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Magnetic Signature of Brushless Electric Motors

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ABSTRACT

Brushless electric motors are used in a number of underwater vehicles. When these underwater vehicles are used for mine clearance operations the magnetic signature of the brushless motors is important.

The magnetic signature of two models of brushless motor designed by the Kollmorgen Motion Technologies Group for use in submersible systems were examined. Magnetic mapping around the motors was performed so the influence of the individual elements of the motors could be isolated. The major component of the magnetic field was determined to be due to the shaft and rotor section of motor.

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Magnetic Signature of Brushless Electric Motors

Executive Summary

Brushless electric motors are used in a number of underwater vehicles (UVs). When these vehicles are to be used in mine hunting and mine disposal roles the magnetic signature of the vehicle and thus their motors is important. The Royal Australian Navy operates the Double Eagle Remotely Operated Vehicle (ROV) from the Huon class Mine Hunter Costal (MHC) to perform mine disposal tasks. The Double Eagle ROV uses brushless electric motors for its main thrusters and its manoeuvring systems.

Given this background it is important to be familiar with the type of magnetic signature produced by brushless electric motors. The magnetic signatures of two brushless motors (not the type, as far as we know used by Double Eagle) were examined.

The DSTO magnetic test facility at Maribyrnong was used to perform the magnetic mapping of the motors. Computer code was written to control, monitor and test the motors. The possible sources of the magnetic field in the motors were considered to be:
i) The stationary part of the motor.
ii) The rotating parts of the motor.
iii) Current in the windings of the motor.

The main source of the magnetic field was determined to be due to rotating parts of the motor, which for a D.C. brushless motor includes a number of permanent magnets (used to create the poles on the rotor) and the shaft.

Increasing the number of magnetic poles used by the motor and employing a non magnetic shaft are suggested as desirable features in any brushless electric motor that is to be considered for use in vehicles with a mine hunting or disposal role.

The work on the brushless electric motors presented in this report demonstrates and provides a method for examining the magnetic signatures generated by brushless electric motors that should prove useful in operating and testing underwater vehicles incorporating these motors.

Authors

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David Clarke commenced work in the Maritime Operations Division (MOD) at AMRL in 1988 after completing a BSc at Sydney University. His work in MOD focused on magnetic sensors and instrumentation. He obtained a Graduate Diploma in computer engineering from RMIT in 1996. In 1998 he joined the Maritime Platforms Division to work on the hydrodynamics of underwater vehicles. His work on underwater vehicles has encompassed experiment, empirical and computational hydrodynamics.

Contents

1. Introduction

Brushless electric motors are of interest as they are used in vehicles such as the Bofors Double Eagle Remotely Operated Vehicle (ROV), which are deployed and operated from the Huon class Mine Hunter Coastal (MHC). The Double Eagle use two 5 kW brushless electric motors for its main thrusters and six 0.4 kW brushless electric motors for manoeuvring. Given the concept of operation of the Double Eagle, it is important to be familiar with the magnetic signature produced by brushless electric motors. The subject of this report is the measurement of the magnetic signature of two brushless motors. To the author's knowledge these particular motors are not the type used by Double Eagle they are however designed for use by underwater vehicles.

Brushless electric motors consist of a rotor, which is made up of permanent magnets and a stator which is composed of a number of windings. The current is switched to the windings using solid state electronics. The timing of the switching is controlled by position sensors as optical, Hall effect or magnetic devices [1].

The permanent magnets on the rotor are orientated to produce a number of poles. In the simplest form of motor one permanent magnet will create each pole. A stylised rotor is shown in Figure 1. In more sophisticated motors a number of physically smaller magnets are used. One of the reasons that this more complex system is used is that a number of smaller, electrically insulated magnets will reduce the eddy currents.

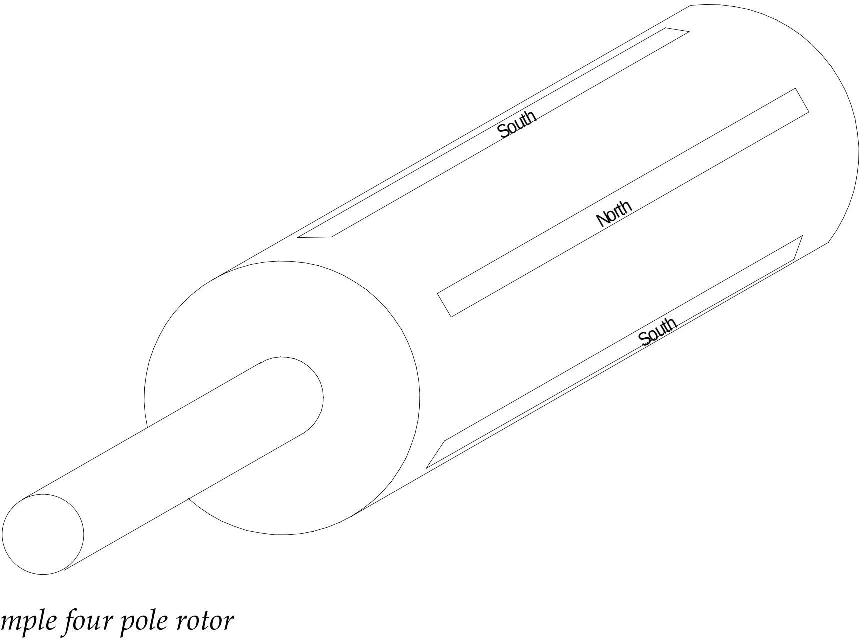

Figure 1 – Simple four pole rotor

The static magnetic signature of these motors may be split into the following elements: -

i) The permanent magnets and ferrous materials on the rotor.
ii) The ferromagnetic materials on the stationary section of the motor.
iii) The current in the windings.

The influence of the rotor on the static magnetic field may be observed by measuring the magnetic field at fixed locations with the motor body stationary, the current set to zero and the rotor stopped at a number of different locations.

The influence of the current in the motor windings on the static magnetic field may be determined by running the motor at different current settings. As long as the rotational speed of the rotor is a number of times greater than the bandwidth of the magnetometers the influence of the current on the magnetic field may be determined from the change in the field as the current is altered.

The influence of the stationary section of the motor on the magnetic field may be determined by repeating the above procedure with the motor (and hence the current) running in the opposite direction and averaging the result.

The motors which are the subject of this report may be operated from 0 – 1800 rpm.

2. Experimental Procedure

The magnetic signatures of two models of brushless motor, designed by Kollmorgorn Motion Technologies Group for use with submersible systems, were examined. Figure 1 is a schematic of the rotor section of the motor. The 'North' and 'South' on the magnets as illustrated in Figure 1, indicate that the north and south poles of the magnets are aligned with the outside of the rotor.

If the shaft of the motor is constructed from a ferrous material it may be the source of a significant portion of the far-field magnetic signature. This is due to the long length of the shaft compared to the other components of the motor.

The experimental testing on the motors was performed in the DSTO magnetic test facility at Maribyrnong. This facility is designed so that the background magnetic field can be nulled out for the duration of testing. Six Thorn LNR1 single axis magnetometers were used to map the magnetic field at set points. The sensitivity and linearity of these magnetometers was measured using a precision wound coil. Figure 2 illustrates the position of the magnetometers with respect to the motor. The origin is taken as the centre of the body of the motor [2] excluding the length of the shaft sticking out from the motor. Additional code was written to enable the magnetic volume controller to control and monitor the speed and rotational position of the motors.
A plastic BMX wheel was modified with the addition of three fins to allow the motors to be tested under different load conditions.

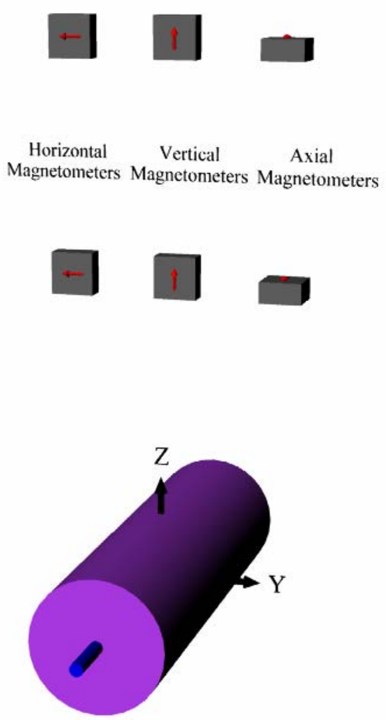

Figure 2- Physical location of motor and magnetometers

2.1 Magnetic Field from Rotor

If a full turn of the rotor is considered, and the axis of revolution of the rotor is defined to be in the axial direction, the average magnetic field due to components of the magnets on the rotor aligned in the radial (horizontal or vertical) direction will be zero. The average magnetic field due to any component of the magnets aligned in the axial direction will not, however, average zero under the same conditions. The average magnetic field due to any magnetic component aligned in the axial direction of the rotor were measured and included in the calculations of the stationary part of the motor. From the design of the motor it was expected that the alignment of the permanent magnets on the rotor would be in the radial direction. Minimal alignment of the permanent magnets in the axial direction is expected. It is worth noting when examining the results that a lack of permanent magnets aligned in the axial direction should not be confused with a small magnetic field in the axial direction.

The static magnetic field from the motor with no current in the windings was measured for many rotor positions. The control and positioning system in the motor was used to move the rotor to a precise (±0.1°) rotational position. The magnetic field from the motor was then measured at this position. The rotor was then returned to 0° and the magnetic field measured again. This procedure was repeated every five degrees.

The difference between the measured field and the field at 0° (zero position on each motor) is shown in Figures 4 through 9 for one of the small manoeuvring motors. The results for the same tests performed on one of the main thrusters is displayed in Figures 10 through 15. These twelve figures, along with all other experimental results are located in Appendix A.

These tests were repeated for a second small manoeuvring motor. Similar results were obtained and they are not presented in this report.

2.2 Magnetic Field at Position Zero

The magnetic field perturbation caused by the motor when the rotor was set at its zero position were measured. These results, when combined with the results from Section 2.1 allow the total magnetic field due to a motor at rest to be determined. The results obtained from measurements for the small manoeuvring motor and main thruster are presented in Figures 16 through 19. Discussion of the strength of the vertical magnetic field observed in Figures 17 and 19 can be found in Section 2.3.

2.3 Magnetic Field due to Non Rotating Parts of the Motor

The contribution to the magnetic field due to the non rotating sections of the motor were determined by measuring the signature of the motor when the rotor was rotating at a rate great enough to stop the radial orientated magnetic components on the rotor influencing the low frequency magnetic field. This measurement, as noted earlier in Section 2.1, includes the average magnetic field due to any axial magnetic component of the rotor. These results provide an indication of the static magnetic signature that may be expected from one of these motors when it is operating at a frequency where the influence of the radial components of the magnets on the rotor are shifted outside the frequency range being measured. The results obtained from measurements of the small manoeuvring motor and main thruster are presented in Figures 20 through 23.

An examination of Figures 20-23 shows that the vertical magnetic field is the dominate feature in the measurements taken at the greater value of z, the second row of magnetometers shown in Figure 2. The shape of these curves, which show the strength of the vertical magnetic field, are consistent with a field due to a dipole lying in the axial direction. The slow decay of the vertical field compared to the field in the other directions suggests that the source of this magnetic field has a much greater dipole length than the sources creating the field in the other two directions. A likely source for the slow decaying magnetic field is the shaft of the motor. If the shaft is the cause of the slow decaying magnetic field replacing the shaft with a non magnetic material should provide a solution.

2.4 Magnetic Field due to Current

As the current supplied to the motors from the controllers was increased no change to the low frequency magnetic field (0 to 15 Hz) was detected. This lack of change in low frequency magnetic field is a result of the high frequency switching of the current being supplied from the controllers to the motors.

3. Discussion

If the rotor is stopped a major contribution to the static magnetic signature of the motor comes from the radial orientated magnetic components on the rotor. This leads to a signature from each motor that can vary widely depending on where the rotor stops. Thus if the motors form an important part of the ROV's signature, the signature of the ROV may also vary significantly depending on where the rotors on ROV's motors stop.

The Kollmorgan S series motors tested use a four pole configuration. This four-pole configuration appears as two periods of a sinusoidal wave on the vertical and horizontal magnetic field data provided in Section 2.1. It may be advantageous, as far as the signature is concerned, to use motors with more poles. An increase in the number of poles cause the magnetic field to drop off at a greater rate as the distance from the motor increases as the distance between the poles is less. The effect of the multipole arrangement is discussed further in Section 4.

When the rotor is moving, the magnetic signature of the rotor will be shifted into the extra low frequency spectrum (ELF), thus increasing the ELF magnetic signature of the motor. The minimum frequency of the major part of the signal, due to the rotor, will be a function of the number of poles on the rotor and the speed of revolution of the rotor. Thus the major part of the magnetic field from a four-pole rotor turning at 200 rpm would lie at 6.7 Hz. Another advantage of a rotor with more poles is that it shifts the frequency of the magnetic field from the rotor out of a region where mines are known to detect magnetic fields at a low motor speed. In a fielded system specific tests would need to be done to measure the ELF magnetic signature of the motors to know if the effects of the turning rotor are likely to cause problems.

If a ROV is operated using two motors running at slightly different speeds there is the possibility that this could cause a beat to occur. The amplitude of this beat is given by the combined amplitude of the signature from each of the rotors. The frequency of the beat is half the difference between their frequency.

While conducting tests on the motors, which required increasing their rotation rate, it was noted that using the motors in opmode 1 (serial current) produced a smoother transition from one speed to another than opmode 0 (serial velocity). The reason for this is that when the motors are used in opmode 0 (serial velocity) and an increase in speed is required, the motor uses extra power to arrive at the new speed quickly where as in opmode 1 (serial current) the motors are using a constant power. A smoother transition of motor velocity results in lower acoustic noise. It may also be possible to reduce the sudden increase in power that occurs in opmode 0 with better tuning of the motor controller.

If the magnetic signature from the motors is considered to be a problem in a fielded system one possible solution involves shielding the motors with a high permeability material. A negative aspect of shielding may be that the induced magnetic field of the motor is increased. Careful design of the shield should optimise the shielding of the motor and reduce the induced field from the shield.

It is desirable to place the motors in a hold mode, which prevents the motor turning, when not being used to provide thrust so that the propellers will be prevented from turning freely. If the propellers are rotating the rotors will also be turning, this is likely to increase the perturbation in the magnetic field caused by the vehicle.

4. Effect of multiple poles on the motor signature

From a comparison of Figure 4, 6, 8, 10, 12, 14 to 5, 7, 9, 11, 13, 15 respectively, it is evident that the magnetic field is decreasing rapidly as a function of distance. This is expected, as the field from a dipole decreases proportionally as the cube of the distance in the far-field. The conditions of far-field are satisfied when the distance from the centre of the dipole is much greater than the length of the dipole. The length of the dipole of the magnetic components orientated in the radial direction in the motor is limited by the diameter of the rotor.

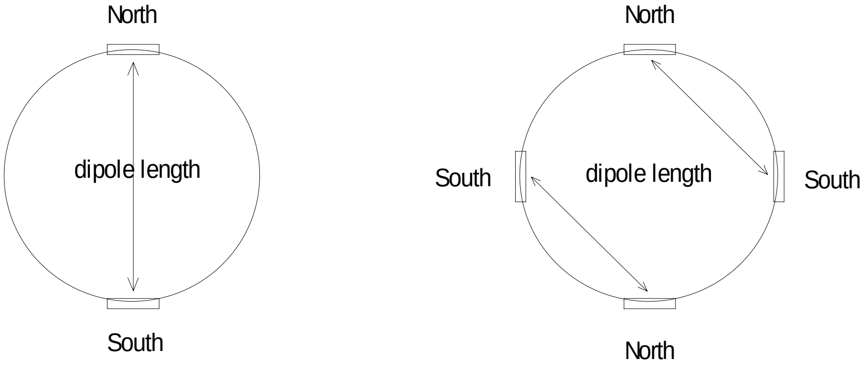

Figure 3 – 2 and 4 motor pole configuration

From an examination of Figure 3, it is apparent that a number of factors will reduce the magnetic signature as the number of poles on the rotor is increased:

i) The effective dipole length will decrease with an increase in number of poles thus reducing the far-field magnetic signature.
ii) An increase in the number of poles will place opposing poles closer and reduce the magnitude of the combined magnetic signature of the rotor.
iii) The strength of each pole will probably reduced as there is decreased space for the magnetic material that is used to construct each pole

This analysis suggests that a brushless motor with more poles will have a reduced signature when compared with a brushless motor of similar power but with fewer poles.

Physical data on the motor, rotor and magnets was requested from Kollmorgen for the Goldline Brushless Motors This information was unavailable as it was “proprietary in nature”. If it was desirable to undertake magnetic modelling on these motors it may be necessary to pull one apart to obtain the physical data that would be a basis for a well defined model.

5. Conclusion

The “Goldline Series Motors” produced by Kollmorgen Motion Technologies Group under test were found to have a significant magnetic signature close to the motor. This result suggests that these motors may be unsuitable for use in an underwater vehicle designed to clear mines. The magnitude of the magnetic signature (0-15 Hz) of these motors would be reduced if a non magnetic shaft was fitted and a greater number of more closely placed lower strength poles were used on the rotor. A brushless electric motors with a greater number of poles and a non magnetic shaft may well be suited for use in a vehicle designed for a mine clearance activities.

The results of testing the static magnetic signature of the brushless electric motors are highly dependent on the position of the rotor when the motor is stopped. Due to this, it is important to realise that apparently inconsistent results may be observed.

6. Acknowledgements

Dr John Ternan designed the magnetic test facility used in this testing. Jack Wilson and the late Jim McBeath from DSTO oversaw the construction of this facility.

Mick Durdin of the Maritime Platforms Division modified the BMX wheel for use with the motors.

7. References

[1] Say, M. G. & Taylor, E. O. , Direct Current Machines, Pitman Publishing Pty Ltd, Melbourne 1980.

[2] 1 The Kollmorgen Guide to motion control, Product Catalog, 1995, pp A176 –A178

Appendix A: Results

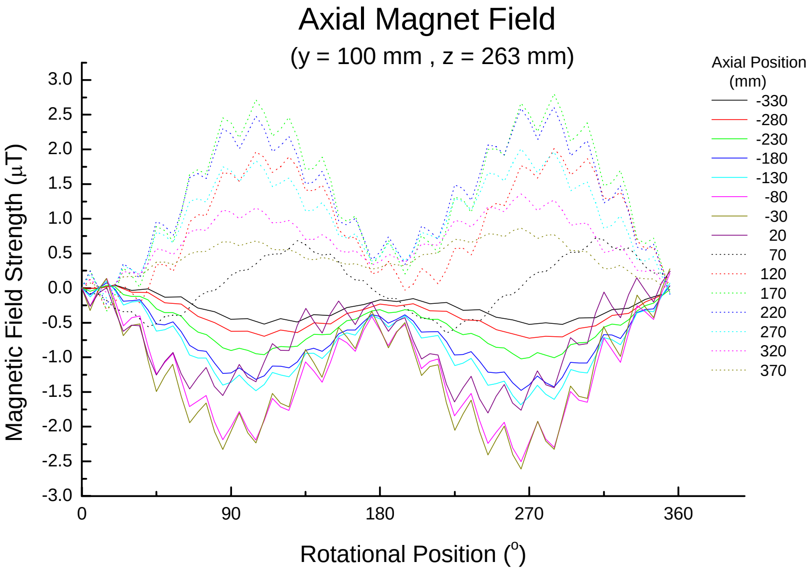

Figure 4- Static axial magnetic field from Kollmorgan Goldline motor S-202A referenced to magnetic field at 0 °

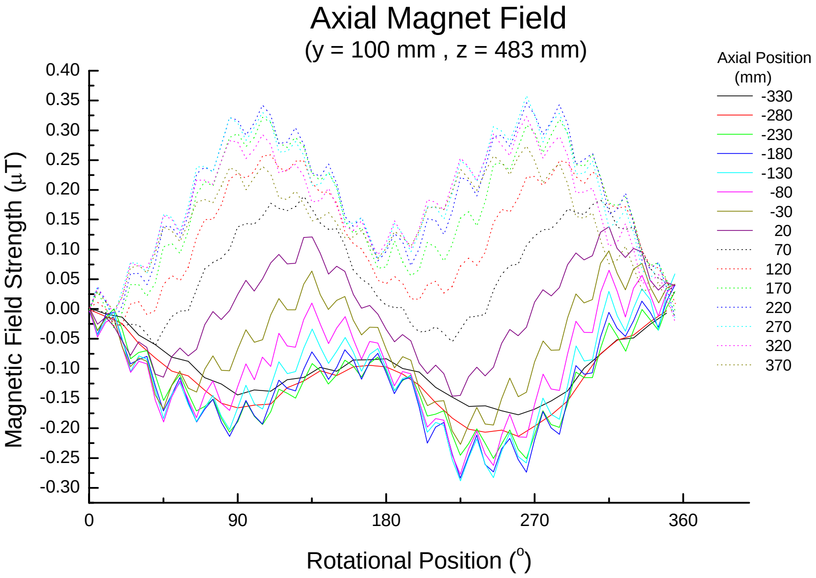

Figure 5- Static axial magnetic field from Kollmorgan Goldline motor S-202A referenced to magnetic field at 0 °

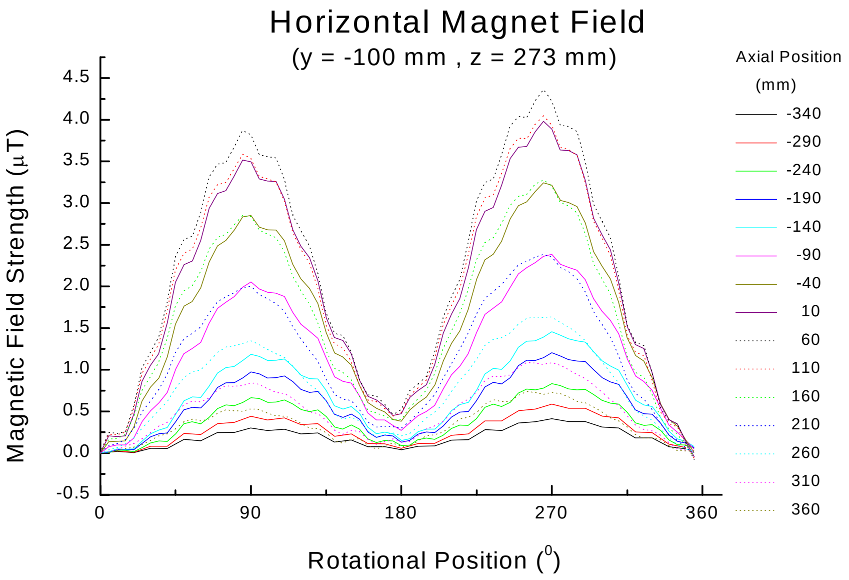

Figure 6- Static horizontal magnetic field from Kollmorgan Goldline motor S-202A referenced to magnetic field at 0°

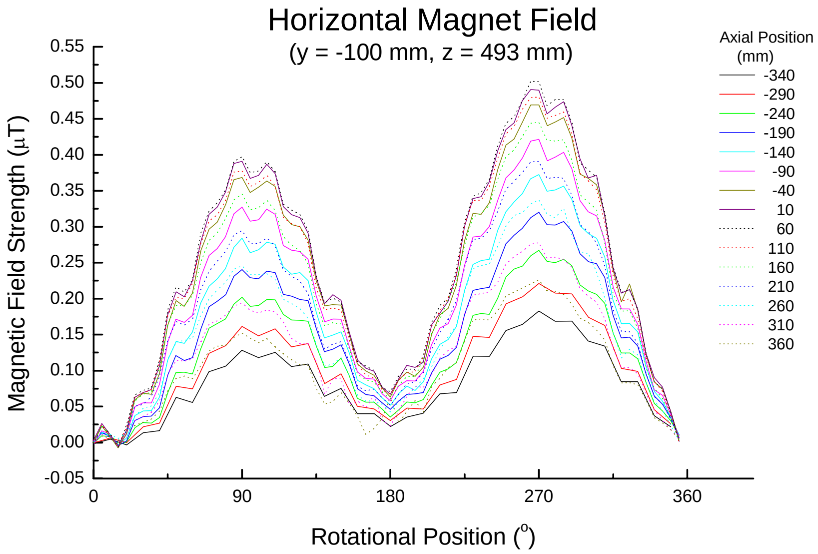

Figure 7- Static horizontal magnetic field from Kollmorgan Goldline motor S-202A referenced to magnetic field at 0°

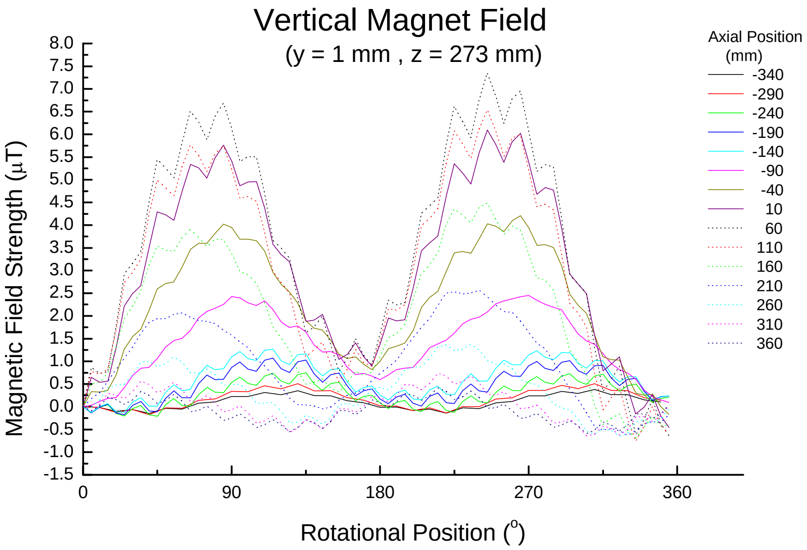

Figure 8- Static vertical magnetic field from Kollmorgan Goldline motor S-202A referenced to magnetic field at 0 °

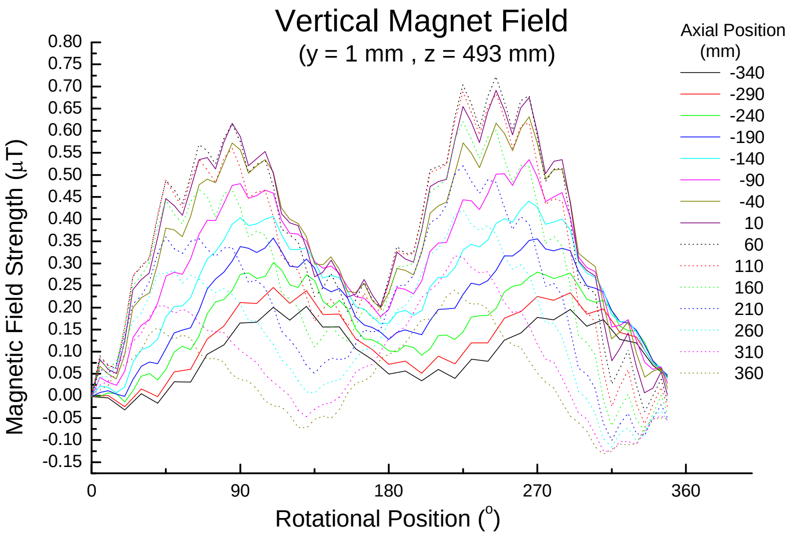

Figure 9- Static vertical magnetic field from Kollmorgan Goldline motor S-202A referenced to magnetic field at 0 °

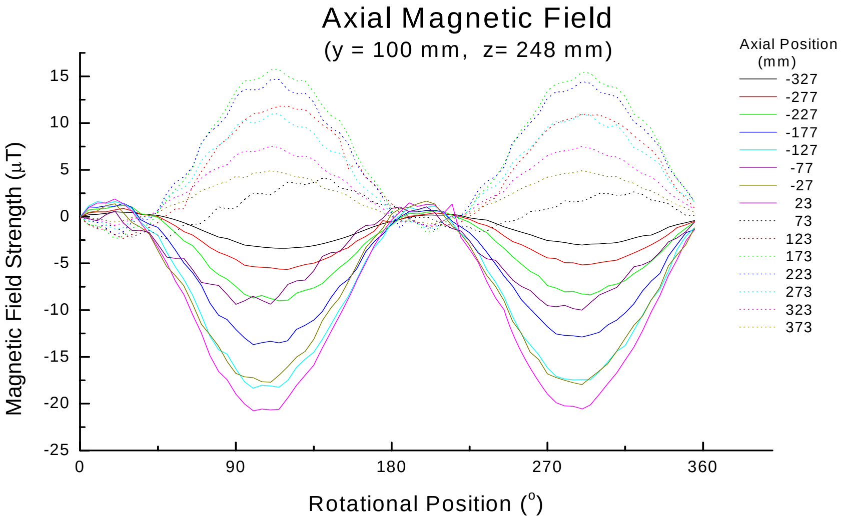

Figure 10- Static axial magnetic field from Kollmorgan Goldline motor S-406A referenced to magnetic field at 0°

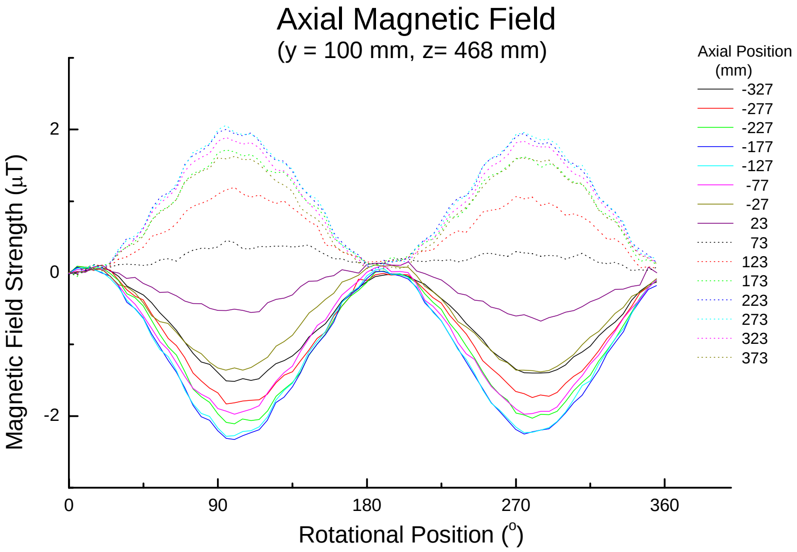

Figure 11- Static axial magnetic field from Kollmorgan Goldline motor S-406A referenced to magnetic field at 0°

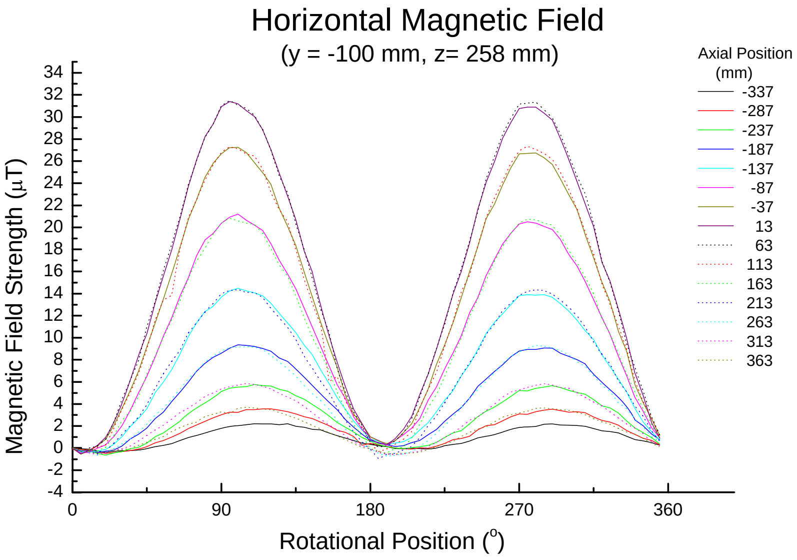

Figure 12- Static horizontal magnetic field from Kollmorgan Goldline motor S-406A referenced to magnetic field at 0°

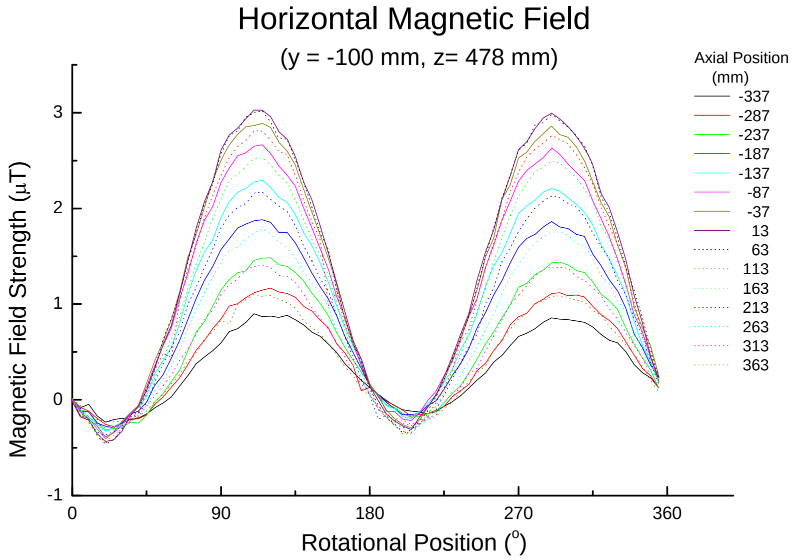

Figure 13- Static horizontal magnetic field from Kollmorgan Goldline motor S-406A referenced to magnetic field at 0°

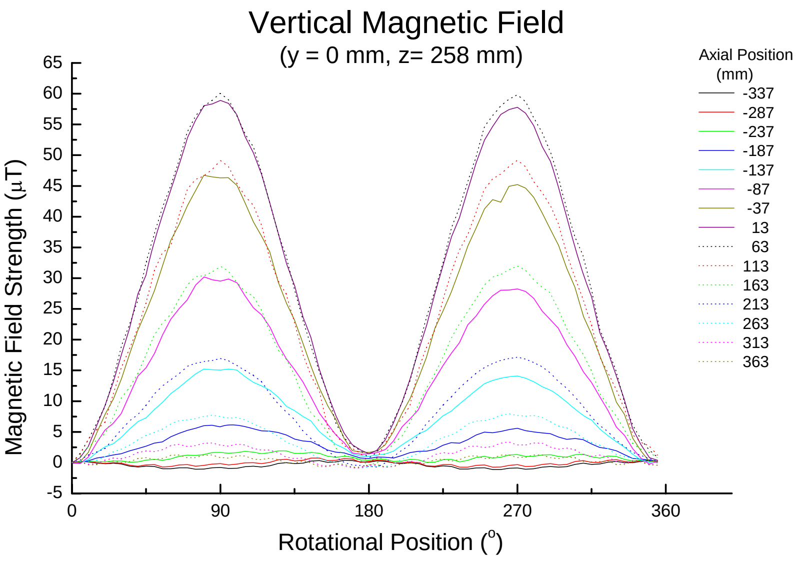

Figure 14- Static vertical magnetic field from Kollmorgan Goldline motor S-406A referenced to magnetic field at 0°

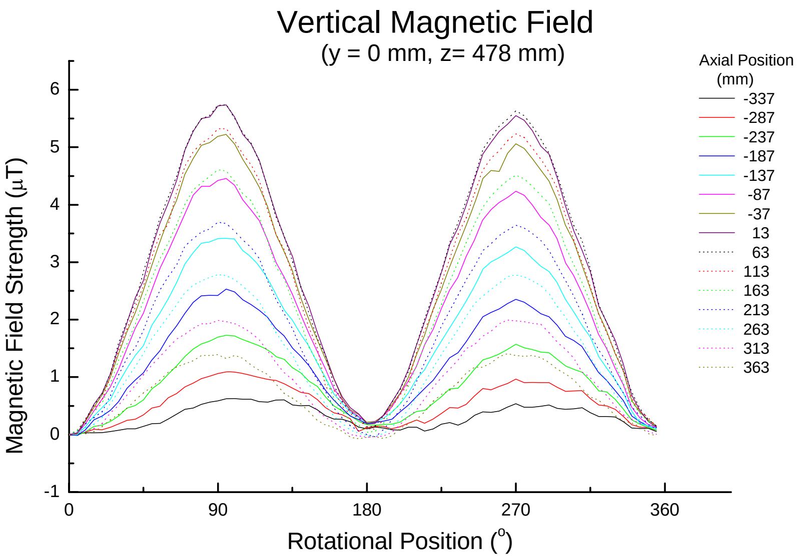

Figure 15- Static vertical magnetic field from Kollmorgan Goldline motor S-406A referenced to magnetic field at 0°

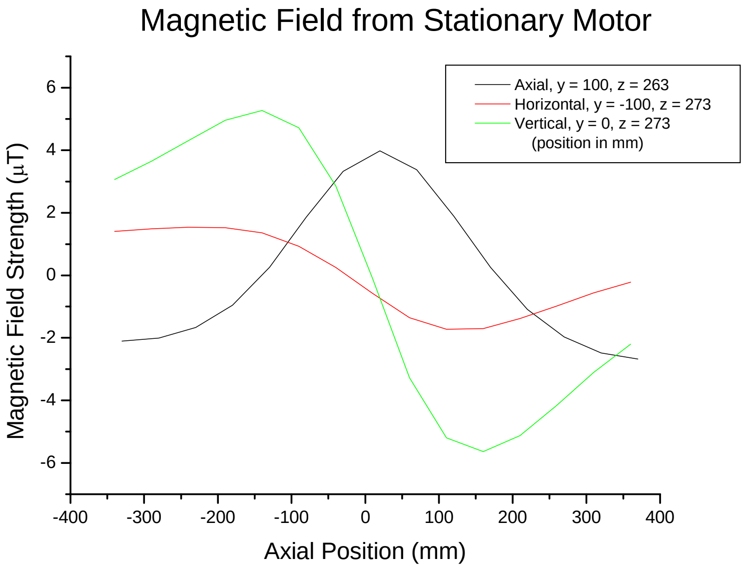

Figure 16- Static magnetic field from Kollmorgan Goldline motor S-202A when the rotor is positioned at its zero position

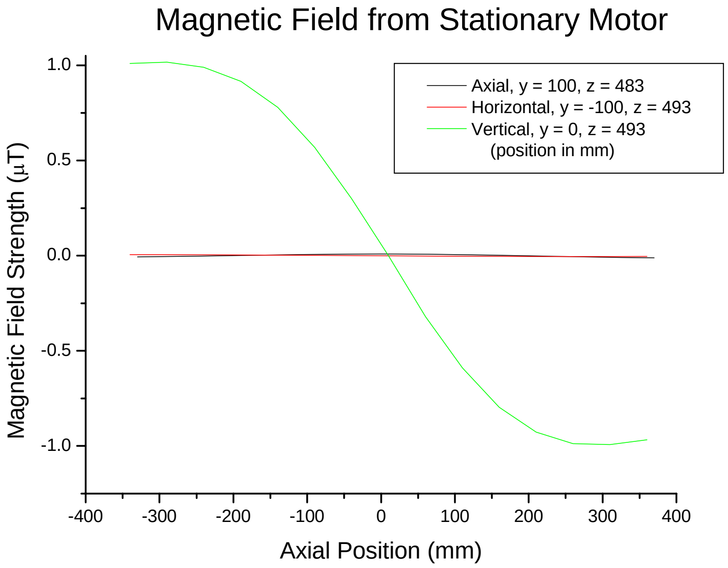

Figure 17- Static magnetic field from Kollmorgan Goldline motor S-202A when the rotor is positioned at its zero position

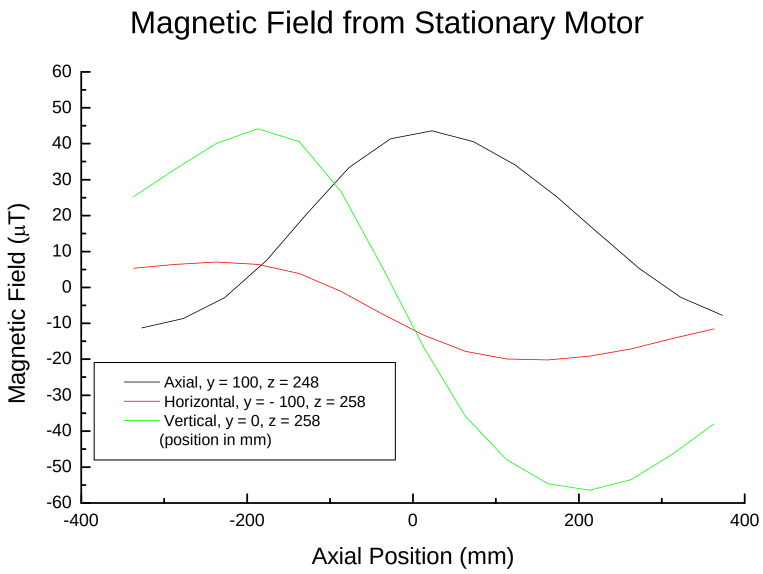

Figure 18- Static magnetic field from Kollmorgan Goldline motor S-406A when the rotor is positioned at its zero position

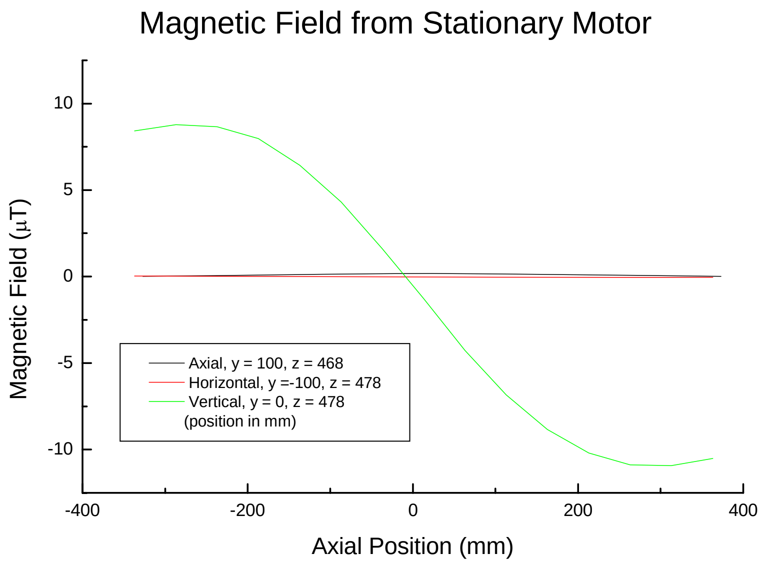

Figure 19- Static magnetic field from Kollmorgan Goldline motor S-406A when the rotor is positioned at its zero position

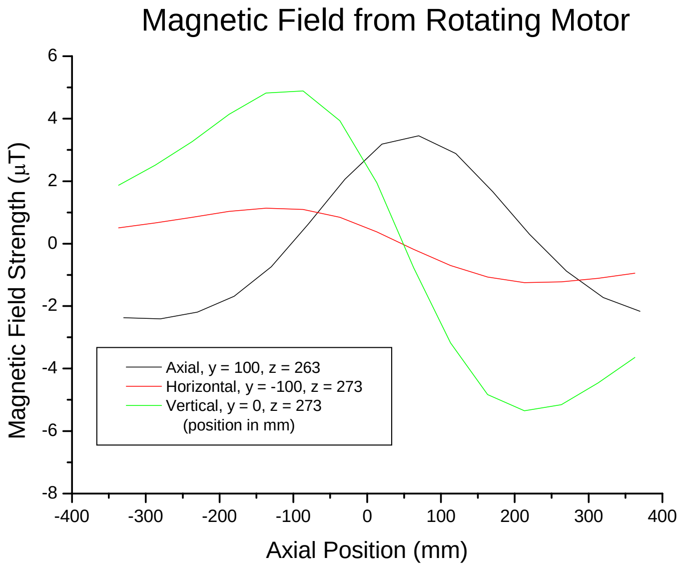

Figure 20- Static magnetic field from Kollmorgan Goldline motor S-202A when the rotor is spinning at 1200 rpm

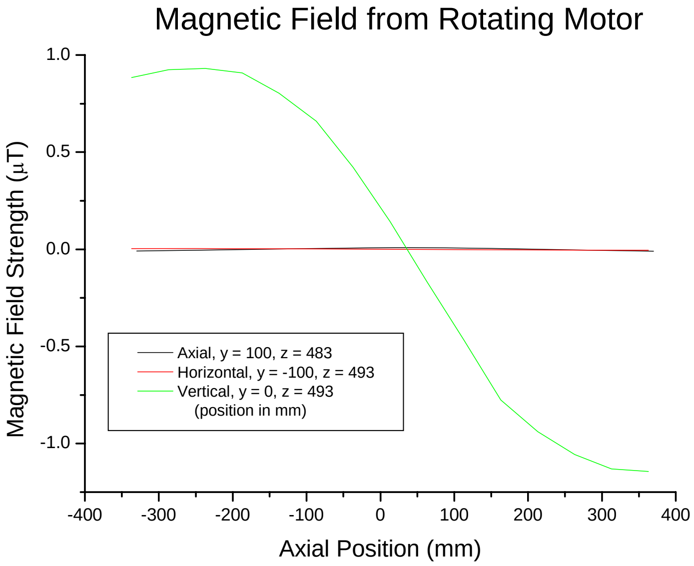

Figure 21- Static magnetic field from Kollmorgan Goldline motor S-202A when the rotor is spinning at 1200 rpm

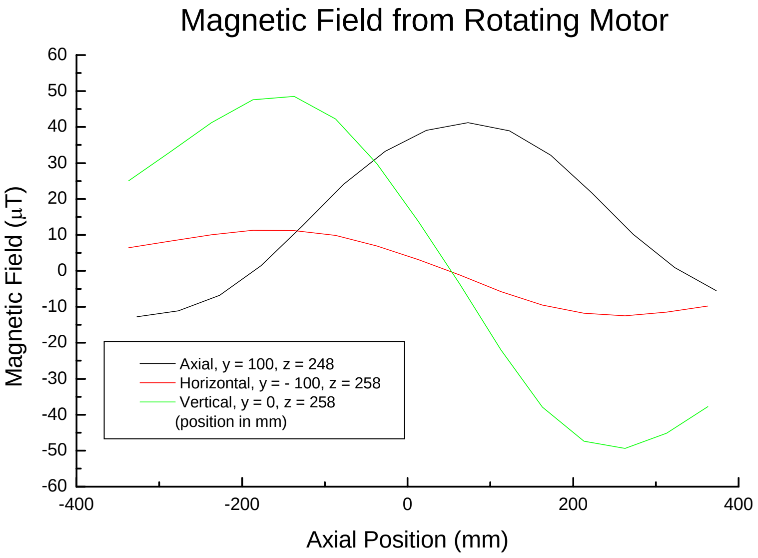

Figure 22- Static magnetic field from Kollmorgan Goldline motor S-406A when the rotor is spinning at 1200 rpm

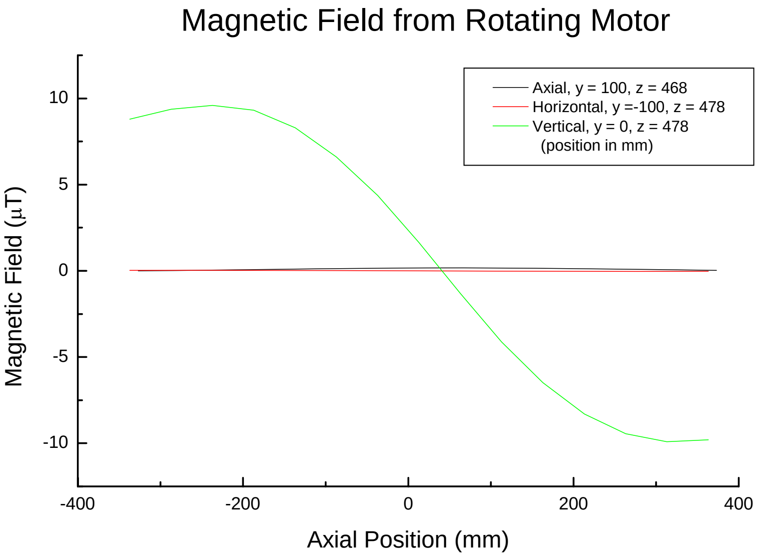

Figure 23- Static magnetic field from Kollmorgan Goldline motor S-406A when the rotor is spinning at 1200 rpm

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David Clarke

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19. ABSTRACT

Brushless electric motors are used in a number of underwater vehicles. When these underwater vehicles are used for mine clearance operations the magnetic signature of the brushless motors is important.

The magnetic signature of two models of brushless motor designed by the Kollmorgen Motion Technologies Group for use in submersible systems were examined. Magnetic mapping around the motors was performed so the influence of the individual elements of the motors could be isolated. The major component of the magnetic field was determined to be due to the shaft and rotor section of motor.