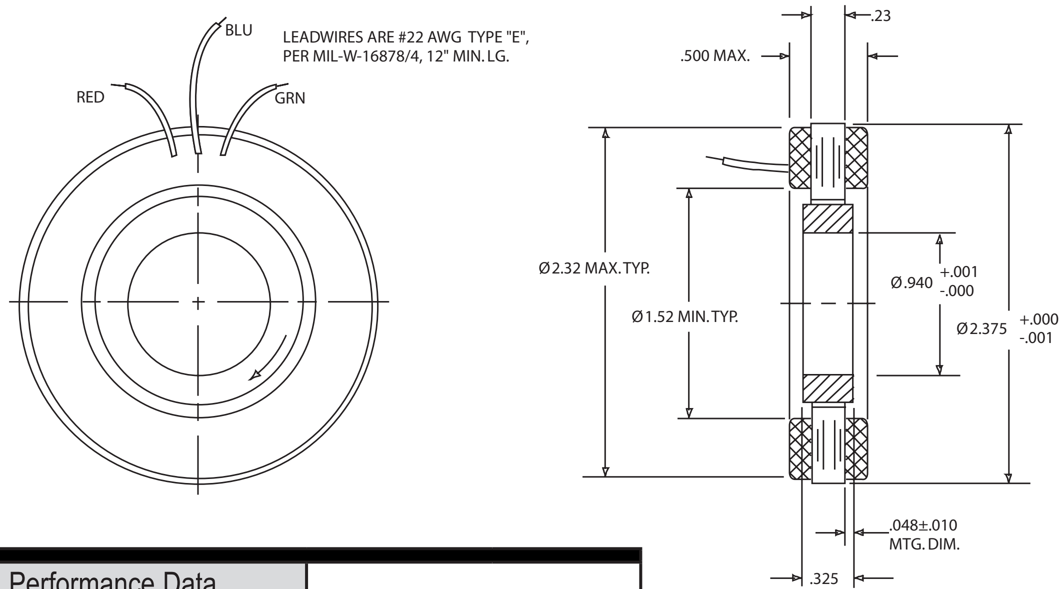
*** * * Order this Winding Designator**

	UNITS	TOL.	SYMBOL	-029	-110	-278
Design Voltage:	Volts	Nominal	Vp	11.6	22.6	35.9
Resistance: R	ohms	+/-12.5%	R	2.9	11	27.8
Inductance: L	mH	+/-30%	L	1	4	10
Torque Sensitivity: Kt	oz-in/A	+/-10%	Kt	5	9.75	15.5
Back EMF Constant: Kb	V/(rad/sec)	+/-10%	Kb	0.035	0.069	0.109
Peak Current @Tp:	Amps	Nominal	Ip	4	2	1.29

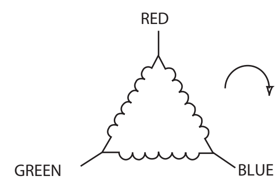
All constants, performance data at 25°C ambient temperature.

2375H-050

BRUSHLESS DC MOTOR / INSIDE ROTOR



ROTATION: FIELD ROTATES CW WHEN VIEWED FROM LEAD SIDE WITH THE FOLLOWING EXCITATION SEQUENCE:
RED+, GREEN-; GREEN+, BLUE-; BLUE+, RED-.



SCHEMATIC

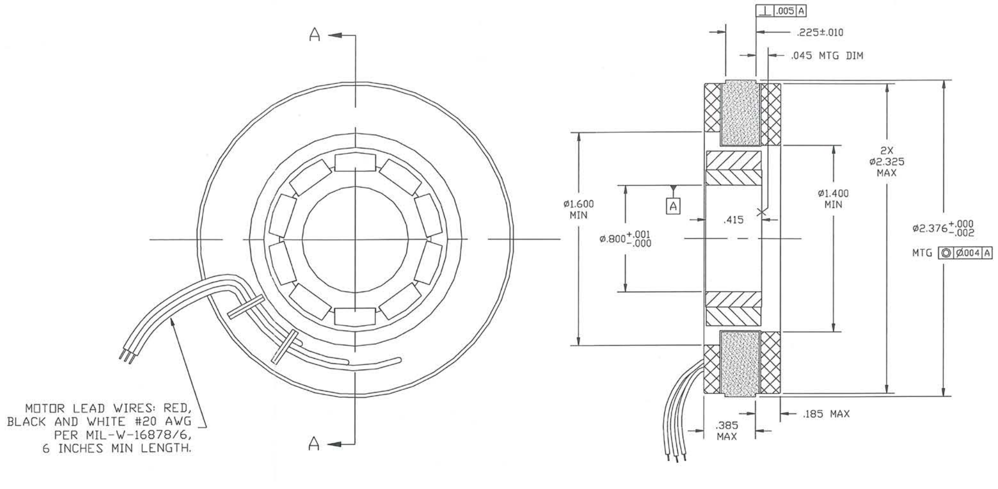
Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	60
Power at Tp (Pp)	watts	160
Motor Constant (Km)	oz-in/$\sqrt{W}$	4.74
Electrical Time Constant (te)	milli-sec	0.54
Mechanical Time Constant (tm)	milli-sec	10.0
Damping Factor (Fo)	oz-in/rad/sec	0.160
Moment of Inertia (Jm)	oz-in-sec2	0.0016
Total Breakaway Torque (Tf)	oz-in	1.0
Temperature Rise (TPR)	°C/watt	4
Max. Allowable Wdg. Temp.	°C	155
Weight	oz	5.5
Number of Poles		8
Number of Phases		3

Winding Constants						
Parameter	UNITS	TOL.	-013	-033	-052	-131
Resistance (R)	ohms	±12.5%	1.3	3.3	5.2	13.1
Voltage at Tp (Vp)	volts	Nominal	14.4	22.4	28.6	45
Current at Tp (Ip)	amps	Nominal	11.1	6.90	5.50	3.46
Torque Sensitivity (Kt)	oz-in/amp	±10%	5.40	8.70	10.9	17.4
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.039	0.061	0.076	0.120
Inductance (L)	millihenries	±30%	0.7	1.8	2.8	8

All constants, performance data at 25°C ambient temperature.

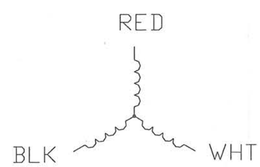
2376-057-(***)

3 PHASE BRUSHLESS DC MOTOR / INSIDE ROTOR MOTOR ONLY



SECTION A-A

Size Constants	UNITS	SYMBOL	VALUE
Peak Torque, Stalled @ Vp:	oz-in	Tp	68
Power I^2R @ Tp:	watts	P	68
Continuous Stall Torque:	oz-in	Tcs	22
Motor Constant:	oz-in/$\sqrt{W}$	Km	8.25
Electrical Time Constant	ms	Te	0.85
Mechanical Time Constant:	ms	Tm	2.3
Damping Factor: (zero impedance)	oz-in/ (rad/sec)	Fo	0.48
Max Breakaway Torque:	oz-in	Tf	1.3
Rotor Inertia:	oz-in-sec^2	Jm	0.0011
Number of Poles:		p	10
Weight:	OZ	WT	5.5
Rated Winding Temperature	°C	Temp.	155
Thermal Resistance:	°C/W	tpr	13



SCHEMATIC

Notes:

1) Direction of rotation CW when viewed from lead exit with excitation sequence of: RED(+)/WHT(-), WHT(+)/BLK(-) and BLK(+)/RED(-)

*** **Order this Winding Designator**

	UNITS	TOL.	SYMBOL	-018	-082	-180
Design Voltage:	Volts	Nominal	**Vp**	**11.1**	**23.6**	**35**
Resistance: R	ohms	+/-12.5%	R	1.52	8.19	18
Inductance: L	mH	+/-30%	L	1.54	6.96	15.3
Torque Sensitivity: Kt	oz-in/A	+/-10%	Kt	11.1	23.6	35
Back EMF Constant: Kb	V/(rad/sec)	+/-10%	Kb	0.078	0.167	0.247
Peak Current @Tp:	Amps	Nominal	Ip	6.13	2.88	1.94

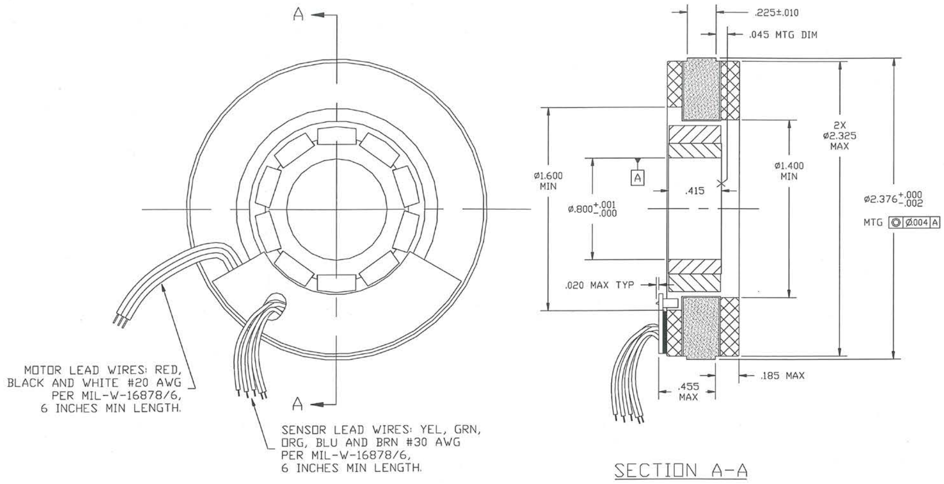
Winding Constants

Ver. 12/2012

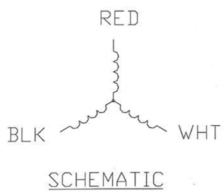
All constants, performance data at 25°C ambient temperature.

2376-064-(***)

3 PHASE BRUSHLESS DC MOTOR / INSIDE ROTOR MOTOR ONLY



Size Constants	UNITS	SYMBOL	VALUE
Peak Torque, Stalled @ Vp:	oz-in	Tp	856
Power I^2R @ Tp:	watts	P	282
Continuous Stall Torque:	oz-in	Tcs	308
Motor Constant:	oz-in/$\sqrt{W}$	Km	51
Electrical Time Constant	ms	Te	0.8
Mechanical Time Constant:	ms	Tm	2.1
Damping Factor: (zero impedance)	oz-in/ (rad/sec)	Fo	18.4
Max Breakaway Torque:	oz-in	Tf	12
Rotor Inertia:	oz-in-sec^2	Jm	0.0039
Number of Poles:		p	26
Weight:	OZ	WT	1.75
Rated Winding Temperature	$^{\circ}$C	Temp.	220
Thermal Resistance:	$^{\circ}$C/W	tpr	3.7



1) Direction of rotation CW when viewed from lead exit with excitation sequence of: RED(+)/WHT(-), WHT(+)/BLK(-) and BLK(+)/RED(-)

*** **Order this Winding Designator**

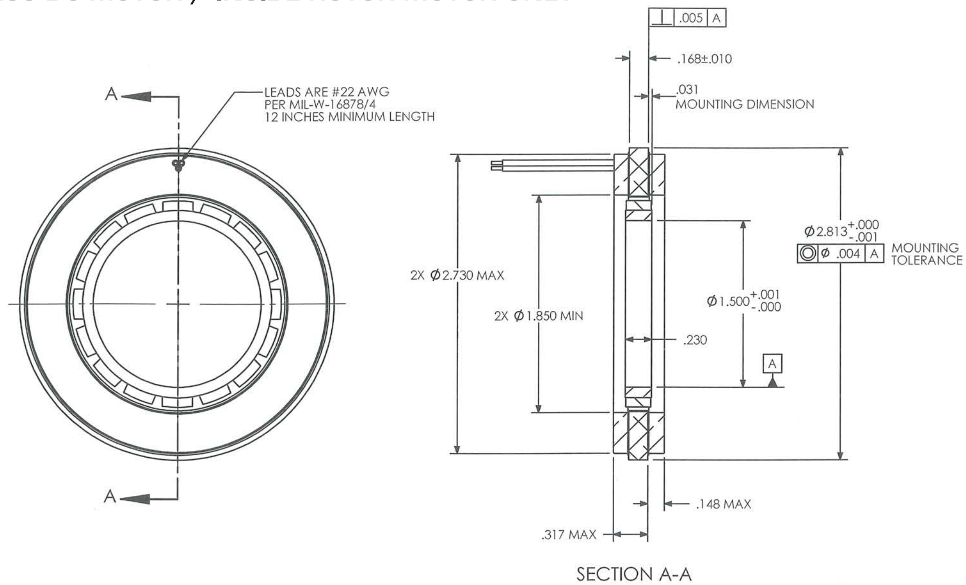
	UNITS	TOL.	SYMBOL	-018	-082	-180	
Design Voltage:	Volts	Nominal	**Vp**	**22.7**	**35.2**	**35**	Winding Constants
Resistance: R	ohms	+/-12.5%	R	1.83	4.4	20.3	
Inductance: L	mH	+/-30%	L	1.45	3.5	16.3	
Torque Sensitivity: Kt	oz-in/A	+/-10%	Kt	69	107	230	
Back EMF Constant: Kb	V/(rad/sec)	+/-10%	Kb	0.487	0.756	1.624	
Peak Current @Tp:	Amps	Nominal	Ip	12.4	8	3.72	

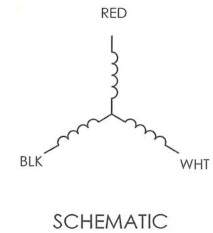
Ver. 12/2012

All constants, performance data at 25°C ambient temperature.

C2813B-047B-(***)

3 PHASE BRUSHLESS DC MOTOR / INSIDE ROTOR MOTOR ONLY





Size Constants	UNITS	SYMBOL	VALUE
Peak Torque, Stalled @ Vp:	oz-in	Tp	64
Power I^2R @ Tp:	watts	P	96
Continuous Stall Torque:	oz-in	Tcs	19
Motor Constant:	oz-in/$\sqrt{W}$	Km	6.53
Electrical Time Constant	ms	Te	0.33
Mechanical Time Constant:	ms	Tm	4.65
Damping Factor: *(zero impedance)*	oz-in/ (rad/sec)	Fo	0.30
Max Breakaway Torque:	oz-in	Tf	1.4
Rotor Inertia:	oz-in-sec^2	Jm	0.0014
Number of Poles:		p	16
Weight:	oz	WT	4
Rated Winding Temperature:	^{o}C	Temp.	155
Thermal Resistance:	^{o}C/W	tpr	12

Notes:

1) Direction of rotation CCW when viewed from lead exit with excitation sequence of: RED(+)/WHT(-), WHT(+)/BLK(-) and BLK(+)/RED(-)
2) Diameter clearance for clamping of rotor hub is 1.670" MAX

*** **Order this Winding Designator**

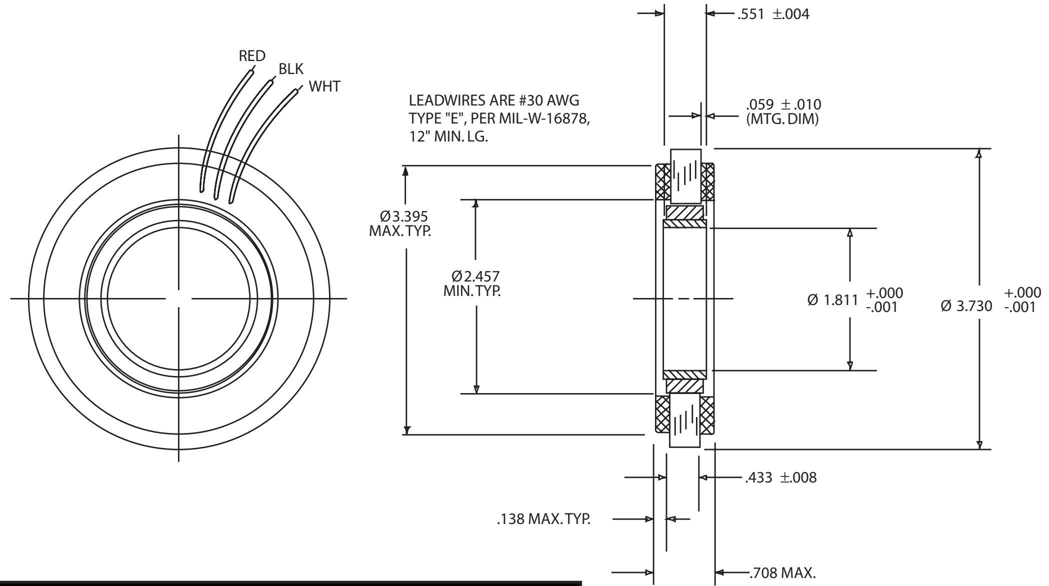
Winding Constants	UNITS	TOL.	SYMBOL	-015	-060	-240
Design Voltage:	Volts	Nominal	**Vp**	**12**	**24**	**48**
Resistance:	ohms	+/-12.5%	R	1.5	6.0	24
Inductance:	mH	+/-30%	L	0.50	2.0	8
Torque Sensitivity:	oz-in/A	+/-10%	Kt	8	16	32
Back EMF Constant:	V/(rad/sec)	+/-10%	Kb	0.0565	0.113	0.226
Peak Current @Tp:	Amps	Nominal	Ip	8.0	4.0	2.0

Ver. 11/8/17

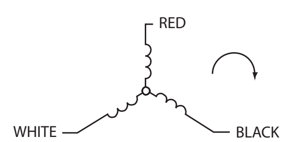
All constants, performance data at 25°C ambient temperature.

3730H-071

BRUSHLESS DC MOTOR / INSIDE ROTOR



ROTATION: FIELD ROTATES CW WHEN VIEWED FROM LEAD SIDE WITH THE FOLLOWING EXCITATION SEQUENCE: RED+, BLACK-; WHITE+, RED-; BLACK+, WHITE-.



SCHEMATIC

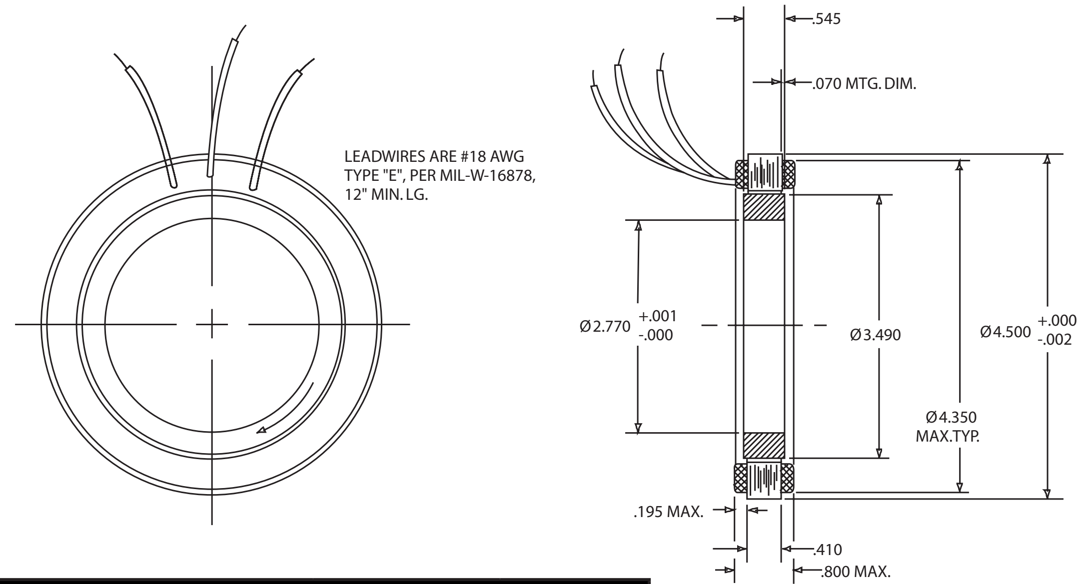
Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	187
Power at Tp (Pp)	watts	100
Motor Constant (Km)	oz-in/$\sqrt{W}$	18.7
Electrical Time Constant (e)	milli-sec	0.5
Mechanical Time Constant (m)	milli-sec	5.1
Damping Factor (Fo)	oz-in/rad/sec	2.5
Moment of Inertia (Jm)	oz-in-sec2	0.0125
Total Breakaway Torque (Tf)	oz-in	6.4
Temperature Rise (TPR)	°C/watt	5.8
Max. Allowable Wdg. Temp.	°C	155
Weight	lbs	1.2
Number of Poles		14
Number of Phases		3

Winding Constants						
Parameter	UNITS	TOL.	-034	-051	-082	-125
Resistance (R)	ohms	±12.5%	3.5	5.16	8.95	12.5
Voltage at Tp (Vp)	volts	Nominal	18.7	22.7	29.9	35.4
Current at Tp (Ip)	amps	Nominal	5.34	4.40	3.34	2.83
Torque Sensitivity (Kt)	oz-in/amp	±10%	35.0	42.5	56.0	66.0
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.247	.300	.395	.466
Inductance (L)	millihenries	±30%	1.75	2.6	4.5	6.2

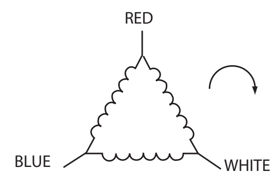
All constants, performance data at 25°C ambient temperature.

4500C-080

BRUSHLESS DC MOTOR / INSIDE ROTOR



ROTATION: FIELD ROTATES CW WHEN VIEWED FROM LEAD SIDE WITH THE FOLLOWING EXCITATION SEQUENCE: RED+, WHITE-; WHITE+, BLUE-; BLUE+, RED-.



SCHEMATIC

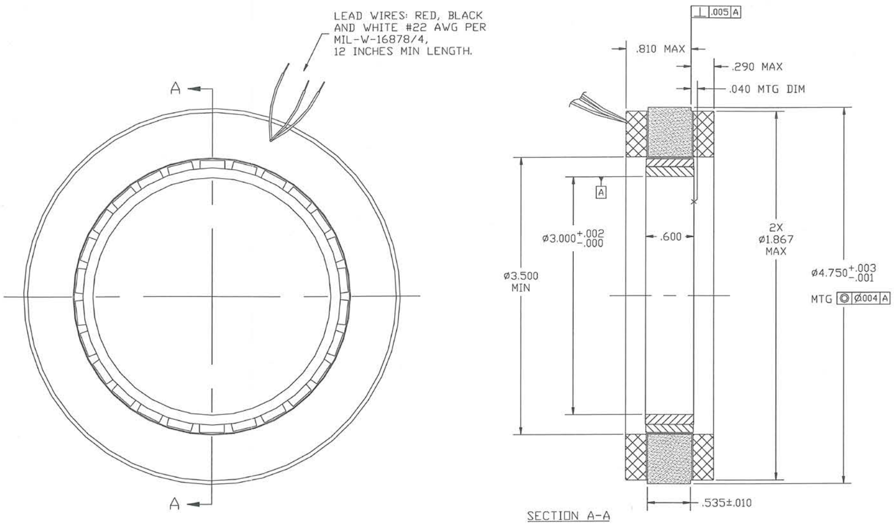
Performance Data		
Parameter	**Units**	**Value**
Peak Torque (Tp)	oz-in	384
Power at Tp (Pp)	watts	116
Motor Constant (Km)	oz-in/$\sqrt{W}$	35.6
Electrical Time Constant (te)	milli-sec	0.50
Mechanical Time Constant (tm)	milli-sec	4.75
Damping Factor (Fo)	oz-in/rad/sec	8.97
Moment of Inertia (Jm)	oz-in-sec2	0.0426
Total Breakaway Torque (Tf)	oz-in	9.6
Temperature Rise (TPR)	°C/watt	4.9
Max. Allowable Wdg. Temp.	°C	155
Weight	oz	22
Number of Poles		20
Number of Phases		3

Winding Constants						
Parameter	UNITS	TOL.	-008	-020	-031	-048
Resistance (R)	ohms	±12.5%	0.84	2.0	3.0	4.8
Voltage at Tp (Vp)	volts	Nominal	9.89	15.24	18.7	23.6
Current at Tp (Ip)	amps	Nominal	11.77	7.62	6.23	4.92
Torque Sensitivity (Kt)	oz-in/amp	±10%	32.6	50.4	61.7	78.0
Back E.M.F. (Kb)	volts/rad/sec	±10%	.230	.356	.436	.551
Inductance (L)	millihenries	±30%	0.42	1.0	1.5	2.4

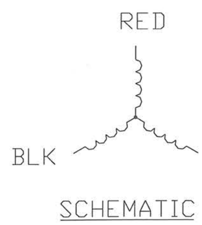
All constants, performance data at 25°C ambient temperature.

4750J-110-(***)

BRUSHLESS DC MOTOR WITH HALL SENSORS / INSIDE ROTOR



Size Constants	UNITS	SYMBOL	VALUE
Peak Torque, Stalled @ Vp:	oz-in	Tp	856
Power I^2R @ Tp:	watts	P	282
Continuous Stall Torque:	oz-in	Tcs	308
Motor Constant:	oz-in/$\sqrt{W}$	Km	51
Electrical Time Constant	ms	Te	0.8
Mechanical Time Constant:	ms	Tm	2.1
Damping Factor: (zero impedance)	oz-in/ (rad/sec)	Fo	18.4
Max Breakaway Torque:	oz-in	Tf	12
Rotor Inertia:	oz-in-sec^2	Jm	0.0039
Number of Poles:		p	26
Weight:	OZ	WT	1.75
Rated Winding Temperature	^{o}C	Temp.	220
Thermal Resistance:	^{o}C/W	tpr	3.7



Notes:

1) Direction of rotation CCW when viewed from lead exit with excitation sequence of: RED(+)/WHT(-), WHT(+)/BLK(-) and BLK(+)/RED(-)

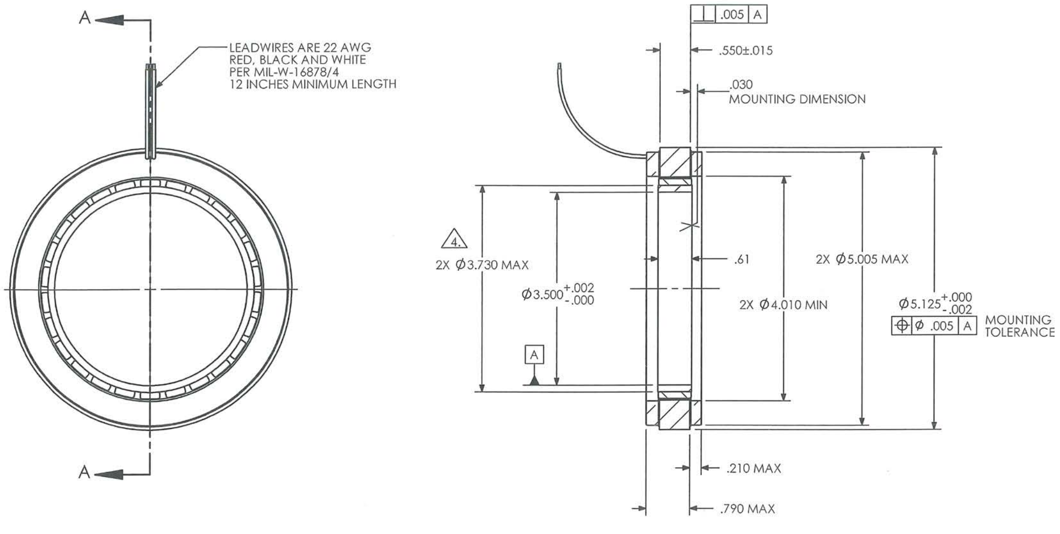
*** **Order this Winding Designator**

	UNITS	TOL.	SYMBOL	-018	-044	-069	-203	
Design Voltage:	Volts	Nominal	**Vp**	**22.7**	**35.2**	**44.1**	**75.6**	Winding Constants
Resistance: R	ohms	+/-12.5%	R	1.83	4.4	6.9	20.3	
Inductance: L	mH	+/-30%	L	1.45	3.5	16.3	16.3	
Torque Sensitivity: Kt	oz-in/A	+/-10%	Kt	69	107	134	230	
Back EMF Constant: Kb	V/(rad/sec)	+/-10%	Kb	0.487	0.756	0.946	1.624	
Peak Current @Tp:	Amps	Nominal	Ip	12.4	8	3.39	3.72	

All constants, performance data at 25°C ambient temperature.

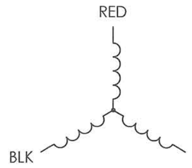
C5125B-100-(***)

3 PHASE BRUSHLESS DC MOTOR / INSIDE ROTOR MOTOR ONLY



SECTION A-A

Size Constants	UNITS	SYMBOL	VALUE
Peak Torque, Stalled @ Vp:	oz-in	Tp	920
Power I^2R @ Tp:	watts	P	240
Continuous Stall Torque:	oz-in	Tcs	-
Motor Constant:	oz-in/$\sqrt{W}$	Km	59.4
Electrical Time Constant	ms	Te	0.83
Mechanical Time Constant:	ms	Tm	2.73
Damping Factor: *(zero impedance)*	oz-in/ (rad/sec)	Fo	24.9
Max Breakaway Torque:	oz-in	Tf	14.5
Rotor Inertia:	oz-in-sec^2	Jm	0.068
Number of Poles:		p	26
Weight:	LBS	WT	1.6
Rated Winding Temperature:	^{o}C	Temp.	155
Thermal Resistance:	^{o}C/W	tpr	3.7



SCHEMATIC

Notes:

1) Direction of rotation CCW when viewed from lead exit with excitation sequence of: RED(+)/WHT(-), WHT(+)/BLK(-) and BLK(+)/RED(-)

4) Diameter designates clearance for clamping

* * * **Order this Winding Designator**

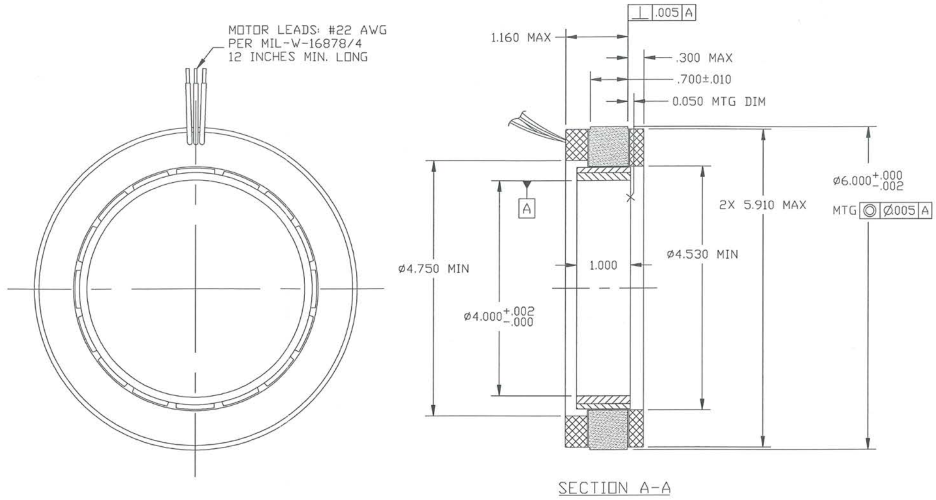
	UNITS	TOL.	SYMBOL	**-024**	**-096**	**-300**	
Design Voltage:	Volts	Nominal	**Vp**	**24**	**48**	**85**	Winding Constants
Resistance:	ohms	+/-12.5%	R	2.4	9.6	30	
Inductance:	mH	+/-30%	L	2.0	8.0	25	
Torque Sensitivity:	oz-in/A	+/-10%	Kt	92	184	325	
Back EMF Constant:	V/(rad/sec)	+/-10%	Kb	0.65	1.30	2.30	
Peak Current @Tp:	Amps	Nominal	Ip	10	5	2.83	

Ver. 11/9/17

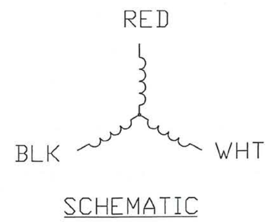
All constants, performance data at 25°C ambient temperature.

6000S-146-(***)

3 PHASE BRUSHLESS DC MOTOR / INSIDE ROTOR MOTOR MOTOR ONLY



Size Constants	UNITS	SYMBOL	VALUE
Peak Torque, Stalled @ Vp:	oz-in	Tp	2100
Power I^2R @ Tp:	watts	P	360
Continuous Stall Torque:	oz-in	Tcs	882
Motor Constant:	oz-in/$\sqrt{W}$	Km	110.7
Electrical Time Constant	ms	Te	1.56
Mechanical Time Constant:	ms	Tm	1.91
Damping Factor: (zero impedance)	oz-in/ (rad/sec)	Fo	86.5
Max Breakaway Torque:	oz-in	Tf	20
Rotor Inertia:	oz-in-sec^2	Jm	0.165
Number of Poles:		p	16
Weight:	OZ	WT	4.0
Rated Winding Temperature	°C	Temp.	220
Thermal Resistance:	°C/W	tpr	2.28



Notes:

1) Direction of rotation CCW when viewed from lead exit with excitation sequence of: RED(+)/WHT(-), WHT(+)/BLK(-) and BLK(+)/RED(-)

*** * * Order this Winding Designator**

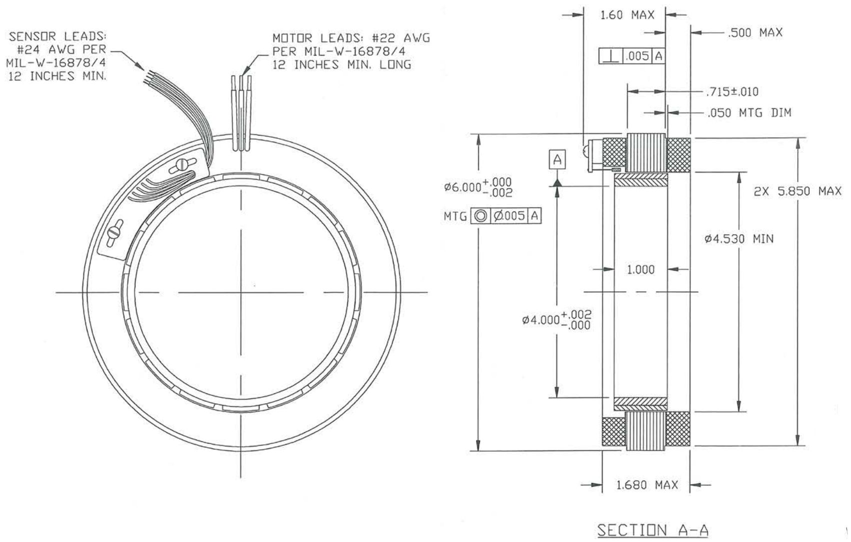
	UNITS	TOL.	SYMBOL	-016	-064	-162
Design Voltage:	Volts	Nominal	**Vp**	**24**	**48**	**76.5**
Resistance: R	ohms	+/-12.5%	R	1.6	6.4	16.2
Inductance: L	mH	+/-30%	L	2.5	10	26
Torque Sensitivity: Kt	oz-in/A	+/-10%	Kt	140	280	445
Back EMF Constant: Kb	V/(rad/sec)	+/-10%	Kb	0.989	1.977	3.142
Peak Current @Tp:	Amps	Nominal	Ip	6.13	7.5	4.72

Winding Constants

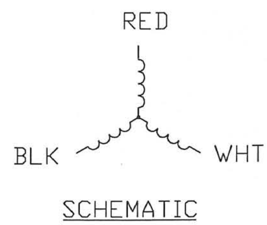
All constants, performance data at 25°C ambient temperature.

6000S-210-(***)

3 PHASE BRUSHLESS DC MOTOR / INSIDE ROTOR MOTOR WITH HALL SENSORS



Size Constants	UNITS	SYMBOL	VALUE
Peak Torque, Stalled @ Vp:	oz-in	Tp	2100
Power I^2R @ Tp:	watts	P	360
Continuous Stall Torque:	oz-in	Tcs	882
Motor Constant:	oz-in/$\sqrt{W}$	Km	110.7
Electrical Time Constant	ms	Te	1.56
Mechanical Time Constant:	ms	Tm	1.91
Damping Factor: (zero impedance)	oz-in/ (rad/sec)	Fo	86.5
Max Breakaway Torque:	oz-in	Tf	20
Rotor Inertia:	oz-in-sec^2	Jm	0.165
Number of Poles:		p	16
Weight:	OZ	WT	4.0
Rated Winding Temperature	°C	Temp.	220
Thermal Resistance:	°C/W	tpr	2.28



Notes:

1) Direction of rotation CCW when viewed from lead exit with excitation sequence of: RED(+)/WHT(-), WHT(+)/BLK(-) and BLK(+)/RED(-)

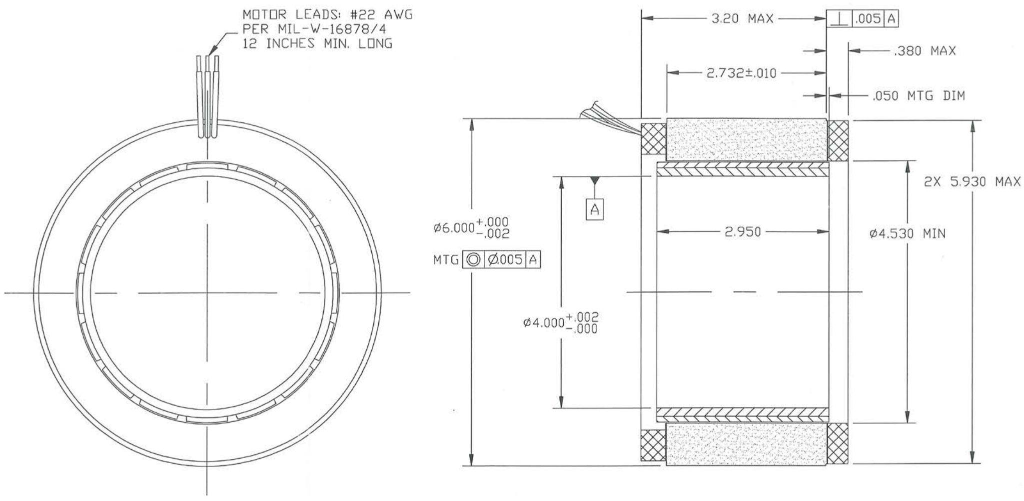
*** **Order this Winding Designator**

	UNITS	TOL.	SYMBOL	-016	-064	-162	
Design Voltage:	Volts	Nominal	**Vp**	**24**	**48**	**76.5**	Winding Constants
Resistance: R	ohms	+/-12.5%	R	1.6	6.4	16.2	
Inductance: L	mH	+/-30%	L	2.5	10	26	
Torque Sensitivity: Kt	oz-in/A	+/-10%	Kt	140	280	445	
Back EMF Constant: Kb	V/(rad/sec)	+/-10%	Kb	0.989	1.977	3.142	
Peak Current @Tp:	Amps	Nominal	Ip	15	7.5	4.72	

All constants, performance data at 25°C ambient temperature.

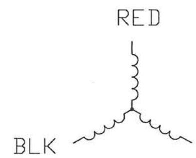
6000S-360-(***)

3 PHASE BRUSHLESS DC MOTOR / INSIDE ROTOR MOTOR ONLY



SECTION A-A

Size Constants	UNITS	SYMBOL	VALUE
Peak Torque, Stalled @ Vp:	oz-in	Tp	5280
Power I^2R @ Tp:	watts	P	384
Continuous Stall Torque:	oz-in	Tcs	3115
Motor Constant:	oz-in/$\sqrt{W}$	Km	269.4
Electrical Time Constant	ms	Te	2.5
Mechanical Time Constant:	ms	Tm	1.0
Damping Factor: (zero impedance)	oz-in/ (rad/sec)	Fo	513
Max Breakaway Torque:	oz-in	Tf	70
Rotor Inertia:	oz-in-sec^2	Jm	0.51
Number of Poles:		p	16
Weight:	OZ	WT	12
Rated Winding Temperature	°C	Temp.	220
Thermal Resistance:	°C/W	tpr	1.1



SCHEMATIC

Notes:
1) Direction of rotation CCW when viewed from lead exit with excitation sequence of: RED(+)/WHT(-), WHT(+)/BLK(-) and BLK(+)/RED(-)

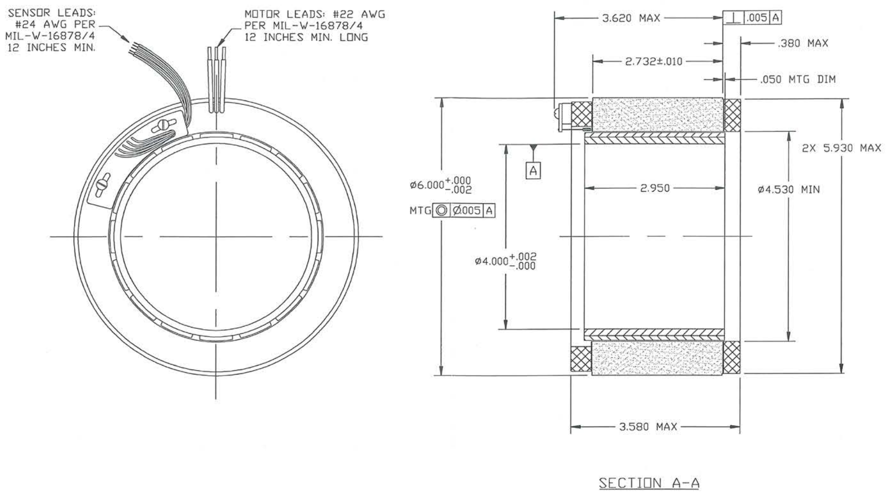
*** **Order this Winding Designator**

Winding Constants	UNITS	TOL.	SYMBOL	-015	-060	-154
Design Voltage:	Volts	Nominal	**Vp**	**24**	**48**	**77**
Resistance: R	ohms	+/-12.5%	R	1.5	6	15.4
Inductance: L	mH	+/-30%	L	3.8	15	38.5
Torque Sensitivity: Kt	oz-in/A	+/-10%	Kt	330	660	1056
Back EMF Constant: Kb	V/(rad/sec)	+/-10%	Kb	2.330	4.661	7.457
Peak Current @Tp:	Amps	Nominal	Ip	16	8	5

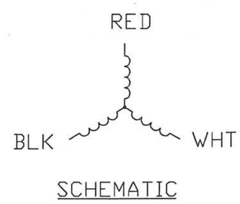
All constants, performance data at 25°C ambient temperature.

6000S-400-(***)

3 PHASE BRUSHLESS DC MOTOR / INSIDE ROTOR MOTOR WITH HALL SENSORS



Size Constants	UNITS	SYMBOL	VALUE
Peak Torque, Stalled @ Vp:	oz-in	Tp	5280
Power I^2R @ Tp:	watts	P	384
Continuous Stall Torque:	oz-in	Tcs	3115
Motor Constant:	oz-in/$\sqrt{W}$	Km	269.4
Electrical Time Constant	ms	Te	2.5
Mechanical Time Constant:	ms	Tm	1.0
Damping Factor: (zero impedance)	oz-in/ (rad/sec)	Fo	513
Max Breakaway Torque:	oz-in	Tf	70
Rotor Inertia:	oz-in-sec^2	Jm	0.51
Number of Poles:		p	16
Weight:	OZ	WT	12.7
Rated Winding Temperature	°C	Temp.	220
Thermal Resistance:	°C/W	tpr	1.1



Notes:

1) Direction of rotation CCW when viewed from lead exit with excitation sequence of: RED(+)/WHT(-), WHT(+)/BLK(-) and BLK(+)/RED(-)

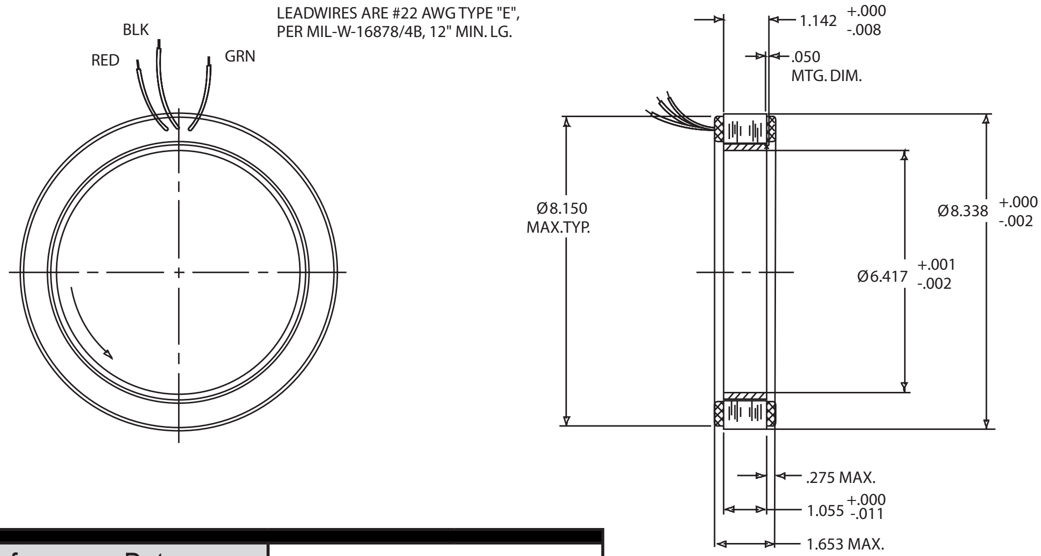
*** **Order this Winding Designator**

	UNITS	TOL.	SYMBOL	-015	-060	-154	Winding Constants
Design Voltage:	Volts	Nominal	**Vp**	**24**	**48**	**77**	
Resistance: R	ohms	+/-12.5%	R	1.5	6	15.4	
Inductance: L	mH	+/-30%	L	3.8	15	38.5	
Torque Sensitivity: Kt	oz-in/A	+/-10%	Kt	330	660	1056	
Back EMF Constant: Kb	V/(rad/sec)	+/-10%	Kb	2.330	4.661	7.457	
Peak Current @Tp:	Amps	Nominal	Ip	16	8	5	

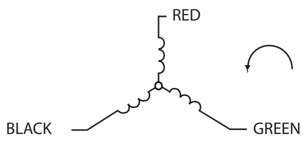
All constants, performance data at 25°C ambient temperature.

8338-157

BRUSHLESS DC MOTOR / INSIDE ROTOR



ROTATION: FIELD ROTATES CCW WHEN VIEWED FROM LEAD SIDE WITH THE FOLLOWING EXCITATION SEQUENCE: RED+BLK-; RED+GRN-; BLK+GRN-; BLK+RED-; GRN+RED-; GRN+BLK-.



SCHEMATIC

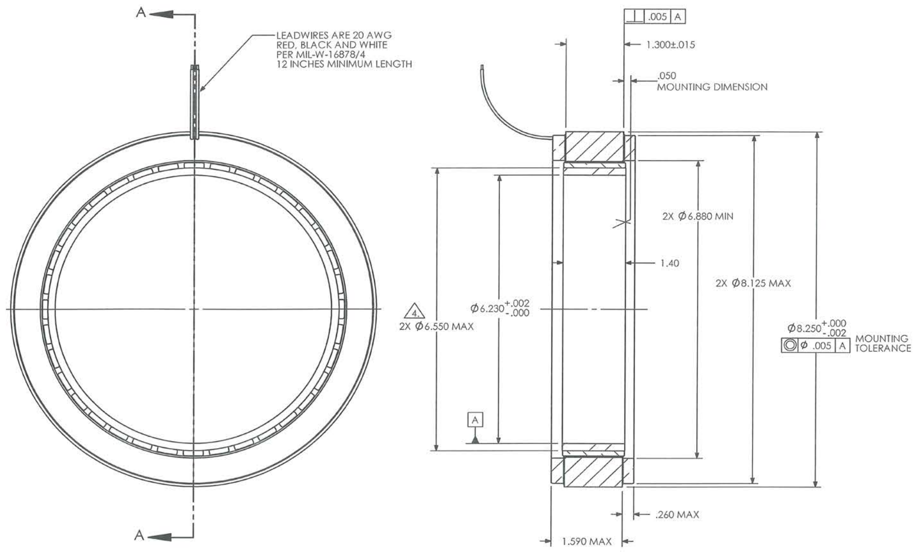
Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	2124min
Power at Tp (Pp)	watts	106
Motor Constant (Km)	oz-in/$\sqrt{W}$	198min
Electrical Time Constant (e)	milli-sec	1.3
Mechanical Time Constant (m)	milli-sec	2.0
Damping Factor (Fo)	oz-in/rad/sec	304
Moment of Inertia (Jm)	oz-in-sec2	0.600
Total Breakaway Torque (Tf)	oz-in	56.6
Temperature Rise (TPR)	°C/watt	1.1
Max. Allowable Wdg. Temp.	°C	155
Weight	lbs	6.6
Number of Poles		36
Number of Phases		3

Winding Constants					
Parameter	UNITS	TOL.	-043	-057	-120
Resistance (R)	ohms	±12.5%	4.40	5.7	11.5
Voltage at Tp (Vp)	volts	Nominal	22.5	24	36.4
Current at Tp (Ip)	amps	Nominal	5.1	4.20	3.17
Torque Sensitivity (Kt)	oz-in/amp	±10%	439	505.5	744.8
Back E.M.F. (Kb)	volts/rad/sec	±10%	3.1	3.42	5.26
Inductance (L)	millihenries	±30%	6	9	16

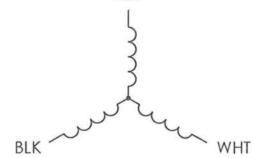
All constants, performance data at 25°C ambient temperature.

C8250B-185B-(***)

3 PHASE BRUSHLESS DC MOTOR / INSIDE ROTOR MOTOR ONLY



Size Constants	UNITS	SYMBOL	VALUE
Peak Torque, Stalled @ Vp:	oz-in	Tp	4200
Power I^2R @ Tp:	watts	P	240
Continuous Stall Torque:	oz-in	Tcs	-
Motor Constant:	oz-in/$\sqrt{W}$	Km	271.1
Electrical Time Constant	ms	Te	1.25
Mechanical Time Constant:	ms	Tm	1.77
Damping Factor: *(zero impedance)*	oz-in/ (rad/sec)	Fo	520
Max Breakaway Torque:	oz-in	Tf	90
Rotor Inertia:	oz-in-sec^2	Jm	0.92
Number of Poles:		p	36
Weight:	LBS	WT	7.5
Rated Winding Temperature:	$^{\circ}$C	Temp.	155
Thermal Resistance:	$^{\circ}$C/W	tpr	1.3



SCHEMATIC

Notes:

1) Direction of rotation CCW when viewed from lead exit with excitation sequence of: RED(+)/WHT(-), WHT(+)/BLK(-) and BLK(+)/RED(-)

4) Diameter designates clearance for clamping

*** **Order this Winding Designator**

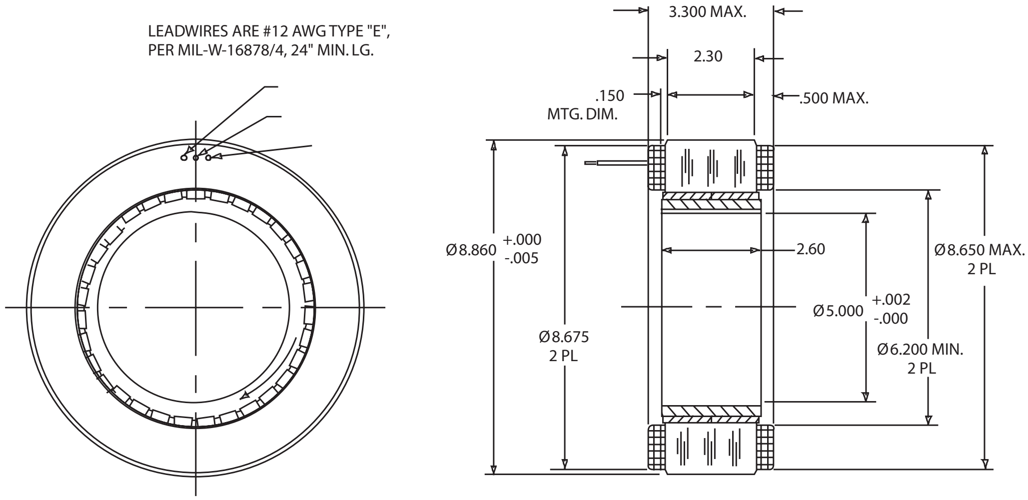
	UNITS	TOL.	SYMBOL	-024	-096	-384	
Design Voltage:	Volts	Nominal	**Vp**	**24**	**48**	**96**	Winding Constants
Resistance:	ohms	+/-12.5%	R	2.4	9.6	38.4	
Inductance:	mH	+/-30%	L	3.0	12	48	
Torque Sensitivity:	oz-in/A	+/-10%	Kt	420	840	1680	
Back EMF Constant:	V/(rad/sec)	+/-10%	Kb	2.97	5.93	11.86	
Peak Current @Tp:	Amps	Nominal	Ip	10	5.0	2.5	

Ver. 11/9/17

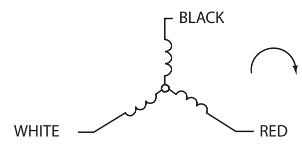
All constants, performance data at 25°C ambient temperature.

8860B-330

BRUSHLESS DC MOTOR / INSIDE ROTOR



ROTATION: FIELD ROTATES CW WHEN VIEWED FROM LEAD SIDE WITH THE FOLLOWING EXCITATION SEQUENCE: BLACK+, WHITE-; BLACK+, RED-; WHITE+, BLACK-.



SCHEMATIC

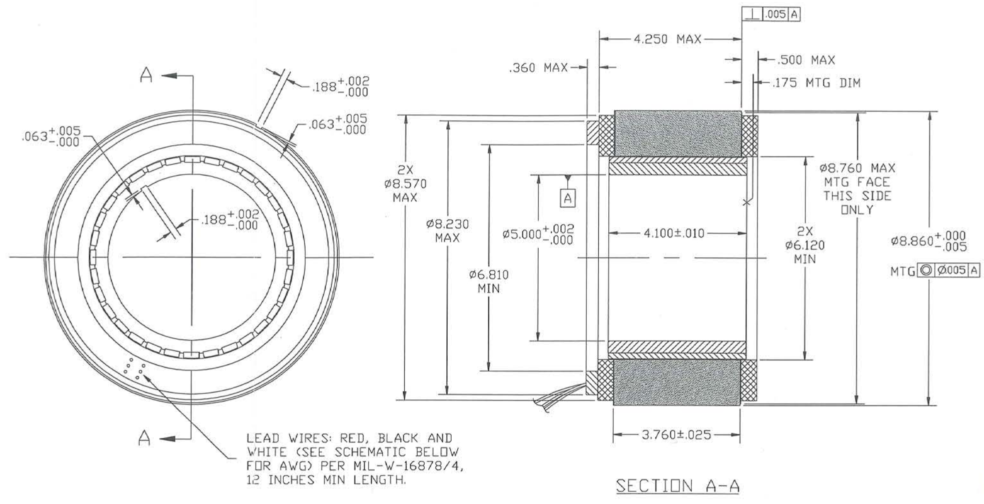
Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	15,294
Power at Tp (Pp)	watts	1020
Motor Constant (Km)	oz-in/$\sqrt{W}$	480
Electrical Time Constant (e)	milli-sec	3.2
Mechanical Time Constant (m)	milli-sec	1.0
Damping Factor (Fo)	oz-in/rad/sec	1635
Moment of Inertia (Jm)	oz-in-sec2	1.62
Total Breakaway Torque (Tf)	oz-in	160
Temperature Rise (TPR)	°C/watt	0.4
Max. Allowable Wdg. Temp.	°C	155
Weight	lb	24
Number of Poles		32
Number of Phases		3

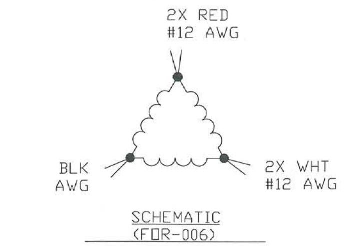
Winding Constants			
Parameter	UNITS	TOL.	-058
Resistance (R)	ohms	±12.5%	5.8
Voltage at Tp (Vp)	volts	Nominal	75.4
Current at Tp (Ip)	amps	Nominal	13.0
Torque Sensitivity (Kt)	oz-in/amp	±10%	1180
Back E.M.F. (Kb)	volts/rad/sec	±10%	8.33
Inductance (L)	millihenries	±30%	18.5

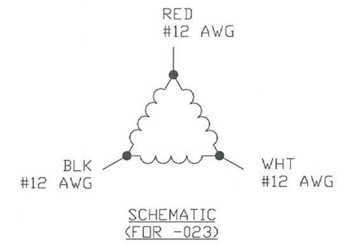
All constants, performance data at 25°C ambient temperature.

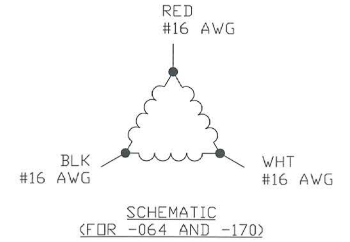
8860B-475-(***)

3 PHASE BRUSHLESS DC MOTOR / INSIDE ROTOR MOTOR ONLY









Size Constants	UNITS	SYMBOL	VALUE
Peak Torque, Stalled @ Vp:	oz-in	Tp	35520
Power I^2R @ Tp:	watts	P	3712
Continuous Stall Torque:	oz-in	Tcs	9590
Motor Constant:	oz-in/$\sqrt{W}$	Km	583
Electrical Time Constant	ms	Te	3.8
Mechanical Time Constant:	ms	Tm	0.96
Damping Factor: (zero impedance)	oz-in/ (rad/sec)	Fo	2402
Max Breakaway Torque:	oz-in	Tf	312
Rotor Inertia:	oz-in-sec^2	Jm	2.3
Number of Poles:		p	32
Weight:	OZ	WT	41.5
Rated Winding Temperature	°C	Temp.	220
Thermal Resistance:	°C/W	tpr	0.52

Notes:

1) Direction of rotation CW when viewed from lead exit with excitation sequence of: RED(+)/WHT(-), WHT(+)/BLK(-) and BLK(+)/RED(-)

*** **Order this Winding Designator**

	UNITS	TOL.	SYMBOL	-006	-023	-064	-170
Design Voltage:	Volts	Nominal	**Vp**	**46.4**	**92.8**	**154.6**	**252**
Resistance: R	ohms	+/-12.5%	R	0.58	2.32	6.44	17
Inductance: L	mH	+/-30%	L	2.2	8.8	24.4	64
Torque Sensitivity: Kt	oz-in/A	+/-10%	Kt	444	888	1480	2400
Back EMF Constant: Kb	V/(rad/sec)	+/-10%	Kb	3.14	6.27	10.45	17
Peak Current @Tp:	Amps	Nominal	Ip	80	40	24	14.8

Winding Constants

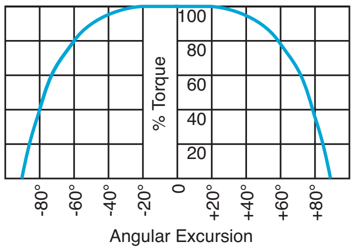
All constants, performance data at 25°C ambient temperature.

Selection Guide: by Peak Torque - Limited Angle Slotless Motors (Toroidally Wound)

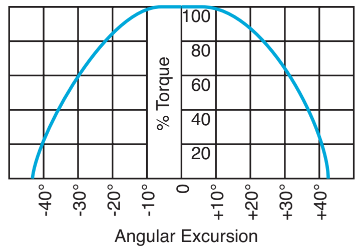
Model Number	Peak Torque (oz-in.)	Power@T_P (watts)	Km (oz-in/$\sqrt{\text{watts}}$)	Ang. Excusion (± degrees)	O.D. (in.)	I.D. (in.)	Axial Length (in.)	Page
BTM10-AD	1.7min	24.4	0.344	60	1.000	0.188	0.350	47
BTM10-N-2	1.8	21	0.4	20	1.000	0.125	0.350	48
BTM10-S	6.0	85	0.650	60	0.960	0.125	0.700	49
BTM14-E	6.0	38.4	0.968	30	1.374	0.500	0.375	50
BTM16-B	6.0	25	1.20	22.5	1.600	0.810	0.350	51
BTM18-G	18	39	2.89	25	1.718	0.250	0.700	52
BTM18-L	20	62	2.58	50	1.719	0.187	0.943	53
BTM15-C	22	158.5	1.75	15	1.500	0.375	0.500	54
BTM30-EX	63	72	7.42	60	3.000	0.500	1.000	55
BTM35-BX	165	118	15.2	20	3.500	1.000	0.950	56
BTM34-SX	170	430	8.20	50	3.400	0.380	1.100	57
BTM34-Q-B	180	100	18.0	5	3.350	1.7260	0.800	58
BTM48-BX	220	214	14.1	5	4.759	2.676	0.600	59

TYPICAL PERFORMANCE CURVES FOR LIMITED ANGLE SLOTLESS MOTORS

TORQUE VS. ANGULAR EXCUSION



X



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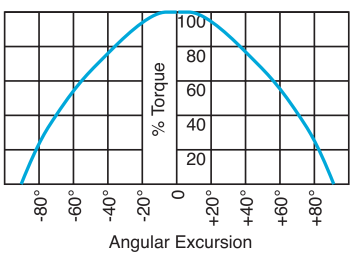

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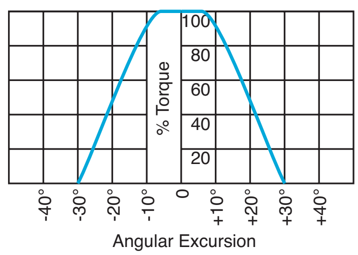
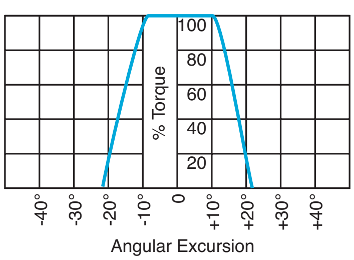


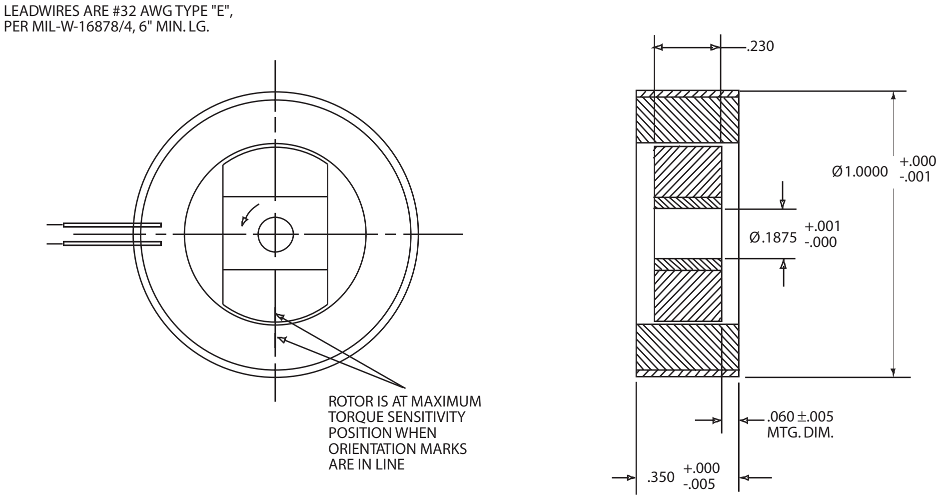
6 Pole



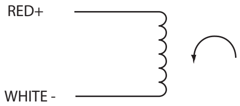
8 Pole

BTM10-AD

BRUSHLESS DC MOTORS



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	1.7min
Power at Tp (Pp)	watts	24.4
Motor Constant (Km)	oz-in/$\sqrt{W}$	0.344
Constinuous Torque (Tc)	oz-in	0.5
Power at Constinuous Torque	watts	1.7
Input Volts at Constinuous Torque	volts	7.5
Electrical Time Constant (Te)	milli-sec	0.15
Mechanical Time Constant (Tm)	milli-sec	17.4
Damping Factor (Fo)	oz-in/rad/sec	0.00075
Rotor Inertia (Jm)	oz-in-sec2	0.000015
Angular Excursion (Page 46, Curve x.)	degrees	±60
Total Breakaway Torque (Tf)	oz-in	0.04
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		2
Weight	oz	0.64



SCHEMATIC

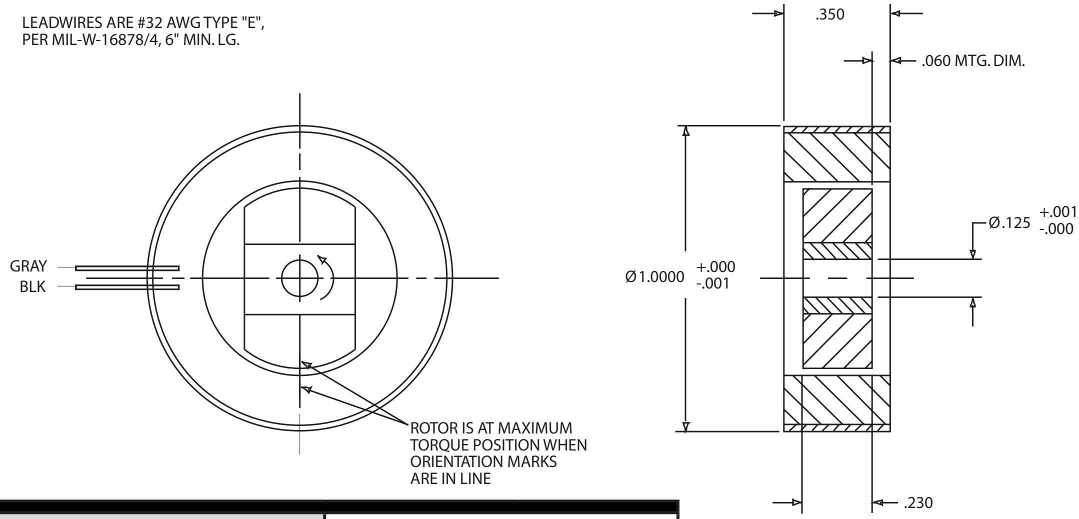
ROTATION CCW VIEWING FROM LEAD SIDE.

Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±12.5%	33.0
Voltage at Tp (Vp)	volts	Nominal	28.4
Current at Tp (Ip)	amps	Nominal	0.86
Torque Sensitivity (Kt)	oz-in/amp	±10%	2.20
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.0155
Inductance (L)	millihenries	±30%	5.0

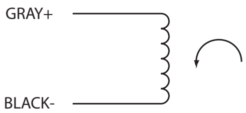
All constants, performance data at 25°C ambient temperature.

BTM10-N-2

BRUSHLESS DC MOTORS



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	1.8
Power at Tp (Pp)	watts	21
Motor Constant (Km)	oz-in/$\sqrt{W}$	0.4
Constinuous Torque (Tc)	oz-in	0.6
Power at Constinuous Torque	watts	2.3
Input Volts at Constinuous Torque	volts	9.6
Electrical Time Constant (Te)	milli-sec	0.30
Mechanical Time Constant (Tm)	milli-sec	16.0
Damping Factor (Fo)	oz-in/rad/sec	0.0011
Rotor Inertia (Jm)	oz-in-sec2	0.000018
Angular Excursion (Page 46, Curve z)	degrees	±20
Total Breakaway Torque (Tf)	oz-in	0.10
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		2
Weight	oz	0.8



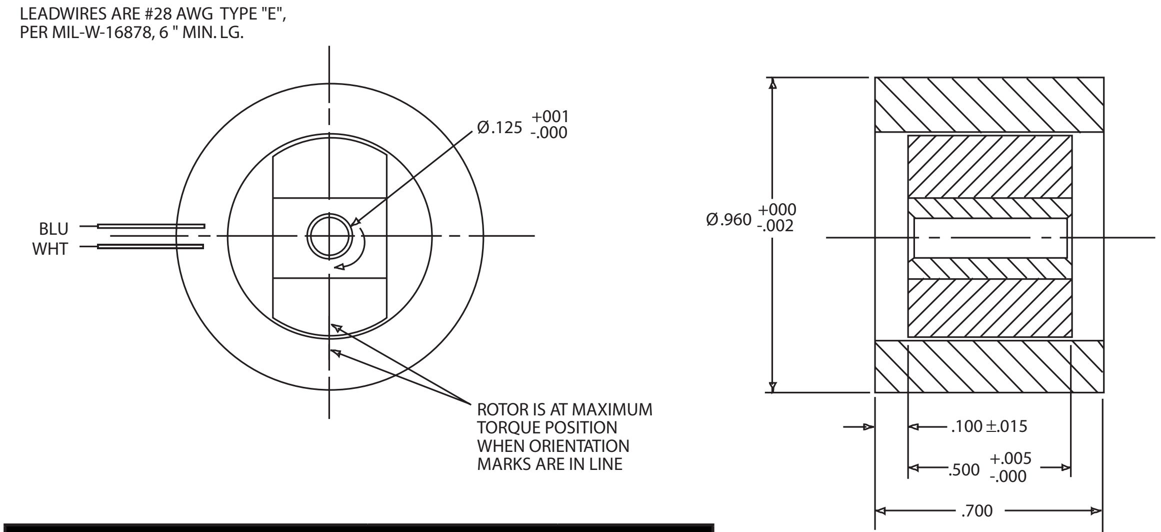
SCHEMATIC

ROTATION CCW VIEWING FROM LEAD SIDE.

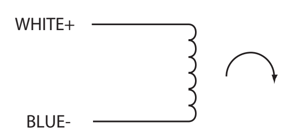
Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±12.5%	40.0
Voltage at Tp (Vp)	volts	Nominal	28.8
Current at Tp (Ip)	amps	Nominal	0.720
Torque Sensitivity (Kt)	oz-in/amp	±10%	2.50
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.018
Inductance (L)	millihenries	±30%	12

All constants, performance data at 25°C ambient temperature.

BTM10-S
BRUSHLESS DC MOTORS



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	6.0
Power at Tp (Pp)	watts	85
Motor Constant (Km)	oz-in/$\sqrt{W}$	0.650
Constinuous Torque (Tc)	oz-in	1.5
Power at Constinuous Torque	watts	5.3
Input Volts at Constinuous Torque	volts	5.6
Electrical Time Constant (Te)	milli-sec	0.20
Mechanical Time Constant (Tm)	milli-sec	-
Damping Factor (Fo)	oz-in/rad/sec	0.0029
Rotor Inertia (Jm)	oz-in-sec2	0.00004
Angular Excursion (Page 46, Curve x)	degrees	±60
Total Breakaway Torque (Tf)	oz-in	0.05
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		2
Weight	oz	-



SCHEMATIC

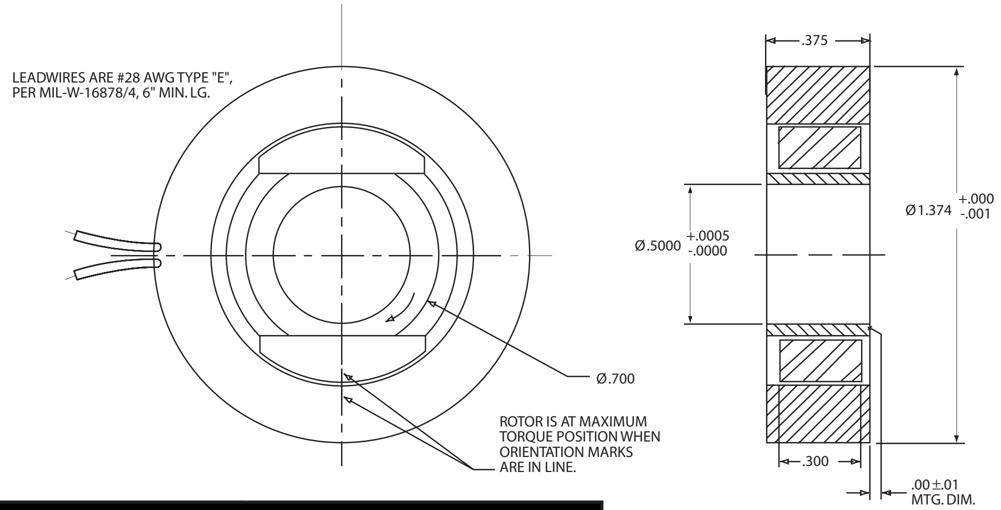
ROTATION CW VIEWING FROM LEAD END.

Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±15%	6.0
Voltage at Tp (Vp)	volts	Nominal	22.5
Current at Tp (Ip)	amps	Nominal	3.75
Torque Sensitivity (Kt)	oz-in/amp	±10%	1.60
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.011
Inductance (L)	millihenries	±30%	1.5

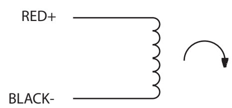
All constants, performance data at 25°C ambient temperature.

BTM14-E

BRUSHLESS DC MOTORS



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	6.0
Power at Tp (Pp)	watts	38.4
Motor Constant (Km)	oz-in/$\sqrt{W}$	0.968
Constinuous Torque (Tc)	oz-in	2.1
Power at Constinuous Torque	watts	4.7
Input Volts at Constinuous Torque	volts	6.7
Electrical Time Constant (Te)	milli-sec	0.42
Mechanical Time Constant (Tm)	milli-sec	33.5
Damping Factor (Fo)	oz-in/rad/sec	0.00656
Rotor Inertia (Jm)	oz-in-sec2	0.00022
Angular Excursion (Page 46, Curve x)	degrees	±30
Total Breakaway Torque (Tf)	oz-in	0.04
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		2
Weight	oz	1.7max



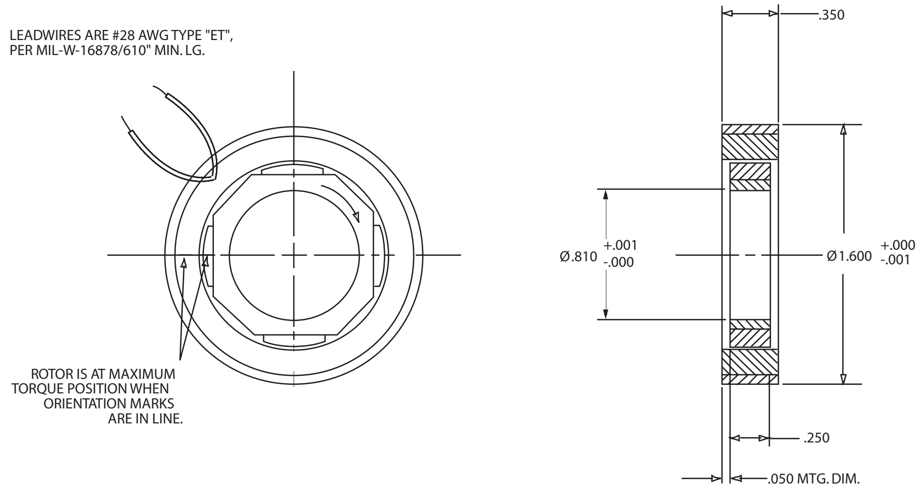
SCHEMATIC

ROTATION CW VIEWING FROM LEAD END.

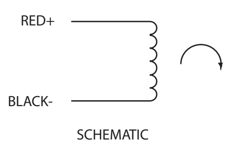
Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±12.5%	9.6
Voltage at Tp (Vp)	volts	Nominal	19.2
Current at Tp (Ip)	amps	Nominal	2.00
Torque Sensitivity (Kt)	oz-in/amp	±10%	3.00
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.021
Inductance (L)	millihenries	±30%	4.0

All constants, performance data at 25°C ambient temperature.

BTM16-B
BRUSHLESS DC MOTORS



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	6.0
Power at Tp (Pp)	watts	25
Motor Constant (Km)	oz-in/$\sqrt{W}$	1.20
Constinuous Torque (Tc)	oz-in	1.7
Power at Constinuous Torque	watts	2.1
Input Volts at Constinuous Torque	volts	5.6
Electrical Time Constant (Te)	milli-sec	0.30
Mechanical Time Constant (Tm)	milli-sec	-
Damping Factor (Fo)	oz-in/rad/sec	0.00101
Rotor Inertia (Jm)	oz-in-sec2	0.00033
Angular Excursion (Page 46, Curve y)	degrees	±22.5
Total Breakaway Torque (Tf)	oz-in	-
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		4
Weight	oz	1.5



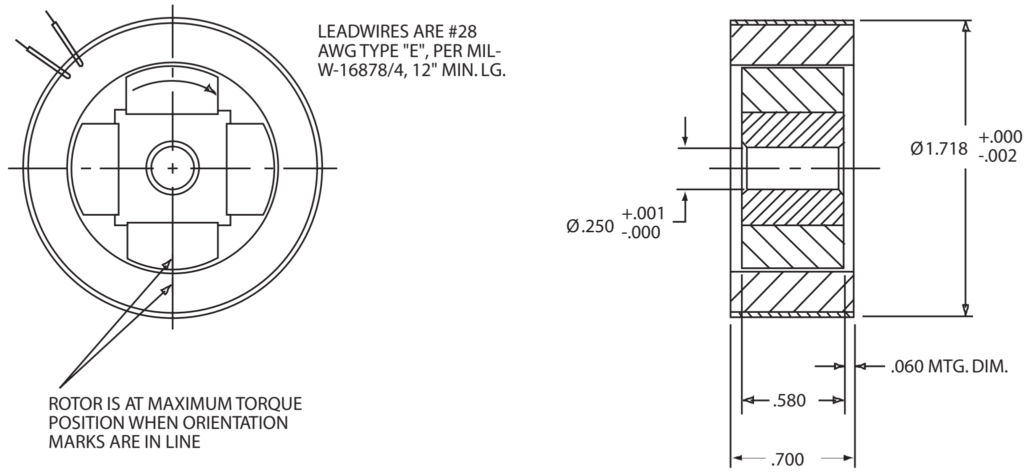
ROTATION CW VIEWING FROM LEAD END.

Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±15%	14.8
Voltage at Tp (Vp)	volts	Nominal	19.3
Current at Tp (Ip)	amps	Nominal	1.30
Torque Sensitivity (Kt)	oz-in/amp	±10%	4.5
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.032
Inductance (L)	millihenries	±30%	-

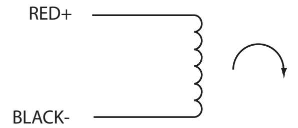
All constants, performance data at 25°C ambient temperature.

BTM18-G

BRUSHLESS DC MOTORS



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	18
Power at Tp (Pp)	watts	39
Motor Constant (Km)	oz-in/$\sqrt{W}$	2.89
Constinuous Torque (Tc)	oz-in	8
Power at Constinuous Torque	watts	7.7
Input Volts at Constinuous Torque	volts	9.6
Electrical Time Constant (Te)	milli-sec	0.58
Mechanical Time Constant (Tm)	milli-sec	14
Damping Factor (Fo)	oz-in/rad/sec	0.06
Rotor Inertia (Jm)	oz-in-sec2	0.00084
Angular Excursion (Page 46, Curve y)	degrees	±25
Total Breakaway Torque (Tf)	oz-in	-
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		4
Weight	oz	4.8



SCHEMATIC

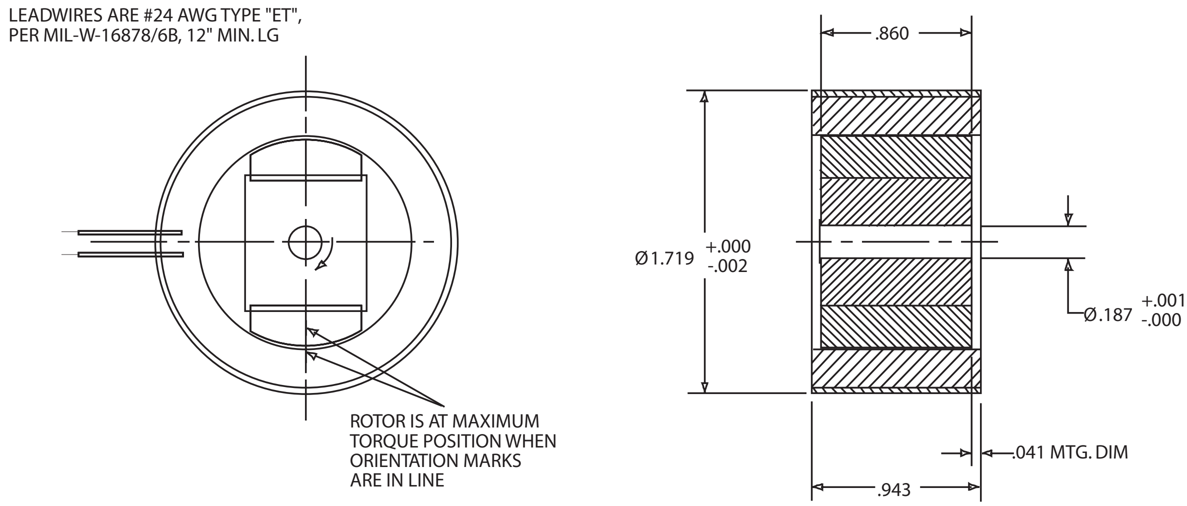
ROTATION CW VIEWING FROM LEAD END.

Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±15%	12.0
Voltage at Tp (Vp)	volts	Nominal	21.6
Current at Tp (Ip)	amps	Nominal	1.80
Torque Sensitivity (Kt)	oz-in/amp	±10%	10.0
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.071
Inductance (L)	millihenries	±30%	7.0

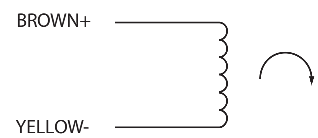
All constants, performance data at 25°C ambient temperature.

BTM18-L

BRUSHLESS DC MOTORS



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	20
Power at Tp (Pp)	watts	62
Motor Constant (Km)	oz-in/$\sqrt{W}$	2.58
Constinuous Torque (Tc)	oz-in	-
Power at Continuous Torque	watts	-
Input Volts at Continuous Torque	volts	-
Electrical Time Constant (Te)	milli-sec	0.77
Mechanical Time Constant (Tm)	milli-sec	25.1
Damping Factor (Fo)	oz-in/rad/sec	0.048
Rotor Inertia (Jm)	oz-in-sec2	0.0012
Angular Excursion (Page 46, Curve x)	degrees	±50
Total Breakaway Torque (Tf)	oz-in	0.60
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		2
Weight	oz	5.6



SCHEMATIC

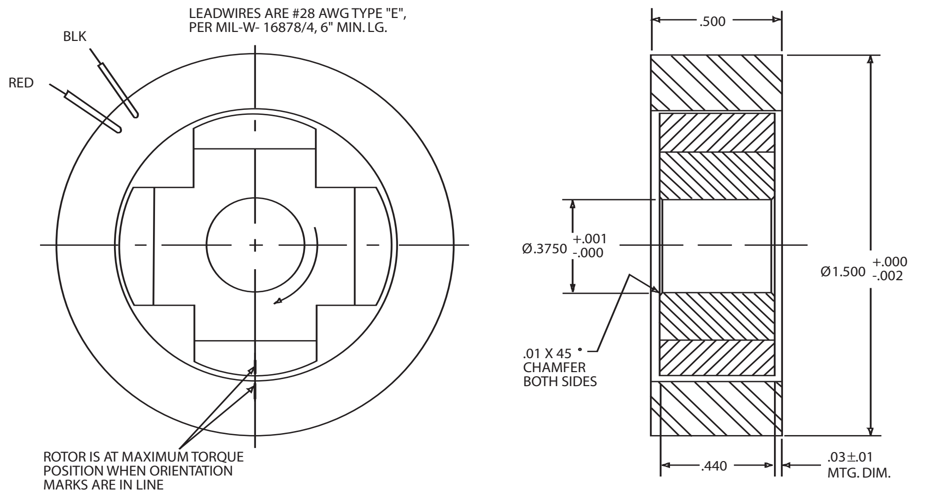
ROTATION CW VIEWING FROM LEAD END.

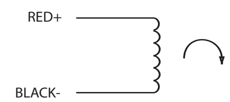
Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±12.5%	6.5
Voltage at Tp (Vp)	volts	Nominal	20
Current at Tp (Ip)	amps	Nominal	3.017
Torque Sensitivity (Kt)	oz-in/amp	±10%	6.60
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.047
Inductance (L)	millihenries	±30%	5.0

All constants, performance data at 25°C ambient temperature.

BTM15-C

BRUSHLESS DC MOTORS





SCHEMATIC

ROTATION CW VIEWING FROM LEAD SIDE.

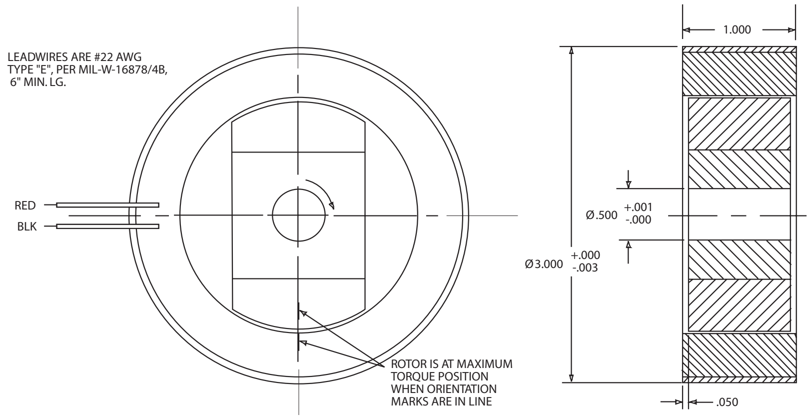
Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	22
Power at Tp (Pp)	watts	158.5
Motor Constant (Km)	oz-in/$\sqrt{W}$	1.75
Constinuous Torque (Tc)	oz-in	4.5
Power at Constinuous Torque	watts	6.6
Input Volts at Constinuous Torque	volts	7.8
Electrical Time Constant (Te)	milli-sec	0.23
Mechanical Time Constant (Tm)	milli-sec	18.8
Damping Factor (Fo)	oz-in/rad/sec	0.021
Rotor Inertia (Jm)	oz-in-sec^2	0.0004
Angular Excursion (Page 46, Curve y)	degrees	±15
Total Breakaway Torque (Tf)	oz-in	0.5
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		4
Weight	oz	2.5

Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±12.5%	9.2
Voltage at Tp (Vp)	volts	Nominal	38.2
Current at Tp (Ip)	amps	Nominal	4.15
Torque Sensitivity (Kt)	oz-in/amp	±10%	5.30
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.037
Inductance (L)	millihenries	±30%	2.1

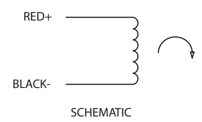
All constants, performance data at 25°C ambient temperature.

BTM30-EX

BRUSHLESS DC MOTORS



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	63
Power at Tp (Pp)	watts	72
Motor Constant (Km)	oz-in/$\sqrt{W}$	7.42
Constinuous Torque (Tc)	oz-in	20
Power at Constinuous Torque	watts	7.3
Input Volts at Constinuous Torque	volts	7.6
Electrical Time Constant (Te)	milli-sec	2.3
Mechanical Time Constant (Tm)	milli-sec	46
Damping Factor (Fo)	oz-in/rad/sec	0.4
Rotor Inertia (Jm)	oz-in-sec2	0.018
Angular Excursion (Page 46, Curve x)	degrees	±60
Total Breakaway Torque (Tf)	oz-in	0.80
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		2
Weight	oz	22



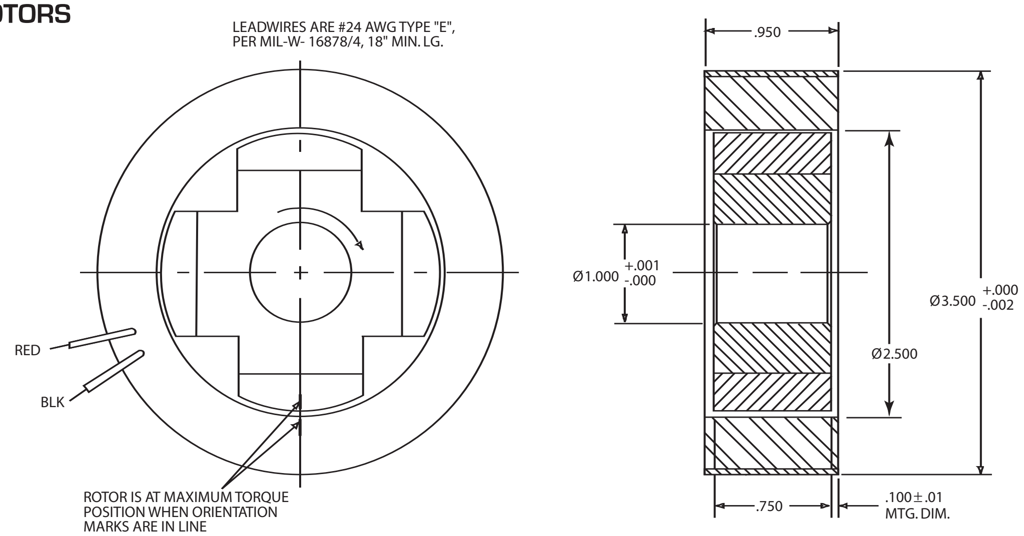
ROTATION CW VIEWING FROM LEAD SIDE.

Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±12.5%	8.0
Voltage at Tp (Vp)	volts	max	24.0
Current at Tp (Ip)	amps	max	3.00
Torque Sensitivity (Kt)	oz-in/amp	min	21.0
Back E.M.F. (Kb)	volts/rad/sec	min	0.148
Inductance (L)	millihenries	±30%	18

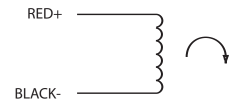
All constants, performance data at 25°C ambient temperature.

BTM35-BX

BRUSHLESS DC MOTORS



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	165
Power at Tp (Pp)	watts	118
Motor Constant (Km)	oz-in/$\sqrt{W}$	15.2
Constinuous Torque (Tc)	oz-in	61
Power at Constinuous Torque	watts	16.1
Input Volts at Constinuous Torque	volts	9
Electrical Time Constant (Te)	milli-sec	1.6
Mechanical Time Constant (Tm)	milli-sec	15
Damping Factor (Fo)	oz-in/rad/sec	1.63
Rotor Inertia (Jm)	oz-in-sec2	0.024
Angular Excursion (Page 46, Curve y)	degrees	±20
Total Breakaway Torque (Tf)	oz-in	-
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		4
Weight	oz	23

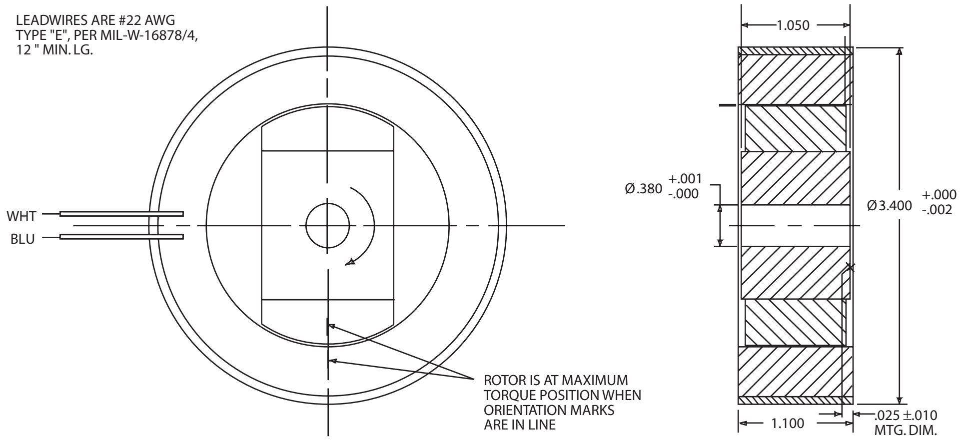


ROTATION CW VIEWING FROM LEAD SIDE.

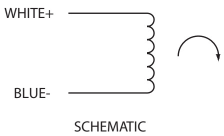
Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±12.5%	5.0
Voltage at Tp (Vp)	volts	Nominal	24.3
Current at Tp (Ip)	amps	Nominal	4.85
Torque Sensitivity (Kt)	oz-in/amp	±10%	34.0
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.235
Inductance (L)	millihenries	±30%	8.0

All constants, performance data at 25°C ambient temperature.

BTM34-SX
BRUSHLESS DC MOTORS



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	170
Power at Tp (Pp)	watts	430
Motor Constant (Km)	oz-in/$\sqrt{W}$	8.20
Constinuous Torque (Tc)	oz-in	49.5
Power at Continuous Torque	watts	36.5
Input Volts at Constinuous Torque	volts	7.1
Electrical Time Constant (Te)	milli-sec	1.6
Mechanical Time Constant (Tm)	milli-sec	38.1
Damping Factor (Fo)	oz-in/rad/sec	0.475
Rotor Inertia (Jm)	oz-in-sec2	0.0182
Angular Excursion (Page 46, Curve x)	degrees	±50
Total Breakaway Torque (Tf)	oz-in	-
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		2
Weight	oz	28



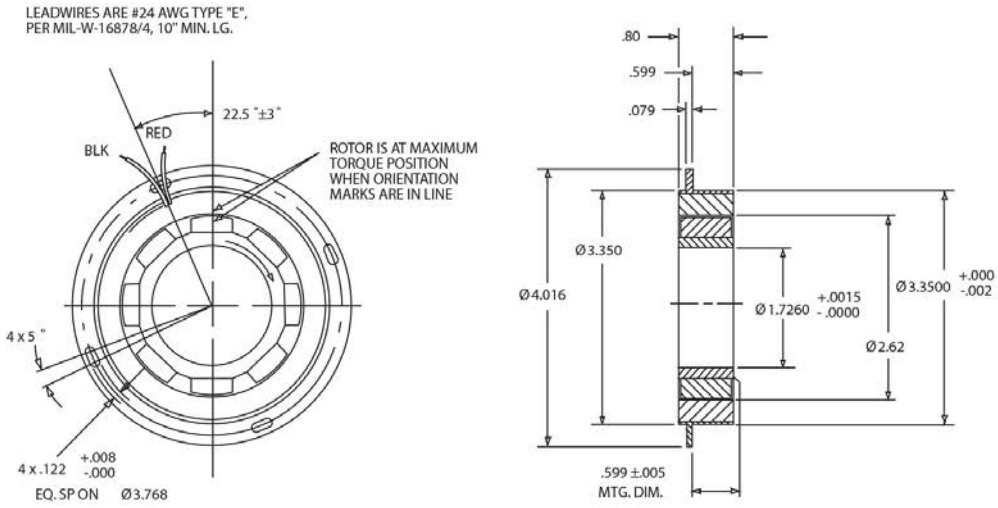
ROTATION CW VIEWING FROM LEAD SIDE.

Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±12.5%	1.4
Voltage at Tp (Vp)	volts	Nominal	24.5
Current at Tp (Ip)	amps	Nominal	17.5
Torque Sensitivity (Kt)	oz-in/amp	±10%	9.70
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.069
Inductance (L)	millihenries	±30%	2.2

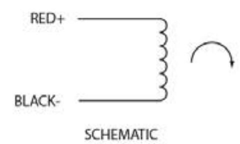
All constants, performance data at 25°C ambient temperature.

BTM34-Q-B

BRUSHLESS DC MOTORS



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	180
Power at Tp (Pp)	watts	100
Motor Constant (Km)	oz-in/$\sqrt{W}$	18.0
Constinuous Torque (Tc)	oz-in	-
Power at Constinuous Torque	watts	-
Input Volts at Constinuous Torque	volts	-
Electrical Time Constant (Te)	milli-sec	0.50
Mechanical Time Constant (Tm)	milli-sec	12.7
Damping Factor (Fo)	oz-in/rad/sec	2.28
Rotor Inertia (Jm)	oz-in-sec2	0.029
Angular Excursion (Page 46, Curve 8 Pole)	degrees	±5
Total Breakaway Torque (Tf)	oz-in	1.50max
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		8
Weight	oz	20



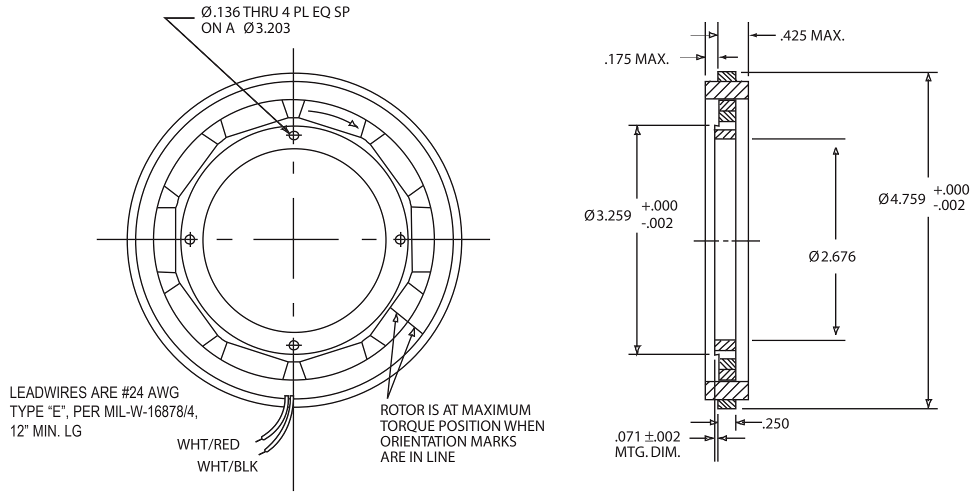
ROTATION CW VIEWING FROM LEAD SIDE.

Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±12.5%	4.0
Voltage at Tp (Vp)	volts	Nominal	20.0
Current at Tp (Ip)	amps	Nominal	5.00
Torque Sensitivity (Kt)	oz-in/amp	±10%	36.0
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.254
Inductance (L)	millihenries	±30%	2.0

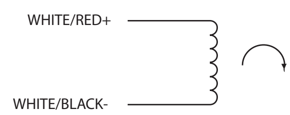
All constants, performance data at 25°C ambient temperature.

BTM48-BX

BRUSHLESS DC MOTORS



Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	220
Power at Tp (Pp)	watts	245
Motor Constant (Km)	oz-in/$\sqrt{W}$	14.1
Constinuous Torque (Tc)	oz-in	40
Power at Continuous Torque	watts	8
Input Volts at Constinuous Torque	volts	17.2
Electrical Time Constant (Te)	milli-sec	0.53
Mechanical Time Constant (Tm)	milli-sec	29
Damping Factor (Fo)	oz-in/rad/sec	1.4
Rotor Inertia (Jm)	oz-in-sec2	0.04
Angular Excursion (Page 46, Curve 8 Pole)	degrees	±5
Total Breakaway Torque (Tf)	oz-in	2.00
Max. Allowable Wdg. Temp.	°C	155
Number of Poles		10
Weight	oz	16max



SCHEMATIC

ROTATION CW VIEWING FROM LEAD SIDE.

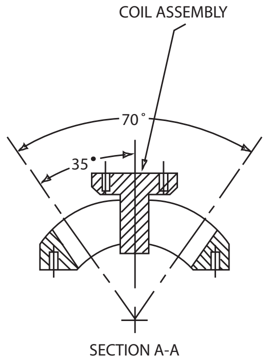
Winding Constants			
Parameter	UNITS	TOL.	Value
Resistance (R)	ohms	±12.5%	36.5
Voltage at Tp (Vp)	volts	Nominal	94.5
Current at Tp (Ip)	amps	Nominal	2.59
Torque Sensitivity (Kt)	oz-in/amp	±10%	85
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.60
Inductance (L)	millihenries	±30%	20

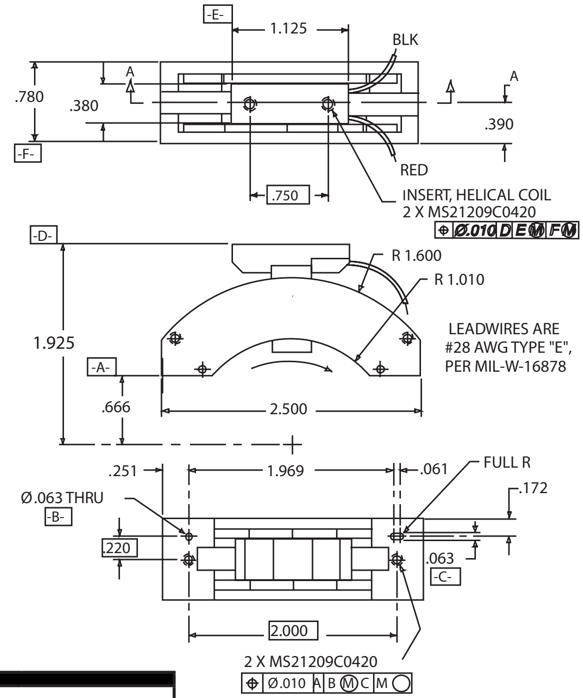
All constants, performance data at 25°C ambient temperature.

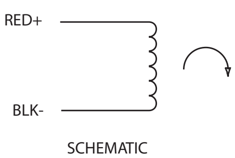
Selection Guide: Limited Angle Moving Coil Motors									
Model Number	Rotation Inner/Outer	Peak Torque (oz-in.)	Continuous Torque (oz-in.)	Actuator Constant (oz-in/$\sqrt{\text{watts}}$)	Angular Excursion (±degrees)	O.D.	I.D.	Axial Length	Page
RA2500A-077	0	7.1	3.7	2.6	35.5	See Drawing			61
RA2500B-078	0	9	4.6	1.84	35	See Drawing			62
RA6240B-119	I	80	43	10.5	20	See Drawing			63
RA6800-119E	I	110	50	24	10	See Drawing			64

RA2500A-077

BRUSHLESS DC MOTORS







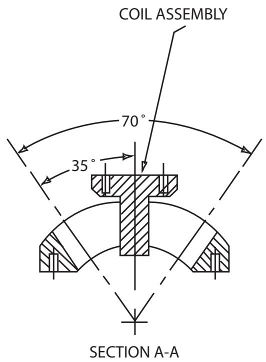
CW ROTATION OF THE COIL ASSY WHEN LEADS VIEWED AS ABOVE AND RED(+), BLACK (-) POLARITY.

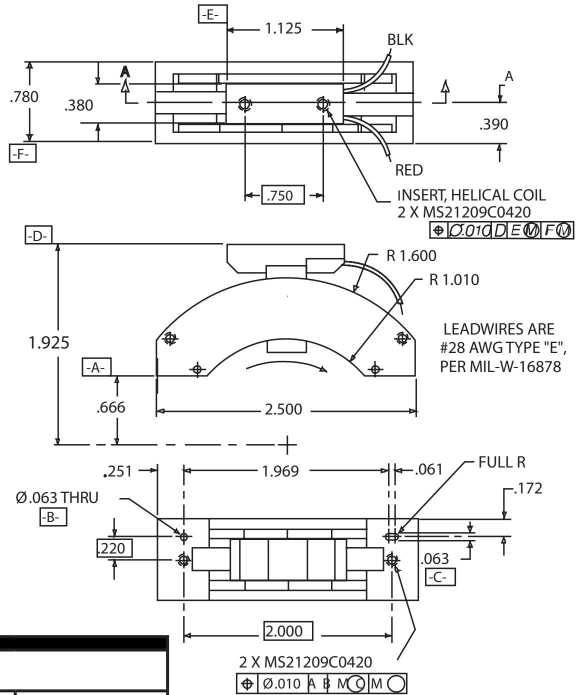
Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	7.1
Power at Tp (Pp)	watts	7.0
Actuator Constant (Ka)	oz-in/$\sqrt{W}$	2.66
Continuous Torque (Tc)	oz-in	3.7
Electrical Time Constant (e)	milli-sec	0.345
Stroke	degrees	±35.5
Clearance on each side of coil	in	0.015
Temperature Rise (TPR)	°C/watt	22
Maximum Winding Temp.	°C	155
Weight of coil assembly	oz	0.45
Total Weight	oz	5.3

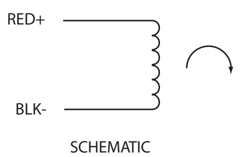
Winding Constants			
Parameter	UNITS	TOL.	-110
Resistance (R)	ohms	±12.5%	11.0
Voltage at Tp (Vp)	volts	Nominal	8.8
Current at Tp (Ip)	amps	Nominal	0.8
Torque Sensitivity (Kt)	oz-in/amp	±10%	8.875
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.0626
Inductance (L)	millihenries	±30%	3.8

All constants, performance data at 25°C ambient temperature.

RA2500B-078
BRUSHLESS DC MOTORS







CW ROTATION OF THE COIL ASSY WHEN LEADS VIEWED AS ABOVE AND RED(+), BLACK (-) POLARITY.

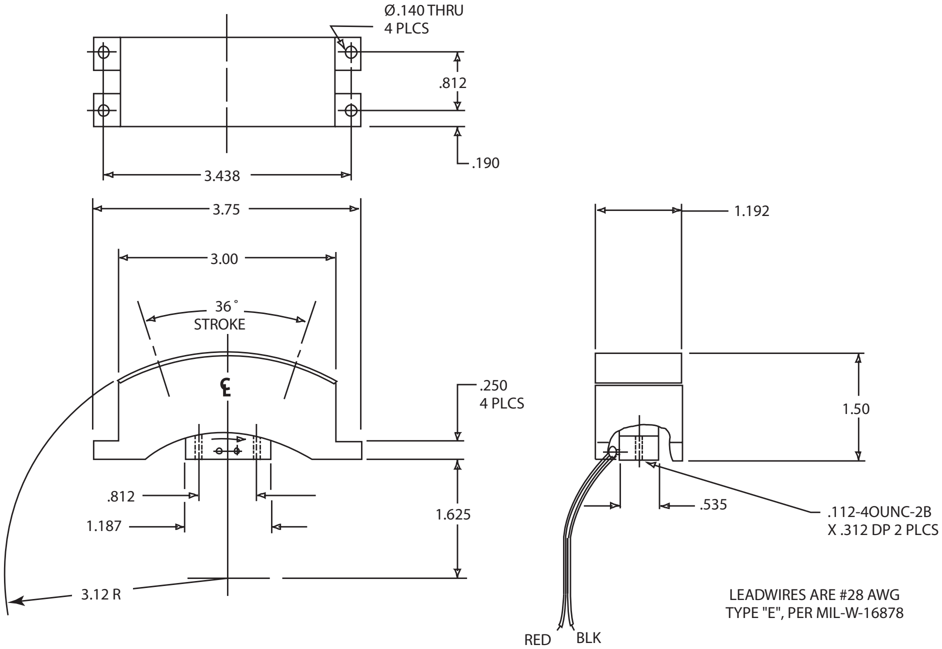
Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	9
Power at Tp (Pp)	watts	23.8
Actuator Constant (Ka)	oz-in/$\sqrt{W}$	1.85
Continuous Torque (Tc)	oz-in	4.6
Electrical Time Constant (e)	milli-sec	0.357
Stroke	degrees	±35
Clearance on each side of coil	mm	0.381
Temperature Rise (TPR)	°C/watt	14
Maximum Winding Temp.	°C	155
Weight of coil assembly	oz	0.63
Total Weight	oz	4.4

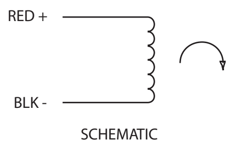
Winding Constants			
Parameter	UNITS	TOL.	-056
Resistance (R)	ohms	±12.5%	5.6
Voltage at Tp (Vp)	volts	Nominal	11.5
Current at Tp (Ip)	amps	Nominal	2.06
Torque Sensitivity (Kt)	oz-in/amp	±10%	4.37
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.031
Inductance (L)	millihenries	±30%	2

All constants, performance data at 25°C ambient temperature.

RA6240B-119

BRUSHLESS DC MOTORS





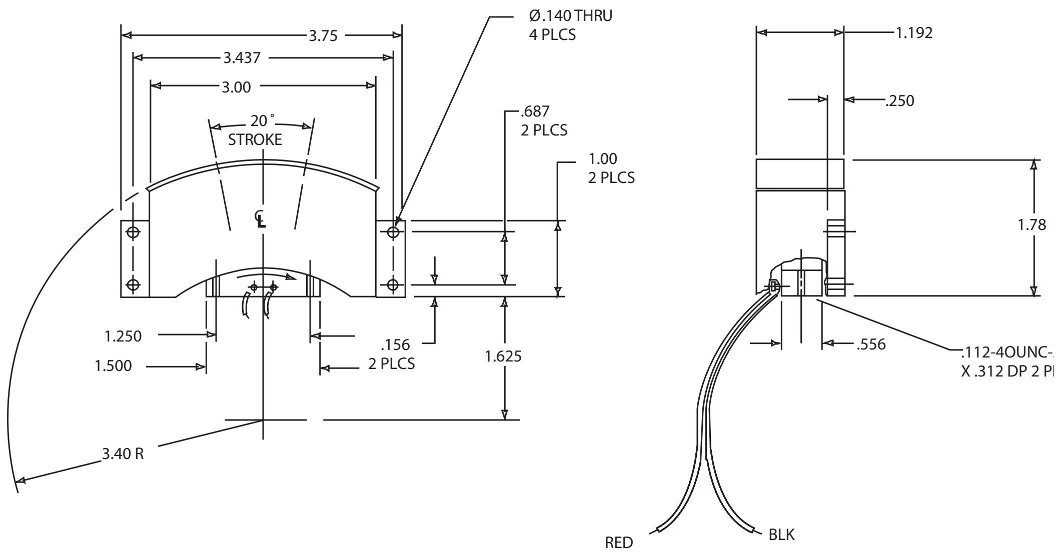
CW ROTATION OF COIL ASSEMBLY VIEWED FROM LEAD SIDE WITH RED(+), BLACK (-) POLARITY.

Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	80
Power at Tp (Pp)	watts	58.1
Actuator Constant (Ka)	oz-in/$\sqrt{W}$	10.5
Continuous Torque (Tc)	oz-in	43
Electrical Time Constant (e)	milli-sec	0.25
Stroke	degrees	±18
Clearance on each side of coil	inch	0.02
Temperature Rise (TPR)	°C/watt	5.1
Maximum Winding Temp.	°C	155
Weight of coil assembly	oz	0.21
Total Weight	oz	14.6

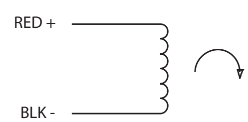
Winding Constants			
Parameter	UNITS	TOL.	-011
Resistance (R)	ohms	±12.5%	1.1
Voltage at Tp (Vp)	volts	Nominal	8
Current at Tp (Ip)	amps	Nominal	7.27
Torque Sensitivity (Kt)	oz-in/amp	±10%	11
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.078
Inductance (L)	millihenries	±30%	0.28

All constants, performance data at 25°C ambient temperature.

RA6800-119E
BRUSHLESS DC MOTORS



LEADWIRES ARE #28 AWG
TYPE "E", PER MIL-W-16878



SCHEMATIC

CW ROTATION OF COIL ASSEMBLY VIEWED FROM LEAD SIDE WITH RED(+), BLACK (-) POLARITY.

Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	110
Power at Tp (Pp)	watts	24
Actuator Constant (Ka)	oz-in/$\sqrt{W}$	22.4
Continuous Torque (Tc)	oz-in	50
Electrical Time Constant (e)	milli-sec	0.72
Stroke	degrees	±10
Clearance on each side of coil	mm	0.02
Temperature Rise (TPR)	°C/watt	15
Maximum Winding Temp.	°C	155
Weight of coil assembly	oz	0.85
Total Weight	oz	18

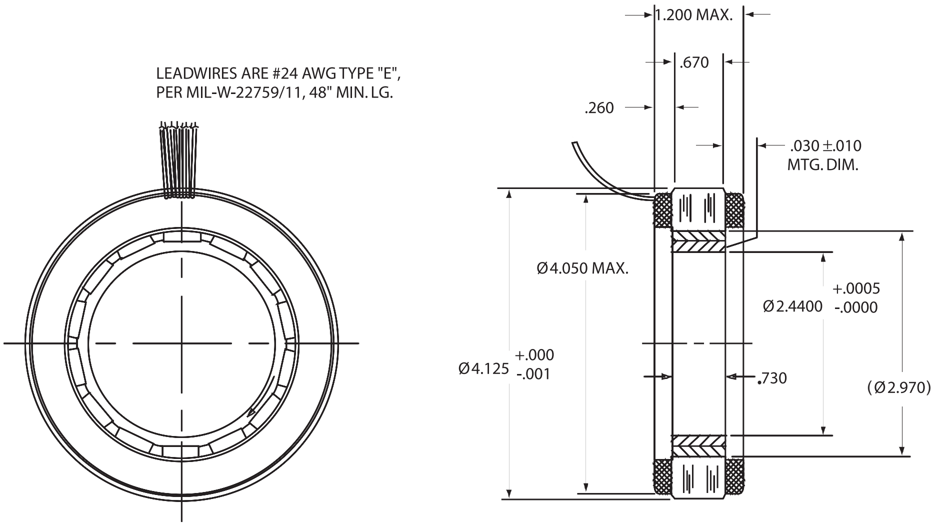
Winding Constants			
Parameter	UNITS	TOL.	-032
Resistance (R)	ohms	±12.5%	2.8
Voltage at Tp (Vp)	volts	Nominal	8.2
Current at Tp (Ip)	amps	Nominal	2.9
Torque Sensitivity (Kt)	oz-in/amp	±10%	38
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.268
Inductance (L)	millihenries	±30%	2.3

All constants, performance data at 25°C ambient temperature.

Selection Guide: Dual Winding Motors									
Motor Type	Model Number	Rotation Inner/Outer	Peak Torque (oz-in.)	Power@TP (watts)	Km (oz-in/$\sqrt{\text{watts}}$)	O.D. (in.)	I.D. (in.)	Axial Length (in.)	Page
2-Phase	4125-120	I	82.5	12.5	33	4.125	2.440	1.200	66
3-Phase	6700-154	I	500	31.1	90	6.700	5.250	1.850	67
3-Phase	8700-100	O	150	10.5	50.3	8.700	7.500	1.000	68

4125-120

BRUSHLESS DC MOTORS

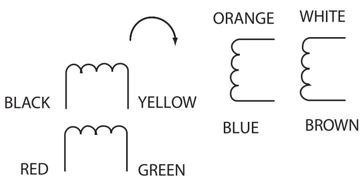


Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	82.5
Power at Tp (Pp)	watts	12.5
Motor Constant (Km)	oz-in/$\sqrt{W}$	33
Electrical Time Constant (e)	milli-sec	0.5
Mechanical Time Constant (m)	milli-sec	8.90
Damping Factor (Fo)	oz-in/rad/sec	3.92
Moment of Inertia (Jm)	oz-in-sec2	0.035
Total Breakaway Torque (Tf)	oz-in	5.0
Temperature Rise (TPR)	°C/watt	2.4
Max. Allowable Wdg. Temp.	°C	155
Weight	oz	29
Number of Poles		14
Number of Phases		2

Winding Constants			
Parameter	UNITS	TOL.	-500
Resistance (R)	ohms	±12.5%	50.0
Voltage at Tp (Vp)	volts	Nominal	24.2
Current at Tp (Ip)	amps	Nominal	0.500
Torque Sensitivity (Kt)	oz-in/amp	±10%	165
Back E.M.F. (Kb)	volts/rad/sec	±10%	1.19
Inductance (L)	millihenries	±30%	25

All constants, performance data at 25°C ambient temperature.

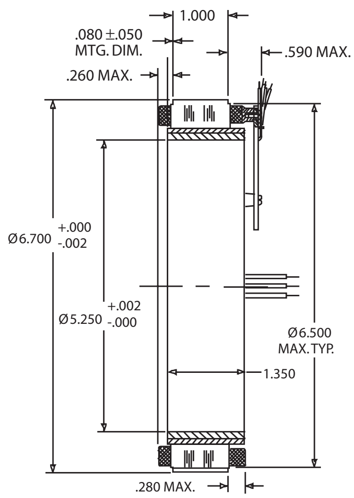
ROTATION: FIELD ROTATES CW WHEN VIEWED FROM LEAD SIDE WITH THE FOLLOWING SEQUENCE: PRIMARY: RED+, GREEN-, BLUE+, ORANGE -; SECONDARY: BLACK+, YELLOW-, BROWN+, WHITE-.

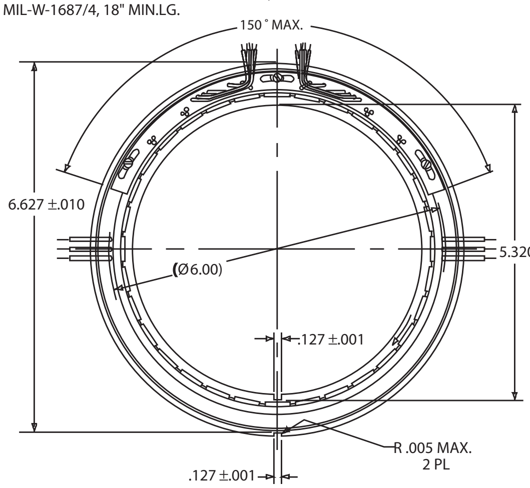


SCHEMATIC

6700-154

BRUSHLESS DC MOTORS





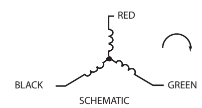
Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	500
Power at Tp (Pp)	watts	31.1
Motor Constant (Km)	oz-in/$\sqrt{W}$	90.0
Electrical Time Constant (e)	milli-sec	0.37
Mechanical Time Constant (m)	milli-sec	7.69
Damping Factor (Fo)	oz-in/rad/sec	57.2
Moment of Inertia (Jm)	oz-in-sec2	0.440
Total Breakaway Torque (Tf)	oz-in	20
Temperature Rise (TPR)	°C/watt	1.2
Max. Allowable Wdg. Temp.	°C	155
Weight	oz	67
Number of Poles		32
Number of Phases		3

Winding Constants			
Parameter	UNITS	TOL.	-019
Resistance (R)	ohms	±12.5%	1.9
Voltage at Tp (Vp)	volts	Nominal	7.7
Current at Tp (Ip)	amps	Nominal	4.03
Torque Sensitivity (Kt)	oz-in/amp	±10%	124
Back E.M.F. (Kb)	volts/rad/sec	±10%	0.876
Inductance (L)	millihenries	±30%	1.3

All constants, performance data at 25°C ambient temperature.

Commutation Table (PRIMARY)

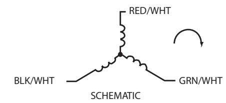
Step		1	2	3	4	5	6	1	Color
Motor	Phase A	+	+	Off	-	-	Off	+	RED
	Phase B	-	Off	+	+	Off	-	-	BLK
	Phase C	Off	-	-	Off	+	+	Off	GRN
Sensor	Sensor 1	1	1	O	O	O	1	1	YEL
	Sensor 2	O	1	1	1	O	O	O	RED
	Sensor 3	O	O	O	1	1	O	O	ORG



BLK=RTN
VIO=+5VDC

Commutation Table (SECONDARY)

Step		1	2	3	4	5	6	1	Color
Motor	Phase A	+	+	Off	-	-	Off	+	RED / WHT
	Phase B	-	Off	+	+	Off	-	-	BLK / WHT
	Phase C	Off	-	-	Off	+	+	Off	GRN / WHT
Sensor	Sensor 1	1	1	O	O	O	1	1	YEL /WHT
	Sensor 2	O	1	1	1	O	O	O	RED / WHT
	Sensor 3	O	O	O	1	1	O	O	ORG / WHT

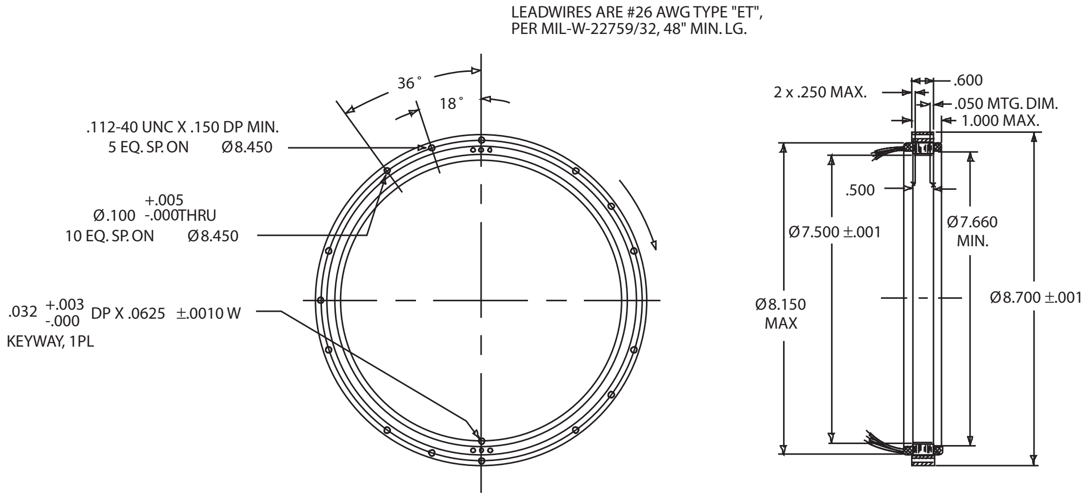


BLK/WHT=RTN
VIO/WHT=+5VDC

ROTATION: CW WHEN VIEWED FROM LEAD SIDE

8700-100

BRUSHLESS DC MOTORS

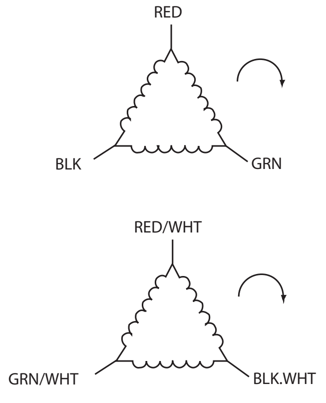


Performance Data		
Parameter	Units	Value
Peak Torque (Tp)	oz-in	150
Power at Tp (Pp)	watts	10.5
Motor Constant (Km)	oz-in/$\sqrt{W}$	50.3
Electrical Time Constant (e)	milli-sec	0.31
Mechanical Time Constant (m)	milli-sec	47.5
Damping Factor (Fo)	oz-in/rad/sec	17.9
Moment of Inertia (Jm)	oz-in-sec^2	0.850
Total Breakaway Torque (Tf)	oz-in	10
Temperature Rise (TPR)	°C/watt	1.4
Max. Allowable Wdg. Temp.	°C	220
Weight	lbs	2.95
Number of Poles		40
Number of Phases		3

Winding Constants			
Parameter	UNITS	TOL.	-800
Resistance (R)	ohms	±12.5%	80
Voltage at Tp (Vp)	volts	Nominal	29
Current at Tp (Ip)	amps	Nominal	0.363
Torque Sensitivity (Kt)	oz-in/amp	±10%	450
Back E.M.F. (Kb)	volts/rad/sec	±10%	3.178
Inductance (L)	millihenries	±30%	80

All constants, performance data at 25°C ambient temperature.

ROTATION: FIELD ROTATES CW WHEN VIEWED FROM LEAD SIDE WITH THE FOLLOWING SEQUENCE: RED+, GREEN-, GREEN+, BLACK-, BLACK+, RED-. AND RED/WHT+ GRN/WHT- GRN/WHT+, BLK/WHT- BLK/WHT+, RED/WHT-.



SCHEMATIC

CAPABILITIES

OVERVIEW

- DC MOTORS - DIRECT DRIVE/BRUSHLESS AND BRUSH TYPE
- DC AND AC TACHOMETERS
- RESOLVERS/SYNCHROS
- PACKAGES, ASSEMBLIES AND SERVOSYSTEMS

General Dynamics Ordnance and Tactical Systems' Motion Control Product's comprehensive component design and manufacturing capabilities are unique in the motion control industry, with expertise developed over more than five decades. This experience allows General Dynamics Ordnance and Tactical Systems' to provide high performance motion control and measurement solutions using the most advanced and reliable technology available.

General Dynamics Ordnance and Tactical Systems' offers a wide array of both standard and custom components, which can be combined as a system to offer optimal solutions for your motion control needs. By incorporating standard components into a single housing, for example, we can provide the most economical and technically sound solution to many motion control problems. Standard or custom-engineered components, sub-assemblies, or entire systems - General Dynamics Ordnance and Tactical Systems has what you need. The following information offers a brief description of each of our product lines, plus examples of how they can be combined into assemblies and systems to meet your motion control needs

DC MOTORS

DIRECT DRIVE / BRUSHLESS AND BRUSH TYPE PERFORMANCE FEATURES

General Dynamics Ordnance and Tactical Systems' complete line of direct drive brushless and brush type torque motors and servomotors are sure to include a motor that meets your system's requirements.

The direct drive motor is equivalent to a conventional servomotor-gearhead, but features improved response characteristics. This gearless DC motor drive is ideally suited for high acceleration applications with rapid starts and stops. The absence of gearing also eliminates errors caused by friction, backlash, and other inaccuracies, making possible a very high threshold sensitivity - to one arc second in high performance positioning systems.

DC torque motors have a space-saving "pancake" shape, i.e. they are axially short compared to the diameter and can be conventionally mounted around a shaft or other load. Limited angle torque motors do not require commutation electronics and have no cogging.

CHARACTERISTICS

Brushless

- Outer diameters 0.5" to 33"
- Torque up to 1,650 ft-lbs
- Housed or frameless
- Rare earth magnets
- 2- or 3- phase winding

Brush

- Outer diameters 1" to 20"
- Torque up to 465 ft-lbs
- Housed or frameless
- Rare earth magnets
- 2-wire control (+/-)

Brushless, Limited Angle Torque Motors

- Outer diameters 0.8" to 14"
- Torque up to 24 ft-lbs
- Angular excursion: to ±60°
- No slot effects

Brushless, Moving Coil, Segmented

- Radius up to 10"
- Torque up to 200 oz-in
- Extremely low cogging
- No commutation required

DC TACHOMETERS

PERFORMANCE FEATURES

General Dynamics Ordnance and Tactical Systems' electromagnetic tachometer generators provide precise velocity feedback by supplying output voltage directly proportional to speed. With these very high output voltage to speed ratios, General Dynamics Ordnance and Tactical Systems' tachometers allow stable voltage output over a wide range of speeds. Their fast response to high-rate velocity changes aid overall system stability. They can be coupled directly to the load to eliminate drive train inaccuracies. A wide dynamic range allows for low speed operation. General Dynamics Ordnance and Tactical Systems' engineers its tachometers to withstand high shock and vibration levels.

CHARACTERISTICS

- Outer diameter 1" to 24"
- Velocity change response less than 100 microsec time constants
- Dynamic range up to 50,000 to 1
- Output ripple as low as 0.03%
- Speed range 1 rpm to 6000 rpm

RESOLVERS/SYNCHROS

PERFORMANCE FEATURES

General Dynamics Ordnance and Tactical Systems' exceptionally reliable single, multispeed and segment resolvers are absolute position sensors, providing a high degree of angular accuracy and extremely high resolution. They are available in transmitter, differential, or receiver functions. These maintenance-free, high-precision resolvers are specifically designed to withstand environments containing dirt, grease, oil or other contaminants. They are available housed or unhoused, in a variety of configurations, with either analog or digital outputs.

They are compact, low weight, easy to install and feature a low noise/signal ratio. The segmented resolver, a patented invention, offers cost savings over full rotation resolvers by providing highly accurate performance in situations that require only limited angle measurements.

CHARACTERISTICS

- Single or multispeed, up to 64 speed
- Accuracy to 5 arcseconds
- Outer diameters 0.7" to 13" - custom sizes available
- Input excitation frequency from 60 to10,000 Hz
- Null voltages 1 to 3 mV/Volt output
- Speeds to 20,000 rpm
- Bare, hub and sleeve housings, or fully housed with bearings available
- Rotor or stator primary
- Compensated windings available
- Brushless versions available
- Transmitter, receiver or differential available

Brushless Resolvers, Multispeed Resolvers, Segmented Resolvers, Synchros and Induction Potentiometers.

PACKAGES, ASSEMBLIES AND SERVOSYSTEMS

ASSEMBLIES

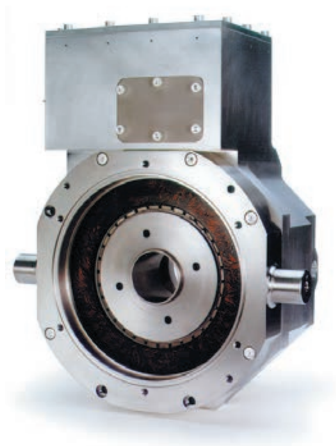
Packaging several electromechanical components onto a common shaft is one way to provide greater system accuracy at lower cost. General Dynamics Ordnance and Tactical Systems can assemble components such as motors, potentiometers, resolvers, encoders, gearheads, or magnetic brakes and clutches into a single housing to save space and increase system reliability. Customers also save procurement, assembly and testing costs, and gain one source accountability, on-time delivery of all parts, and a single documentation package. The result: a ready-to-install servomechanism optimized for the application, and backed by General Dynamics Ordnance and Tactical Systems' guaranteed quality and service.

SYSTEMS

In addition to custom sub-assemblies, General Dynamics Ordnance and Tactical Systems also provides complete servosystems consisting of motor, velocity feedback, position feedback, gear reduction, electronic control units, motor drivers and amplifiers. Like custom sub-systems, complete servosystems provide ready-to-install products uniquely optimized for the application. The result is lower cost, greater accuracy, and all the advantages of single-source accountability.

DIRECT DRIVE MOTOR ASSEMBLIES

General Dynamics Ordnance and Tactical Systems produces custom-designed motion control packages and assemblies. Brushless torque motors can be integrated with matching resolvers to provide smooth commutation and high accuracy, absolute positioning. These products provide efficient solutions in demanding motion control applications from industrial robot drives to space mechanisms. Our customers enjoy the performance, cost and logistics benefits of procuring integrated component sets from a single source.



High torque brushless motor-resolver assembly with integral ferro-fluid seal for vacuum semiconductor process mechanism provides high positioning accuracy and speeds up to 1200 RPM.

DC MOTOR DESIGN GUIDE

Application ______________________________
____
____
____

PHYSICAL REQUIREMENTS:

- ☐ Brushless
- ☐ Brush
- ☐ Inner Rotating
- ☐ Outer Rotating
- ☐ Limited Angle
- ☐ Frameless
- ☐ Housed
- ☐ Maximum OD
- ☐ Maximum Length
- ☐ Minimum ID

FOR HOUSED MOTORS ONLY:

OD ______________________________
Length ______________________________
Shaft OD______________________________
Shaft Length______________________________

FOR BRUSHLESS MOTORS ONLY:

Commutation:
☐ Hall Sensors ☐ Resolver
☐ Encoder ☐ None

Drive Output Waveform:
☐ 6 Point Trapezoidal ☐ Sinusoidal

Winding:
☐ Single Phase ☐ 2-Phase ☐ 3-Phase
☐ Delta ☐ Wye ☐ Open

PERFORMANCE/WINDING DATA:

Peak Torque:
______________ ☐oz-in ☐ N-m
Motor Constant:
______________ ☐oz-in/$\sqrt{W}$ ☐N-m/$\sqrt{W}$
Torque Sensitivity:
______________ ☐oz-in/Amp ☐N-m/Amp
Back EMF________________ Volt/rad/s
Power ________________ Watt
Current ________________ Amp
Voltage ________________ Volt
Resistance ________________ Ohms
Inductance ________________ mH

Max Winding Temperature: 155°C is standard for Brush type, 220°C is standard for Brushless type.
Other Max. Winding Temperature if required ______________________ °C

ENVIRONMENTAL REQUIREMENTS:

Temperature of Operation:
Minimum ________ °C Maximum ________ °C
Shock ______________________________
Vibration ______________________________
Altitude ______________________________
Other ______________________________

REQUESTED BY:

Name ______________________________
Title ______________________________
Company ______________________________
Address ______________________________
City ______________________________
State ______________________________
Zip ______________________________
Country ______________________________
Phone ______________________________
Fax ______________________________
Email ______________________________