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Development of a Tilt Sensor for the Momentum Management System

by

MICHAEL J. WIKTOWY, B.Eng.

a thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Engineering

Ottawa-Carleton Institute for
Mechanical and Aerospace Engineering

Department of
Mechanical and Aerospace Engineering
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Abstract

Carleton University and Bristol Aerospace Limited are jointly developing an attitude control system for spacecraft called the Momentum Management System. Within this system is a gimbaled rotor whose angular position must be determined very accurately while the rotor is spinning. This thesis outlines a simple, low cost solution to this angular determination problem.

The system uses a combination of a pattern on the periphery of the rotor and a corresponding sensor to detect the pattern. The system detects changes in the sensed pattern as the rotor tilts and the output corresponds to a calibrated tilt angle. This tilt detection is performed in two axes to determine the orientation of the rotor spin axis and, consequently, the rotor momentum vector.

Hardware was manufactured and testing of the tilt sensor was performed. The included results guided the development of the sensor and prove the feasibility of this system.

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Nomenclature

Symbol	Label
A	Cross-sectional area
B	Magnetic flux density
B_r	Remanence
DC	Duty cycle
DR	Difference ratio
DF	Damping factor
f	Frequency
ϕ	Magnetic flux
φ	Local surface angle
φ_m	Mid-pattern local surface angle
k	Interaction coefficient
k_x	x-axis flexure spring constant
k_y	y-axis flexure spring constant
H	Magnetic field strength
I	Current
I_{gt}	Gimbal inertia about the transverse axis
I_{gs}	Gimbal inertia about the spin axis
K	Calibration factor, Normalized interaction coefficient
H_c	Coercive Force

L	Length of permanent magnet, Semi-length of rotor, Inductor
ℓ	Length of magnetic circuit element
m	Pattern slope
μ	Magnetic permeability
$\mathfrak{N}$	Magnetomotive force
N	Number of turns, Number of patterns
R	Resistance, Rotor radius
$\mathfrak{R}$	Magnetic reluctance
θ	Rotor spin angle
t	time
V	Voltage
τ	Time constant
ω_s	Motor shaft spin speed
ω_c	Corner frequency
ψ	Rotor tilt angle
ψ_o	Reference rotor tilt angle
ψ_p	Pattern tilt angle range

1. Introduction

1.1 Background

1.1.1 Attitude Control Description and Examples

An important subsystem of a satellite or other spacecraft is the Attitude Control System (ACS). This system uses sensors to determine the current orientation of the spacecraft and also controls various actuators to orient the onboard payload in a particular direction that may change with time. This payload may contain sensors or communication antennae that require a particular line-of-sight or reference in order to operate properly. The type of spacecraft payload generally dictates the type of ACS and its performance characteristics that are required.

1.1.1.1 Remote Sensing

A category of payloads that commonly rely heavily on the ACS is remote sensing. These spacecraft typically orbit the body that they are observing (Earth, Sun, Moon, etc.) and the observing sensors are usually always pointed at the body. This suggests that these payloads do not require a large attitude control range. The pointing accuracy depends on the field of view of the observing sensor. If the view is wide (as in a weather satellite) then the required accuracy is low. But if the field of view is narrow (as in a reconnaissance satellite), the required accuracy is high. The pointing accuracy impacts directly on the resolution of the image if long exposure times are needed.

1.1.1.2 Spacecraft Communication

Communication satellites are another group of payloads that rely on the ACS. Like remote sensing satellites, they typically point their payload at the body around which they orbit. However, communication antennae usually have a large field of view. This means that not only does the spacecraft not require a large attitude control range but they do not require the accuracy in pointing that the remote sensing satellites require. However, future trends indicate that this will change. With the implementation of constellations of satellites with inter-satellite communication, the pointing accuracy requirement of the communication payload is increased. This increase is due to fact that another satellite is a smaller target for a communication beam. Also, since the number of satellites per constellation is quite high, the antenna beam width would have to be reduced to ensure that the communication beam is not directed at multiple satellites and corrupting the network.

1.1.1.3 Astronomical Observatory Spacecraft

Astronomical observatory spacecraft (such as the NASA Hubble Space Telescope) is the most demanding class of spacecraft from the standpoint of the ACS of the three examples covered. This type of spacecraft would be used to study the positions and characteristics of various astronomical bodies that are far from the Earth. Since different objects in quite different positions are being observed, the range of attitude control is large compared to the previous two examples. One factor in the degree of resolution of the resulting images of the observed bodies is how steadily can the sensor

be trained on the object of interest. Very accurate images require very accurate and steady attitude control.

1.1.2 Attitude Control Methods

1.1.2.1 Gravity Gradient Stabilization

Gravity gradient stabilization attitude control takes advantage of the natural tendency for an object to align itself with the gradient of a gravitational field. This alignment occurs since the portion of the object closest to the source of the gravity is attracted to the source more than the portion farthest away. If the moment of inertia around one axis of the object is less than around the other axes, the object will have a stable orientation. A spacecraft that uses this method would be long and slender to maximize the difference in moments of inertia. This means of attitude control is passive; meaning it is an inherent part of the structure of the object and requires no power source. However, the application of such an ACS is quite restricted. The natural orientation is limited to pointing towards the source of the gravity. This condition limits this control method to low orbiting satellites. Also, dynamic effects and gravity variation will cause the object to oscillate around the stable point causing a pointing inaccuracy. The Moon has an offset of its iron core from its centre causing one of its moments of inertia to be less than the others. This is what causes one face to always be oriented towards the Earth and this is an example of gravity gradient attitude control.

1.1.2.2 Thrusters

Thrusters affect the attitude of a spacecraft by using gases that are expelled at high velocity to provide a force. The thrusters are mounted so that their direction of force does not pass through the centre of mass of the spacecraft. This provides a torque that can point the spacecraft in the chosen orientation. Thrusters are typically paired so that they can be activated simultaneously and provide pure torque. With this arrangement, it is required that there are at least four thrusters (or thrust nozzles) for each axis about which the angular position is to be controlled. This is a good general form of coarse attitude control that can also be used for minor orbit adjustments. However, this method requires that fuel be on-board, which increases initial weight and complexity. Also, once the fuel is spent the ability to control the attitude of the spacecraft is lost.

1.1.2.3 Magnetic Torque Rods

Magnetic torque rods are simply ferromagnetic rods that are wound with a conductor to form an electromagnet. When current is passed through the conductor, the rod will produce a torque that will line up the rod with the ambient magnetic field. It can be implied from the description of the operation of the magnetic torque rods that an ambient magnetic field must be present for this system to operate. This fact limits this particular attitude control device to spacecraft with a low orbit around a body with a magnetic field (i.e. the Earth). Furthermore, the non-uniformity of the magnetic field within a spacecraft orbit greatly complicates the implementation of this method of attitude control. Oftentimes, this counteracts the benefits gained by the method's simplicity of design, light weight and fact that a fuel supply is not needed.

1.1.2.4 Momentum Wheels

The momentum wheel is probably the most popular and most flexible form of attitude control. This system takes advantage of the fact that a spinning object will tend to remain in the same orientation if disturbed by an outside force. This is a consequence of the fact that a system will conserve its angular momentum. The angular momentum in the wheel is monitored and controlled and torque can be placed on the momentum wheel. The reaction torque is applied to the spacecraft to orient it in a selected direction.

Typically, to fully control the angular positioning of a spacecraft in all three axes, three momentum wheels are employed. However, if maneuvering restrictions are accepted, a spacecraft can maneuver into any orientation with less than three momentum wheels. One example of this is using two momentum wheels: one controlling one axis oriented normal to the orbit plane and the other controlling the other axes at points 90° apart in the orbit path. Another example is to use some method of steering the momentum vector of the wheel to a desired orientation. One steering mechanism that is used is screw jacks mounted on the base of the momentum wheel case. These screws can be driven by electric motors to orient the wheel within a fixed orientation envelope. Another steering mechanism is to place the momentum wheel in a system of gimbals and control the various gimbal angles. This is the method that the MMS utilizes.

Table 1-1 compares the four attitude control systems mentioned with respect to pointing accuracy, power, weight and cost.

Control Type	Pointing Accuracy	Power (W)	Weight (kg)	Cost
Thrusters	0.1 to 5°	Low	0.1 to 4.5	High
Magnetic Torque Rods	$\pm 5^\circ$	0.6 to 16	0.4 to 50	Medium
Gravity Gradient	$\pm 5^\circ$ (Limited to Earth pointing)	0	Medium(Part of structure)	Low
Momentum Wheels	$\pm 0.001^\circ$ to $\pm 1^\circ$	10 to 110	2 to 20	High

Table 1-1: Table Comparing ACS Configurations [1]

1.2 Momentum Management System Description

The Momentum Management System (MMS) employs a gimballed momentum wheel system. The gimbals consist of flexures that are “tuned” so that they act as if they have zero stiffness. The gimbal and flexures are shown in Figure 1-2. The momentum wheel is actuated to tilt in two axes by magnetic torque coils acting on permanent magnets mounted on the rotor. The rotor is driven by an electric motor and its speed is also controlled. These features enable the angular momentum of the rotor to be controlled within a fixed envelope. Figure 1-2 shows how the MMS is classified in the ACS hierarchy discussed in the previous sections.

Figure 1-1: Schematic of MMS Gimbal Showing Arrangement of Flexures [2]

Figure 1-2: Organisation Chart Showing ACS Hierarchy and Position of MMS

1.2.1 Momentum Wheel

The momentum wheel system is designed for a range of angular momentum from 1 N·m·s to 4 N·m·s. These momentum limits correspond to the minimum operating speed of 1200 RPM and the maximum operating speed of 6000 RPM. The diameter of the rotor is 150 mm and the height is 102 mm. The rotor is fabricated out of stainless steel and has a mass of approximately 2.9 kg.

1.2.2 Flexure Dynamics

The momentum wheel is supported by crossed flexure bearings. These bearings allow the rotor to tilt around the axes transverse to the shaft axis. These flexures allow a limited tilting of the rotor with respect to the shaft before they plastically deform. A factor of safety protecting this angular limit is provided by built in stops that reduce the tilt range to $\pm 7^\circ$. The flexures consist of thin strips of material that are built into a gimbal system in a crossed arrangement.

These flexures can be designed for a wide range of stiffness and load capacity by varying the thickness of the flexure and the angle at which the strips cross. The flexures for the MMS were designed to operate at a load of 1g to $-1g$ with a nominal stiffness of 92.1 N·mm/rad.

1.2.3 Tuned Rotor Gyroscope (TRG)

The MMS, in certain modes, can act as a tuned rotor gyroscope or TRG. “Tuned” refers to the arrangement of the gimbal and the flexures. In a tuned rotor gyroscope the

stiffness of the flexures and the gimbal mass are related such that the resultant dynamic stiffness of the system is zero. The equation giving the parameters that meet this tuned condition given an operating speed is [3]:

$$k_x + k_y - 2 \cdot \left(I_{gr} - \frac{I_{gs}}{2} \right) \cdot \omega_s^2 = 0$$

where k_x = x-axis flexure spring constant

k_y = y-axis flexure spring constant [1-1]

I_{gr} = gimbal inertia about the transverse axis

I_{gs} = gimbal inertia about the spin axis

ω_s = motor shaft spin speed

This means that when the rotor is tuned and is placed at some angle relative to null, the rotor will remain at that angle unless acted upon by some outside force.

This is a particularly useful property for a momentum wheel system since it subtracts-out an uncontrollable angle-dependent influence of the gimbal flexure on the rotor torque. However, this effect only occurs at a particular tuned speed. If the momentum wheel is operated at an off-tuned speed at an off-null angle, a corrective torque must be constantly applied to maintain the angle. While the main purpose of this dynamic tuning is to eliminate the need for this corrective torque, operating close to the tuned speed greatly reduces the magnitude of the required torque and therefore reduces the power and size requirements of the torque mechanisms.

1.3 Comparison of MMS to Conventional Momentum Wheel

1.3.1 Single vs. Multiple Wheel

There are several benefits to one wheel momentum control methods over multiple wheel systems. Using one wheel means that the system will have less mass and be smaller. One wheel means that there is only need for one electric drive motor. This represents a saving in both mass and electrical power. Also, a single drive train reduces the number of ball bearings that need to be employed and reduces the complexity of the system.

However, there are some disadvantages to the single wheel momentum wheel system. With a single wheel system, there generally is a smaller momentum selection envelope. The range of controllable momentum is smaller than that with a multiple wheel system that has a separate wheel for each axis. Also, there is a much more complex control system associated with a single wheel system if it is to be used to control momentum in all three axes. The actuation and dynamics of a wheel with three degrees of freedom (DOF) is more complex than that of three wheels with only one DOF each. The mechanism for allowing these degrees of freedom is generally more complex and error-prone than a single DOF system.

1.3.2 Flexures vs. Bearings

There are numerous benefits to using flexures over ball bearings. One benefit is that there is no need for lubrication in flexures. Lubricants have a tendency to out-gas and this can cause failures in other systems that are sensitive to contaminants (electrical

circuit boards, optical systems). Also, the viscous forces of the lubrication are highly variable and very difficult to accurately characterize. Since knowing these forces is important to the momentum system, this effect would ideally be simple or absent altogether. This is the case with flexures. Flexures can be designed to have a constant stiffness and exhibit very low hysteresis in their force vs. displacement response.

Also, flexures are generally more rigid in their off-axis displacement modes. Ball bearings are generally more susceptible to axial loads and moments that are not around the rotation axis. For the ball bearings to be as resistant to these off-axis displacement modes, they would have to be designed to be much larger or would need to be paired with another ball bearing.

Due to their simplicity, flexures are typically lighter than ball bearings. For flexures to bend through a large range of motion, they must be made relatively thin. Also, the loads in a flexure are much more distributed than the point loads that occur between the balls and bearing races in ball bearings. This “mechanical efficiency” leads directly to the fact that flexures will have a higher applied load to weight ratio.

There are disadvantages to using flexures that may make them unsuitable for some applications. Flexures have a limited rotational range that is not shared with ball bearings. Ball bearings have an unlimited rotational range while flexures are generally limited to $\pm 30^\circ$. Also, the rotation centre of a flexure bearing displaces with a rotational displacement. This is not a large effect but can become a problem with some applications that rely on very precise concentricity.

A cross-section view of the MMS is shown in Figure A-5. This illustration shows the drive train, the TRG gimbal and the flexures.

1.4 Similar Example: Canadian Strap-down Gyroscope – Version 2 (CSG-2)

A very similar design to the MMS is the CSG-2 designed by Litton Systems Canada Limited for use as a angular motion sensor in inertial navigation systems. While the CSG-2 is a gyroscopic rotational motion sensor, not a momentum wheel, the similarities and differences illustrate the influence of and the deviations from the design of the MMS.

1.4.1 Similarities

The CSG-2 shares many attributes with the MMS. The most predominant is the fact that the MMS can act like a TRG as described in Section 1.2.3. The effectiveness and reliability of these systems has been proven with the CSG-2.

Another feature that is shared between the two systems is the method of tilt actuation. The torque on the rotor about the non-spin axes is applied by a coil and permanent magnet arrangement. The permanent magnet resides in the rotor creating a radial magnetic field. In to this field is placed a conductive coil with the coil normal direction aligned with the magnetic field. When a current is passed through the coil, a Lorentz force is created which creates a torque on the rotor. These coils are placed on either side of the rotor to create equal and opposite forces which create a pure moment on the rotor. There are two coils per axis generating a total of four coils per MMS.

The gimbal bearings in both the CSG-2 and the MMS are crossed strip flexures. These flexure strips are comprised of very thin (several thousandths of an inch) sheets of metal that are cut out of the gimbal block typically by a wire EDM (Electro-discharge Machining) process. Since the rotor is designed to have a limited angular displacement, the use of flexures over ball bearings is permitted. The flexures are lightweight and small compared to ball bearings so they do not impact as much on the mass characteristics of the rotor or gimbal.

1.4.2 Differences

In addition to the similarities between the CSG-2 and the MMS, there are fundamental differences between them. The primary difference is the size of the MMS relative to the CSG-2. The mass of the MMS rotor is approximately 650 times that of the CSG-2. This is a difference that impacts greatly on the design of the MMS and imposes differences in the structure and relative importance of dynamic forces compared to the CSG-2.

Somewhat compensating for the fact that the MMS rotor is more massive is the fact that the MMS rotor spins at a lower speed. The tuned speed for the CSG-2 is fairly steady at 103 Hz (6180 RPM). In contrast, the spin rate for the MMS varies from 20 Hz (1200 RPM) to 100 Hz (6000 RPM). This speed range is not the operational speed range, rather it is the range of tuned speeds for which appropriate tuned gimbals are to be manufactured. In operation, the MMS will be run at a $\pm 10\%$ of the design tuned speed.

Another main difference that is particularly important to the topic of this thesis is the difference in allowable rotor tilt range. Both the CSG-2 and the MMS are strap-down systems meaning that both are rigidly fixed to a platform rather than attached through a gimbal. As was mentioned previously, the rotor tilt is actuated by an inductive coil to compensate for motion of the platform. In the CSG-2, the allowable tilt range is very close to zero. In the MMS, the allowable tilt range is $\pm 7^\circ$. This influences the design of the tilt sensors since the sensors must accurately determine the tilt angle over a vastly larger range of angular motion. This enlarged range introduces complications since most sensor systems are only linear over a small range. A sensor with a linear variation is easier to calibrate accurately. The design of a linear tilt sensor to measure angle over a $\pm 7^\circ$ range, as well as other requirements imposed by other systems in the MMS and the expected operating environment, is the topic of this thesis.

2. Project Description

2.1 Angle Measurement

Since the MMS rotor is required to tilt through a range of angles, a sensor must be developed to accurately sense the tilt angle in two axes over an extended range. Additionally, this angle measurement must be made on a rotating object. This greatly complicates the design of any tilt sensor.

There are two general methods of measuring the angle of a spinning rotor: physical contact or indirect sensing. If physical contact is to be made with the rotor then the sensor must be spinning at the same rate as the rotor. If this method is chosen, the tilt sensor signal must be passed out of the spinning apparatus via an electrical slip ring of some sort. Also, the portion of the sensor on the rotor must not disturb the dynamic characteristics of the momentum wheel since these are the parameters that are of interest. If the tilt sensor is designed so that no physical contact is made then some sort of indirect displacement measurement will need to be designed that utilizes a physical phenomenon or property such as light, magnetism, capacitance or sound to make a displacement measurement.

Both methods of angle measurement must not apply any significant torque to the rotor. An applied external torque will constitute an error in the overall dynamics of the momentum wheel. Therefore, any forces applied to the rotor should pass through the centre of rotation or be balanced with an opposing force to result in a zero net torque.

2.1.1 Requirements for MMS Tilt Sensor

The requirements of the MMS system, and in particular, the angular characteristics were driven by current and future requirements of Earth-pointing satellites. These include communication and Earth observation satellites. There are plans to place vast constellations of satellites in orbit in the near future. The last satellite (of 66 plus spares) of the Iridium communication constellation owned by Motorola has just gone into orbit. These systems offer a new challenge in inter-satellite communication. Future systems are expected to use laser communication between satellites. This type of communication requires very high pointing accuracy. Also, these satellites are expected to be smaller than communication satellites in the past. This translates into smaller power availability and the need to fit systems into a smaller volume. The MMS is designed to fill these future needs.

2.1.1.1 Precision

For the MMS to be implemented into these future roles, the angular pointing precision requirement of the various future systems must be met or exceeded. The various payloads carried by the satellite dictate these requirements. These roles, as noted earlier, include remote sensing and communications and define the type of payload carried.

Communications typically do not require as great a precision in pointing an antenna as remote sensing applications. Broadcast communications have a wide field of view that does not put large constraints on the pointing precision. High throughput communications with ground stations are typically more focused and begin to press the

abilities of typical ACS methods. Typically, there is the ability built into satellites to receive and transmit low bandwidth signals through an omni-directional antenna that does not depend on the spacecraft orientation. Secure communications can be achieved by tightly controlling the angular dispersion and precisely pointing the antenna at the intended recipient of a communication signal. However, privacy is more effectively maintained by using encryption routines to scramble the signal.

A future communication system that may place a burden on pointing precision is satellite-to-satellite laser communication. This consists of using modulated lasers of the type that are used in ground-based fibre-optic communications to provide a very high throughput signal between satellites. This system would be used in the upcoming satellite constellations to relay transmissions around the globe and to pass the signal to other satellites as the satellite presently handling the transmission moves out of range of the transmitter or receiver.

Remote sensing applications require a great deal of angular discrimination for their Earth pointing optical or radar instruments. This precision translates directly into the clarity of the image recorded by the instruments.

Therefore, general remote sensing and inter-satellite communication are the two applications that will define the limits for the precision of the angular discrimination. These two uses both require an angular precision of about 0.1° [4]. This precision is for the spacecraft as a whole. For the internal momentum wheel angular precision, a general rule would be to decrease this limit by an order of magnitude to allow for any errors that other components of the system may introduce. This would bring the required precision

down to the arcsecond level. The rate sensing requirements imposed on the MMS also require this level of precision. For the initial design process, it remains a good target to strive to meet.

2.1.1.2 Range

The range of the tilt of the momentum wheel is related to the amount of angle control that is needed over the satellite. In Earth-pointing satellites, there is usually not very much need for large angle changes after initial orbit injection and set-up. Therefore, the angular range requirement is driven by the magnitude of torque disturbances that the MMS is expected to absorb.

In addition, the flexures used for the suspension system are limited in angular range. If these limits are reached, plastic deformation occurs and the flexures will fail or perform unpredictably after that point. This limit is usually about $\pm 30^\circ$ and it is difficult to design flexures to deflect past that point.

To allow a fairly large safety margin, the angular tilt range was limited to $\pm 7^\circ$. At this point, mechanical stops halt the tilt but do not stop the rotation of the rotor.

2.1.1.3 Bandwidth

Bandwidth of the tilt sensor signal is dictated by the control system using the signal input and the frequency of the various dynamic effects of interest. The rotor has a strong dynamic tilt effect that occurs at a frequency that is twice the spin frequency. This effect needs to be characterized and compensated for by the control system. Using

Nyquist's rule, the minimum sample frequency that is required to observe a particular signal is twice the frequency of the signal. Therefore, the minimum frequency that the tilt sensor should provide readings is at four times the spin frequency.

There is another more strict limit on the bandwidth imposed by the control system. The system implemented uses filters that require higher bandwidth for adequate performance and stability. The lower limit of these filters is about 120 Hz and this corresponds to a tilt measurement taken 6 times per rotation at a rotation speed of 1200 RPM. At higher rotation speeds, the required number of measurements per rotation would be less so 6 times per rotation represents the lower limit.

2.1.1.4 Power

In most satellite systems, power is not plentiful and decreases through the lifetime of the system. Also, with the decrease of satellite size and orbit radii, power will become more and more scarce. For these reasons, the design of the MMS system should endeavour to minimize its power requirement.

2.1.1.5 Other Requirements

There are other requirements that are important to impose on the design of the tilt sensor. The first of these is that the tilt sensor should not be rotor speed dependent. The MMS is designed to operate through a range of speeds around its tuned speed. The tilt sensor should not have any dependencies on this variation in operation.

Also, there are expected to be several models of the MMS operating around different tuned speeds ranging from 1200 to 6000 RPM. It would be beneficial if the same tilt sensor could be used in all of these models without fundamental changes. This is due to the fact that in the aerospace industry there is an intensive, expensive qualification procedure that must be followed each time a change is made to a spacecraft component. By minimizing significant changes, great cost savings can be achieved.

Since the current general trend in satellites is for the size of the satellites to become smaller (with the possible exception of communication satellites), there is going to be less room inside each satellite to house the ACS. Therefore, it is a sound design goal to minimize the size of the tilt sensor and its impact on the size of the rest of the MMS.

The cost of the MMS must be kept to a minimum. This can be achieved through selection of inexpensive materials and the selection of off-the-shelf components that do not have to be specially made.

Weight is typically one of the most important characteristics of a satellite. This is due to the fact that every kilogram of mass that is launched into orbit costs about \$10,000 to \$30,000 depending on the launch vehicle. Therefore, satellite weight impacts heavily on the total cost of the entire project.

2.1.2 Review of State of the Art

2.1.2.1 CSG-2 – Inductive Balance

As was mentioned earlier, the CSG-2 shares many characteristics with the MMS. Their similarities and differences are outlined in Section 1.4. It is worthwhile then, to examine how the CSG-2 addresses the rotor angle measurement.

The operation of the CSG-2 is such that it requires feedback from the tilt sensors to keep the rotor at null angular displacement. This means that the range of the rotor tilt is kept as small as possible. The range would be limited to the precision of the tilt sensor used. Therefore, the CSG-2 requires a very high degree of precision in the angular tilt sensor so that the control system can counteract any deviation of the rotor from its null position.

The CSG-2 achieves the required high precision by using an inductive balance tilt sensor shown schematically in Figure 2-1. This sensor consists of two horseshoe transformer cores per tilt axis. Each core is wound with a primary and secondary coil. The primary coils are driven by an oscillating current to excite the secondary coils. The secondary coils are connected in opposition so that a voltage measured between them is an indication of the difference in inductances between the two coils. The open ends of the horseshoe transformers are placed close to the bottom edge of the rotor with one across the rotor diameter from the other. The horseshoes are placed so that the rotor itself completes the magnetic circuit through the transformer core.

Figure 2-1: Schematic of CSG-2 Tilt Sensor Method Showing the Relative Positions of Sensors When the Rotor is in Level and Tilted Positions

This arrangement of sensors provides sub-arcsecond resolution in angular displacement. When the rotor tilts, the inductance of the sensor that the rotor is approaching rises sharply while the inductance of the sensor that the rotor is moving away from falls sharply. The combination of these two effects gives a strong signal when the rotor is off-null and zero when it is at the null position. This type of sensor can be used to indicate angular motion with sub-arcsecond resolution.

However precise this sensor type is, it does not have the range necessary for use in the MMS system. If the sensors were placed far away from the rotor in its null condition to accommodate the range of tilt desired, then the sensor signals would be very weak. This would require signal amplification that also amplifies signal noise. In addition, one can assume a linear variation in signal amplitude with respect to tilt angle over a very small tilt range around null. However, when this tilt is extended, a very strong non-linearity develops which is hard to model and deal with accurately in the control system. For these reasons, it is necessary to find another solution to the rotor tilt measurement problem for the MMS.

2.2 General Concept

2.2.1 Overview

A tilt sensor design that has the ability to readily satisfy all of the requirements was chosen. The concept consists of a sensor combined with a pattern placed on the circumference of the rotor. The sensor tracks along various latitudes as the rotor spins and observes the pattern as the rotor is tilted. The pattern placed on the rotor is made such that the signal output by the sensor gives an indication of what latitude the sensor is tracking. This latitude corresponds to the tilt angle of the rotor relative to the coordinate system of the sensors.

Figure 2-2: Layout of Angle Sensing Concept Showing the Relative Placement of the Pattern, Sensor Coil and Spherical Rotor. Note the spherical shape of the rotor is designed to ensure a constant gap distance between rotor and sensor.

2.2.2 Pattern Description

A pattern that differs as the rotor is tilted can be placed into the circumference of the rotor. As the rotor tilts to different angles, the sensor point tracks along more or less of the region of the rotor which is marked. A sensor can be made that indicates when the sensor passes by an edge and it could be made to discriminate between transfers from region B to A or from region A to B.

Figure 2-3: Equidistant Cylindrical Projection of Pattern Showing Variation of Pattern Regions with Change in Latitude

If the time of each transfer was measured, and the relationship between the location of the edge around the spin axis with respect to the tilt angle is linear, the resulting tilt angle can be calculated using the formula:

$$\text{Angle from Mid - Pattern} = -\frac{K}{2} + K \frac{t_A}{t_{AB}} \quad [2-1]$$

Where K = Calibration Factor
 = Tilt angle between consecutive pattern vertices
 t_A = time that tilt sensor is in region A
 = time between B - A pulse and A - B pulse
 t_{AB} = time that tilt sensor is in region A and region B
 = time between consecutive B - A pulses (or A - B pulses)

2.2.3 Sensor Description

An inductive coil could make a simple sensor that would give a useful signal when passed over the rotor pattern. A more detailed schematic of the inductive sensor indicated in Figure 2-2 is shown in Figure 2-4. When the coil is part of a magnetic circuit (by including an excitation signal or a permanent magnet), a voltage is induced into the coil that is dependent on the rate of change of magnetic flux through the coil. In other words, if the distance between the coil and a ferromagnetic material was varied, a voltage would be induced in the coil that is a derivative of the distance with respect to time.

Figure 2-4: Cross-section and 3D View of Cylindrical Tilt Sensor Layout

The appropriate pattern for use with this sensor would be marked on the circumference by machining away an area at a constant radial depth in region A on Figure 2-3. The edge between the recessed (region A on Figure 2-3) and non-recessed (region B on Figure 2-3) region will cause a voltage spike due to the increase in magnetic flux caused by the sudden change in the magnetic reluctance of the circuit formed by the tilt sensor and the rotor. The direction of voltage pulse at a pattern edge for a crossing from region A to region B will be opposite to that for a crossing from region B to region A.

2.2.4 Pattern-Sensor System Considerations

The characteristics of the pulses, as well as the angular resolution, depend on a number of factors that can be immediately identified.

2.2.4.1 Mean Pattern Angle

One factor that influences the output of the sensor is mean pattern angle, ϕ_m . This value gives an indication of the magnitude of the slope of the pattern edges. The change in the location of the edge in the spin angular direction per unit angle in the tilt angular direction is the local pattern surface angle. The expression that gives this angle is defined in Section 3.3.5. This angle is not constant over the pattern tilt range but ϕ_m , the local pattern surface angle at the mid-pattern range, is a useful reference.

A large ϕ_m has several implications to the sensor signal. With a large ϕ_m , more repetitions of the pattern can fit on the circumference of the rotor. This means that there will be a tilt reading more times per revolution of the rotor or, in other words, the sensor has a higher output frequency. With a higher sensor output frequency, there is also the possibility of more averaging of pattern inconsistencies. Also, variances of tilt angle that occur at a much higher frequency than the spin frequency can be resolved. However, the negative aspect of this is that the change in pulse-to-pulse times with a change in tilt angle will be lower. This makes a much higher clock speed a necessity to get the required angular resolution.

A small ϕ_m has exactly the opposite effect as a large ϕ_m . It leaves room on the circumference for fewer patterns and consequently has a lower sensor bandwidth.

However, there is a larger change in pulse times with a change in tilt angle. This effect means that a lower clock speed can be used to achieve the required angular resolution. Clearly, the selection of ϕ_m is a trade-off between parameters.

2.2.4.2 Pattern Sharpness

Another effect that is not so obvious is the sharpness of the pattern edge. If the pattern has large radius fillets along the bottom of the edges, the output signal will be attenuated due to the gradual nature of the change in gap distance and, consequently, the magnetic flux change. Chamfers on the edges themselves will also have the same effect. The ideal edge sharpness would occur if the transition from raised to milled portion of the pattern was aligned with the radial direction of the rotor or even slightly undercut to compensate for the tendency of the flux path to follow the edge of the pattern as it moves away. Such a sharp edge may prove difficult to manufacture with a standard milling machine.

2.2.4.3 Gap Distance

The rotor must be made spherical in shape as shown in Figure 2-2. This is done to ensure a small and uniform distance between the tilt sensor and the rotor over the complete range of tilt. If this is not done, non-linearity of the sensor signal will be introduced. The rotor need only be spherical over the pattern range and not over the whole rotor as shown in Figure 2-2.

Another factor involved in gap distance is the pattern depth. If the pattern is cut deeper then there will be more of a difference between the magnetic reluctance in the gap between the sensor and the rotor. See Section 3.1.2 for an analysis of this effect.

Also, a change in the distance of the sensor to the raised portion of the pattern will cause the patterns to phase shift slightly. If the change in gap size is at a much slower rate than the rate at which a single pattern passes by, the phase shift will not affect the sensor output. This is due to the fact that the phase shift will occur nearly equally in the up-going and down-going pulses resulting in no change in the various times used in Equation 2-1. Such a gap change could occur due to temperature changes causing thermal expansion and contraction.

2.2.4.4 Axial Tension/Compression

If there is axial compression or tension in the flexures, the flexures will strain and the rotor will have an axial displacement. On each sensor, this axial displacement will appear as a tilt angle. However, two sensors on opposite sides of the rotor can be combined to cancel out this offset and automatically find the null angle. This will compensate for any axial displacement that may occur. Gravitational loads would be one possible cause of axial displacement. Another possible axial load could occur if the coils providing the rotor tilt torque were unbalanced and not providing a pure moment.

2.2.4.5 Rotor Speed

The speed of the rotor will also have an effect on the signal pulse. Similar to the effect of pattern depth, the faster the pattern edge passes by the sensor, the greater the rate

of change of magnetic flux and the greater the signal strength. This means that the sensor should be designed to operate at the lowest expected rotor speed to ensure that it will generate adequate signal strength over the complete speed range.

2.2.4.6 Magnetic Flux – Sensor Coil Coupling

Another factor that will affect the magnitude of the pulse is the magnetic coupling between the magnetic field source and the sensor coil. The position of the coil in the magnetic field will impact the ability of the coil to convert the change in magnetic flux into a sensor voltage. This effect will be analyzed in Section 3.2.1.

3. Analysis

3.1 Magnetic Analysis

3.1.1 Magnetic Circuit

A very effective method of understanding the characteristics of a magnetic system is the use of an electrical circuit analogy. In electrical circuits the voltages and currents around a particular circuit are determined by three laws:

Ohm's Law:

$$V = I \times R$$

where V = Voltage

I = Current

and R = Resistance

[3-1]

Kirchoff's Voltage Law:

The sum of the voltage drops around any closed circuit is zero.

$$\sum_{Loop} \Delta V = 0$$

[3-2]

Kirchoff's Current Law:

The sum of the currents into a point equals the sum of the currents out.

$$\sum I_{IN} = \sum I_{OUT}$$

[3-3]

The similarity between electric and magnetic fields demonstrated by the similarity between the field equations describing each phenomenon lead to analogous ideas being applied to magnetic systems.

An equivalent magnetic circuit can be established with analogous components. The voltage, or electromotive force (V), that drives an electric circuit can be replaced with a magnetomotive force ($\mathfrak{N}$) that drives the equivalent magnetic circuit. The resistance (R) of an electric circuit can be replaced by the reluctance ($\mathfrak{R}$) in a magnetic circuit. The resulting current (I) that flows through the electric circuit can be replaced with a magnetic flux (ϕ) that “flows” through the magnetic circuit.

The “Equivalent Magnetic Ohm’s Law” would be:

$$\phi = \frac{\mathfrak{N}}{\mathfrak{R}} \quad [3-4]$$

where

$$\mathfrak{R} = \sum \frac{\ell}{\mu \cdot A} \quad \text{for series circuit elements}$$

$$\frac{1}{\mathfrak{R}} = \sum \frac{\mu \cdot A}{\ell} \quad \text{for parallel circuit elements}$$

where ℓ = Length of circuit element

μ = permeability of circuit element

A = Cross-sectional area of circuit element

and

$$\begin{aligned}\mathfrak{K} &= NI && \text{for an electromagnetic source} \\ &= HL && \text{for a permanent magnet source}\end{aligned}$$

where N = Number of turns in the electromagnetic winding

I = Current in winding

H = Magnetic field strength of permanent magnet

L = Length of magnet

A simple mathematical model of the magnetic circuit would reveal the systems sensitivities to particular parameters that can be controlled in the design of the magnetic sensor. Therefore, a first iteration theoretical analysis was performed in order to investigate the various parametric sensitivities. Some general magnetic characteristics and rules of thumb were also discovered. The ultimate goal of this analysis was to refine the dimensions and material selection for the magnetic tilt sensor and the rotor pattern giving particular attention to weight, stability and impact on other systems within the MMS.

After an extensive literature search, an analytical solution to the particular magnetic geometry of the test apparatus could not be found. The test apparatus consisted of a magnetic dipole with the axis (the line joining the two poles) perpendicular to a spherical ferromagnetic surface and an air gap between the two. A solution to a magnetic dipole near a flat surface would have been approximate but that could not be found either.

The actual layout of the MMS system provided a somewhat easier system to model since it could be designed so that there would be a high permeability return path for tilt sensor magnetic circuit. The disadvantage to modelling this system is that it would

be inaccurate to compare this model with the test results. The advantage would be that this model would readily provide guides for the design of the final tilt sensors by providing parametric sensitivities.

For the magnetic circuit, five reluctance elements were selected: the variable path between the tip of the sensor and the surface of the rotor, the path through the sensor core, the return path through the rotor, the return path through the case and the return path through the air. This can be expressed mathematically with the variables defined previously as:

$$\mathfrak{R} = \frac{\ell_{gap}}{\mu_{gap} A_{gap}} + \frac{\ell_{gapR}}{\mu_{gapR} A_{gapR}} + \frac{\ell_{core}}{\mu_{core} A_{core}} + \frac{\ell_{rotor}}{\mu_{rotor} A_{rotor}} + \frac{\ell_{case}}{\mu_{case} A_{case}} \quad [3-5]$$

The last four terms of this series combination of reluctance elements are constant. These can be grouped for convenience into a constant C .

The induced voltage per sensor winding can be expressed by:

$$\begin{aligned} -V &= \frac{d\phi}{dt} \\ &= \frac{d\phi}{d\ell} \frac{d\ell}{dt} \quad \text{using the chain rule} \\ &= \frac{d}{d\ell} \left(\frac{\mathfrak{K}}{\frac{\ell_{gap}}{\mu_{gap} A_{gap}} + C} \right) \frac{d\ell}{dt} \\ &= \frac{-\mathfrak{K}}{\mu_{gap} A_{gap} \left(\frac{\ell_{gap}}{\mu_{gap} A_{gap}} + C \right)^2} \frac{d\ell}{dt} \end{aligned} \quad [3-6]$$

If it is assumed that there is a linear variation of the gap length with time when the gap is at the initial gap length, $\ell_{gap i}$, then:

$$\frac{d\ell}{dt} = \frac{\Delta\ell}{\Delta t} = \frac{\ell_{gap i} - \ell_{gap f}}{\Delta t} \quad [3-7]$$

Therefore, the resultant equation for the induced voltage per sensor winding would be:

$$V = \left(\frac{N}{\mu_{gap} A_{gap} \left(\frac{\ell_{gap i}}{\mu_{gap} A_{gap}} + C \right)^2} \right) \frac{\ell_{gap i} - \ell_{gap f}}{\Delta t} \quad [3-8]$$

The constant C (reluctance of the return path) is somewhat difficult to deal with. An accurate value for this constant can only be found by knowing the precise characteristics of the magnetic circuit and then using finite element analysis to determine the flux path. Since these characteristics are not known and the exact magnitude of the induced voltage is not important for the tilt sensor functionality, the circuit will be further analysed at the point where the voltage is a maximum. This maximum will exist when the constant C is set to zero (meaning that there is no return path reluctance). While this will not be the case, the analysis of this condition still reveals the relative dominance of the various parameters.

Assuming $C=0$

$$\begin{aligned}
 V &= \left(\frac{N}{\mu_{gap} A_{gap} \left(\frac{\ell_{gapi}}{\mu_{gap} A_{gap}} \right)^2} \right) \frac{\ell_{gapi} - \ell_{gapf}}{\Delta t} \\
 &= \frac{\mu_{gap} A_{gap} N}{\Delta t} \left(\frac{\ell_{gapi} - \ell_{gapf}}{\ell_{gapi}^2} \right)
 \end{aligned} \tag{3-9}$$

The value of Δt can be further expanded.

$$\Delta t = \frac{d_{core}}{v_{rotor}} \tag{3-10}$$

where d_{core} = diameter of the sensor core

v_{rotor} = speed of the circumference of the rotor

$$v_{rotor} = \omega_{rotor} \cdot r_{rotor} = \frac{60}{2\pi} N \cdot r_{rotor}$$

where N = rotor speed [RPM]

r_{rotor} = rotor diameter at sensor position

Therefore,

$$\Delta t = \frac{2\pi \cdot d_{core}}{60N \cdot r_{rotor}}$$

Also, assuming that there is little fringing, the value of the cross-sectional area of the gap, A_{gap} , is approximately equal to the cross-sectional area of the sensor core.

$$A_{gap} = \frac{\pi \cdot d_{core}^2}{4} \tag{3-11}$$

Substituting the above expressions into the equation for induced voltage per coil winding gives:

$$V = \frac{15}{2} \kappa \cdot \mu_{gap} \cdot d_{core} \cdot N \cdot r_{rotor} \left(\frac{\ell_{gap_i} - \ell_{gap_f}}{\ell_{gap_i}^2} \right) \quad [3-12]$$

3.1.2 Gap Selection

Looking at Equation 3-12, there are some indications on what the gap size should be. One can easily see that the maximum output of the sensors will occur when the initial gap size is the smallest it can possibly be (i.e. $\ell_{gap_i} = 0$). While it would be a good thing to optimize the output of the sensor in this way, zero gap spacing proves to be unrealistic. Small machining errors, lateral shifts in the centre of flexure rotation, inaccuracies in the rotor shaft alignment and lateral motion of the rotor due to applied loads all can cause the rotor to rub on the sensors causing possibly disastrous results. For this reason, the gap spacing is defined not by the magnetic properties of the sensor but by the clearance allowed to the rotor.

The initial gap subtracted from the final gap length gives the pattern depth. Equation 3-12 shows that the sensor output is linearly dependent on pattern depth. This means that the greater the pattern depth, the greater the output. The fact that the relation is linear is likely an artefact of the simplifying assumptions stated throughout the derivation, but the general trend is valid. Once again, however, it is not realistic to optimize this part of the equation. It is not favourable to the dynamics or the strength of the rotor for the pattern to be cut too deeply into the rotor circumference.

The pattern depth is therefore defined by what is realistic with respect to the machining process. A discussion of the pattern depth will therefore be contained in Section 3.3.2 – Equation for Pattern Machining.

3.1.3 Permanent Magnet Material Selection

Permanent magnets are materials that contain residual magnetic fields after an external field is removed. With no applied external field, the magnetic characteristics (Magnetic field strength, H and Magnetic field density, B) remain in the demagnetization area (second quadrant) of the material hysteresis curve (see Figure 3-1).

Figure 3-1: Hysteresis Curve Showing Demagnetization Curve, Remanence (B_r) and Coercive Force (H_c)

3.1.3.1 Type I vs. Type II

There are two general classifications of permanent magnets that represent magnetic material at the two extremes of magnetic characteristics: type I and type II.

Type I permanent magnets share several common characteristics. The demagnetization curve of a type I magnet is non-linear. This means that the type I magnet is sensitive to a demagnetizing field and may lose field strength if the demagnetizing field is high enough. This type of magnetic material is also called soft magnetic material. Type I magnets have a relative magnetic permeability much greater than 1. This effect will allow a lot of leakage flux to occur and in some cases only 45% of the flux reaches the end of the magnet [5]. As a result, type I magnets store much of their energy in the leakage flux where it is very difficult to utilize. Magnet of this type can be machined easily and very complex shapes are possible. The type I magnets are tough so they can withstand physical impacts. Magnets of this type include Magnetized Iron, Magnetized Steel and Alnico (an alloy of Aluminum, Nickel and Cobalt).

Type II permanent magnets have characteristics dissimilar from type I magnets. The demagnetization curve (the portion of the hysteresis curve in the second quadrant shown in Figure 3-1) of a type II magnet is relatively linear. This linearity extends into the third quadrant of the hysteresis curve. This means that the type II magnets are very resistant to demagnetizing fields and do not readily lose field strength. This type of magnetic material is also called hard magnetic material. Type II magnets have a relative magnetic permeability very close to 1. This results in most of the flux reaching the end of the magnet and very little leakage flux along the length of the magnet. Since there is little

leakage, most of the magnetic field is available at the poles of the magnet where it can be more readily utilized. Type II magnets tend to be made out of ceramic materials. This makes them brittle and not easily machined. Magnets of this type include RECo (Rare-Earth Cobalt) Ceramics, Ferrite Ceramics, Ferrite Ceramics and NbFeB (Neodymium-Iron-Boron).

Looking at the various characteristics of the type I and type II magnets indicate that a type II magnet would have characteristics that are most suitable for the tilt sensor application. This is due to the fact that magnetic stability is important as is the fact that most of the flux is available at the magnet poles. The negative aspects of type II magnets can be tolerated. By not using the magnets to bear loads, the fact that the type II magnets are brittle does not hinder the design. The design of the sensor does not require a complex shape for the magnet so the magnetic material does not have to be precisely machined.

3.1.3.2 Energy Product

The energy product of a magnetic material is a figure of merit that indicates the strength of a magnet and its ability to produce an external magnetic field. The actual value is derived by finding the area of the largest rectangle that can be drawn under the demagnetisation curve of a particular magnetic material. The higher the energy product, the less magnetic material one needs to establish a certain magnetic flux. The energy product of magnetic materials has risen dramatically in recent years. The highest energy products are available from NbFeB magnets.

3.1.3.3 Cost

Many of the type II magnets tend to be quite expensive compared to type I magnets. This is because the type II magnets contain rare and consequently expensive materials. Also, the price tends to be directly dependent on the energy product of the magnetic material and since many of the type II magnets have a higher energy product, they are more expensive.

The size of the magnet has large effect on the overall cost. The cost per mass of the magnetic material tends to go up exponentially with magnet size. There are only four sensors per MMS system and they are very small. Therefore, the small amount of magnetic material required will not be costly.

3.1.3.4 Stability

As was mentioned in Section 3.1.3.1, the stability of the type II magnetic material is better than that of the type I material with respect to demagnetisation fields. However, this stability does not necessarily extend to temperature sensitivity and corrosion resistance.

As can be seen in Table 3-1, there is no clear trend in temperature characteristics grouping Type I and II magnets. However, some generalizations can be drawn. Many of the very high energy product Type II magnets have a low maximum service temperature. Since they depend on the anisotropy of the crystal lattice for their strong magnetism, they also have anisotropic thermal expansion properties. Both Type I and II groups have magnet materials whose fields are sensitive and insensitive to temperature variation. The

highest variation of magnetic field with temperature is found in the ferrite ceramics and NbFeB magnets.

Magnetic Material	Alnico VIII Cast	Ceramic 10 (Ferrite)	RECo ₅ Grade 22/15	Crumax 3714 (NbFeB)
Maximum Energy Product (MGOe)	5.3	4.00	22	37
Thermal Expansion (°C × 10 ⁻⁶)	11.0	10	13 ⊥ to Orientation 6 to Orientation	-0.30 ⊥ to Orientation 6.8 to Orientation
Temperature Coefficient of B _r (%/°C)	-0.02	-0.20	-0.045	-0.110
Maximum Service Temp. (°C)	520	400	250	150

Table 3-1: Thermal Characteristics of Various Type I and Type II Permanent Magnets [6]

In general, type I magnets are more resistant to corrosion than type II magnets. Corrosion of the magnetic material tends to degrade the magnetic field over time. Alnico is very resistant to corrosion (almost as resistant as stainless steel). So little of the magnetization loss in Alnico comes from corrosion. SmCo and NdFeB magnetic material is very sensitive to corrosion. High temperatures also exacerbate this susceptibility to corrosion. This is the cause of the low maximum operating temperatures for these materials shown in Table 3-1. These materials can be protected from corrosion by the application of a nickel coating. The nickel bonds well to both materials and protects them from oxidation.

3.2 Sensor Design

3.2.1 Sensor Configuration

For the sensors to operate properly, the path of the magnetic circuit described in Section 3.1.1 must pass through the coil of the sensor. The coil will register the change in circuit magnetic flux with a voltage output. There are two methods of insuring this flux path. One method is to wind the coil around a cylindrical magnet that is polarized axially (core-driven). The other is to place a magnet behind the coil and utilize a highly permeable material as a pole piece around which the coil is wound (pole-driven). Both configurations are shown in Figure 3-2.

Figure 3-2: Cylindrical Tilt Sensor Cross-section of Core and Pole Magnet Driven Configurations Showing Various Constituent Materials

The core-driven configuration has some advantages and disadvantages. There is a very good coupling between the magnetic field and the coil since all of the flux is forced to pass through the coil. This means that the change in flux will be optimally sensed by the coil and very little will leak back through. Since the coil and the magnet are parallel to rather than inline with one another, the total length of the sensor will be smaller. This means there will be a greater use of the limited space provided for the sensors.

However, for the magnet to generate a lot of magnetic flux, it needs to have a substantial area. This will lead to a larger core diameter. This may seem beneficial with reference to Equation 3-12 but it does lead to problems. While a larger core diameter means a larger peak voltage, the signal pulse width also becomes large. This presents difficulties in signal processing that will be discussed in Section 3.4. Consequently, the magnet will have to be made longer to compensate for the cross-sectional area constraints. This will increase the overall reluctance of the return path of the magnetic circuit unless a high permeability magnet is used. However, if a high permeability magnet is used, there will be more flux leakage (see Section 3.1.3.1).

The pole-driven configuration also has some advantages and disadvantages. The pole piece can be shaped in a way to provide flux focusing through the core of the coil. A larger diameter magnet can then be used to generate the flux while still maintaining a small diameter core. Also, the magnet can be made short to offset the disadvantage of the inline arrangement since the cross-sectional area of the magnet has less stringent size limitations. This arrangement will not have as good a magnetic coupling as the core-

driven configuration since the pole piece cannot focus the magnetic flux perfectly. This will lead to more leakage flux not passing through the coil core. To compensate for this, a low permeability (type II) magnet will have to be used. This will reduce the amount of leakage between the poles of the magnet and allow more useable flux at the poles. The small length of the magnet will counteract the increase in the total return path reluctance due to the low permeability of the magnet.

3.2.2 Wire Selection

3.2.2.1 Gauge (*thickness*)

The selection of wire gauge for the windings is influenced by a number of factors. The number of windings that fit within a certain coil cross-sectional area depends directly on the gauge of the wire. The smaller the diameter of the wire, the more windings fit on the sensor. The more windings, the higher signal output of the sensor has. However, the smaller the diameter of the wire, the higher the resistance distributed throughout the windings. Therefore, there is a practical lower limit to the diameter of the wire imposed by desirability of a low resistance. Also, the strength of the wire decreases with a decrease in wire diameter. This has an impact on ease of manufacture and on the resistance of the sensor to thermal expansion stresses. Looking at other similar spacecraft applications, a gauge number of 32 (0.0085 inches in diameter) was selected for the original prototypes. This was later changed to 34 (0.0065 inches in diameter) for later testing iterations.

3.2.2.2 Material

The material selection was based on a number of factors. The windings of the sensor are of very small diameter. Therefore, a wire material would have to be ductile enough to be able to bend around this small diameter without affecting the strength of the wire. Also, as was mentioned in Section 3.2.2.1, the resistance of the wire affects the signal output. Therefore, a material with a high electrical conductivity should be selected. This will also help with reduce the thermal stresses since less heat will be generated by the low resistance wire. The insulation around the wire will have to protect against short circuits in the winding as well as be thin enough to allow room for more windings. For these reasons, a copper conductor with epoxy insulation was selected. This type of wire is used extensively in inductive coils in electrical motors and generators.

3.2.3 Number of Windings

The number of windings has a direct impact on the signal output by the sensor. More windings give a stronger signal but the relation between the number of windings to the output voltage is not linear. As was mentioned in Section 3.2.2.2, there are diminishing returns to increasing the number of windings since the sensor resistance increases faster. However, if the impedance of the circuitry taking the voltage across the sensor coil is high, this effect will be minimized since little current will flow through the coil. It is consequently beneficial to try to have as high a number of windings as possible.

There are some factors that place an upper limit on the number of windings. The first is the constraint of physical space. There is not much room for the sensor to fit

between the rotor and the MMS case (see Figure A-5), thus the number of windings is limited by the space allowed for the tilt sensor. The volume allows a cylindrical sensor of about 12mm ($\frac{1}{2}$ inch) diameter to be about a total of 25mm (1 inch) long. This includes the magnet, mounting mechanism and the coil elements. The second constraint is the return path for the magnetic flux should not return back through the sensor coil. The larger the coil diameter, the more this will occur and the adding of more windings will have less effect.

3.3 Pattern Analysis

3.3.1 Equation for Pattern Edges

The equation for the pattern edges is most readily expressed in terms of spherical co-ordinates. The variables used for the expression are defined in Figure 3-3. The rotor pattern area is simply a portion of a complete spherical surface.

Figure 3-3: Layout of Rotor Coordinates and Dimensions for Mathematical Definition of Pattern Edges

For ease of conversion of sensor voltage output to angular output, a linear correlation between the two is desired. In order for this to happen, the pattern edges must be defined such that there is a linear relationship between the θ axis and the ψ axis. This is easily defined in mathematical form as:

$$\psi = m \cdot \theta + \psi_0$$

where m = slope of pattern diagonal $\left(\frac{d\psi}{d\theta} \right)$

$$\psi = \text{Latitude Angle} \quad [3-13]$$

$$\theta = \text{Longitude Angle}$$

$$\psi_0 = \text{Latitude Angle at } \theta = 0^\circ$$

This is represented as a straight line on an equidistant cylindrical projection. A line of constant latitude and two diagonals that are defined by the equation above will define the pattern edges.

3.3.2 Equation for Pattern Machining

For manufacturing purposes, the form of this equation is suitable for a milling machine that has two axes of rotation (the θ axis and the ψ axis). While this equipment does exist, it is not common. It would be useful, therefore, to convert this equation a form that can be programmed into a typical 3-axis (x-y-z translation) CNC milling machine

To accomplish this conversion, an expression will have to be derived which gives the projection of any point defined by R , θ and ψ onto a y-z plane that is perpendicular to the rotor radius, tangent to the rotor equator and point $(y,z) = (0,0)$ on the projection plane corresponds to point $(\theta, \psi) = (0,0)$ on the rotor surface.

The basic equations defining the edge equation and the relations of spherical to Cartesian co-ordinates are:

$$y = R \cdot \cos(\psi) \cdot \sin(\theta)$$

$$z = R \cdot \sin(\psi)$$

[3-14]

$$\psi = m \cdot \theta$$

Figure 3-4: Edge View of Rotor (Normal View of Projection Plane) Showing Coordinates and Pattern Placement

The general expression for the projection of these equations on to the plane can be found by simple substitution.

$$\theta = \frac{\psi}{m}$$

$$\psi = \sin^{-1}\left(\frac{z}{R}\right)$$

[3-15]

Substitute expressions for ψ and θ into that for y :

$$y = R \cdot \sin\left(\frac{\sin^{-1}\left(\frac{z}{R}\right)}{m}\right) \cdot \cos\left(\sin^{-1}\left(\frac{z}{R}\right)\right) \quad [3-16]$$

$$y = R \cdot \sin\left(\frac{\sin^{-1}\left(\frac{z}{R}\right)}{m}\right) \cdot \sqrt{1 - \left(\frac{z}{R}\right)^2} \quad [3-17]$$

The resulting general equation is not simple however. If $m=1$, the equation simplifies to:

$$y = z \cdot \sqrt{1 - \left(\frac{z}{R}\right)^2} \quad [3-18]$$

In the above derivation, the ψ intercept, ψ_o , is omitted. This can be done since this basic equation can be used in situation where the pattern vertex does not occur at the equator (i.e. $\psi_o \neq 0$). This is achieved by using a distinct machining plane for each edge. These planes will be defined as above and the origin of each plane will be tangent to the rotor at the intersection of the edge and the equator. This allows the creation of trapezoidal patterns stretching from the equator to the edge of the rotor. For this reason, the edge labeled Edge 2 in Figure 3-4 is dashed since it may not start right next to Edge 1.

This equation can be applied to many different patterns that are allowed to vary in pattern number and range. The given value of $m=1$ corresponds to 6 symmetric patterns spanning 30° of the rotor. This slope could also be used for 8 patterns spanning 22.5° .

z (inch)	y position of Edge 1 (inch)	y position of Edge 2 (inch) (see Note 2)
0.000	Note 1	Note 1
0.100	0.09993	-0.09993
0.200	0.19947	-0.19947
0.300	0.29812	-0.29812
0.400	0.39572	-0.39572
0.500	0.49162	-0.49162
0.600	0.58546	-0.58546
0.700	0.67681	-0.67681
0.800	0.76521	-0.76521
0.900	0.85016	-0.85016
0.9845	0.91888	-0.91888

Table 3-2: Tabulation of points for both edges of pattern generated using latest design dimensions: L=25.0 mm (0.9845 inch), R=69.660 mm (2.7425 inch), m=1 and N = 8

Figure 3-5: Portion of Top View of Rotor Showing Edge Undercut as Edge is Milled Farther Away from Pattern Centre-line

Pattern Machining Notes:

- 1 Point at $y = 0$ can be a fillet with radius equal to the smallest end mill practical
- 2 Edge 2 will be machined in a reference frame 2° from that of Edge 1.
- 3 Pattern is symmetrical across mid-line ($x = 0$)
- 4 The smallest common ball end mill is $1/32''$ diameter. This would put a 0.397 mm ($1/64$ inch) radius fillet at the bottom of the edge. In order to avoid a gradual change of pattern depth near the edge, the pattern should be cut deeper than one tool radius (see Section 2.2.4.2 - Pattern Sharpness). Therefore, the depth of the pattern was chosen to be a constant depth of 1.27 mm (0.050 inch) (measurement of depth is in radial direction). The CAM software can control the cut in the x direction.
- 5 This equation defines the edge of the pattern projected onto a plane that is tangent to the equator and normal to the machine tool shaft.

- 6 This is the equation for the edge, not the tool path. The tool path would be dependent on the radius of the ball end milling tool used. Typically, code generators used on NC milling machines do this conversion automatically (i.e. by generating the tool path by offsetting the line by the tool radius in the direction transverse to the desired edge). It is customary to do this using CAM software rather than mathematically.
- 7 Since the tool bit is not cutting into the rotor in the radial direction, there will be a slight undercut of the edge as the tool moves away from the pattern centre. This will improve the pattern sharpness and consequently, the sensor output (See Figure 3-5).

3.3.3 Maximum Number of Patterns

The rotor has a number of symmetric patterns each having an angular width defined by the expression:

$$\theta = \frac{360^\circ}{2N} \quad [3-19]$$

This leads to the total pattern range, ψ_p :

$$\psi_p = m \cdot \frac{360^\circ}{2N} \quad [3-20]$$

where N = number of patterns

This equation sets the ψ_p for a given N patterns with edge slope m .

Conversely,

$$N = \frac{180^\circ}{\psi_p} \cdot m \quad [3-21]$$

sets the allowable N for a given ψ_p and m.

Therefore, for $\psi_p = 20^\circ$ and $m = 1$, there can be a maximum of 9 patterns around the perimeter of the rotor.

3.3.4 Equation for Pattern Slope (m)

The basic equation in spherical coordinates is:

$$\psi = m \cdot \theta + \psi_o \quad [3-22]$$

For a pattern that spans from the equator to the edge:

$$\psi = \psi_p = \sin^{-1}\left(\frac{L}{R}\right) \quad [3-23]$$

If N is the number of patterns to be milled around the circumference then:

$$\theta = \frac{360^\circ}{2 \cdot N} \quad [3-24]$$

This is valid for a symmetric pattern (not a saw-tooth shape).

Therefore, the equation to find the slope m that will ensure that the N patterns fit perfectly around the circumference is:

$$m = \frac{2 \cdot N}{360^\circ} \sin^{-1} \left(\frac{L}{R} \right) \quad [3-25]$$

The operation " $\sin^{-1}(\text{ratio})$ " must give an answer in degrees (not radians) for m to be a dimensionless slope.

3.3.5 Local Pattern Surface Angle (ϕ)

Figure 3-6: Differential Surface Area Element on Spherical Rotor Surface Showing Portion of Pattern Edge

Taking the equation for the diagonal:

$$\psi = m \cdot \theta + \psi_o \quad [3-26]$$

and differentiating with respect to θ , we get:

$$\frac{d\psi}{d\theta} = m \quad [3-27]$$

Using the dimensions and variables outlined in Figure 3-6:

$$\tan \phi = \frac{dn}{de} \quad [3-28]$$

$$dn = R d\psi \quad [3-29]$$

$$de = R \cos(\psi) d\theta \quad [3-30]$$

Therefore,

$$\begin{aligned} \tan \phi &= \frac{1}{\cos(\psi)} \frac{d\psi}{d\theta} \\ &= \frac{m}{\cos(\psi)} \end{aligned} \quad [3-31]$$

As $\psi \rightarrow 90^\circ$, $\phi \rightarrow 90^\circ$.

At the equator ϕ relates to m using the relation:

$$\phi = \tan^{-1}(m) = \phi_E \quad [3-32]$$

Normally a value of ϕ will be chosen for a desired sensitivity while allowing enough patterns for the desired sensor bandwidth (see Section 2.1.1.3). Assuming the pattern will start from one of the ends of the rotor, a useful reference point would be mid-pattern tilt angle. The relevant ψ to substitute into Equation 3-31 to get ϕ_m will be governed by the ratio of L to R :

$$\psi = \sin^{-1}\left(\frac{L}{R}\right) - \frac{\psi_p}{2} = \psi \text{ at mid - pattern} \quad [3-33]$$

3.4 Signal Analysis

3.4.1 Pulse to Angle Conversion

As is described in Equation 2-1, the time between up-going pulses (or between down-going pulses) and the time between up and down-going pulses (or between down and up-going pulses) needs to be found in order to find the tilt angle. The simplest method of getting this information is with a counter running at a specific frequency and its output controlled by the sensor signal. To facilitate the extraction of this information, the signal can be processed into a square wave that has sharp edges at the time reference points of interest. This square wave would rise on the rising edge of the signal up-going pulse, fall on the falling edge of the down-going pulse and then rise again on the rising edge of the subsequent up-going pulse. This is illustrated in Figure 3-7.

Figure 3-7: Conversion of Single Sensor Signal to Square Wave Used to Obtain Timing Information

The signal is converted in this way by a simple electronic circuit. First, the signal is sent through two comparators. This circuit element inputs a signal and a threshold voltage and outputs a reference voltage when the threshold is exceeded. This can also be done for negative voltages by reversing the inputs to the comparator and the comparator outputs a reference voltage when the signal drops below a negative threshold voltage. The signals from a positive and negative comparator are fed into a flip-flop. This circuit element inputs two signals. When the first signal is at the reference voltage the flop-flop switches its output to its reference voltage. When the second input is at the reference voltage, the flip-flop switches to output to zero. The condition where both flip-flop inputs are at the reference voltage is not an issue since this case cannot occur. The output of the flip-flop will be the square wave shown in Figure 3-7.

Figure 3-8: Layout of Circuit to Convert Single Tilt Sensor Raw Signal into Duty Cycle Square Wave

3.4.1.1 Threshold Detection

It will be shown (see Figure 4-8), the pulse that comes from the sensor has a finite width. This presents the problem of when to take the time to calculate the various times to substitute into Equation 3-35 to get the difference ratio. In order to make the threshold time least sensitive to variation in sensor signal peak voltage, the threshold should be set at a level of signal at which the slope is the maximum. Examination of the actual sensor output indicates that the maximum slope occurs at 50 to 60% of peak voltage.

Setting the threshold at the level of maximum slope also has a benefit to the electronic conversion. The comparators used in the conversion circuit have a finite response time. If the signal rises slower than the comparator can respond, the comparator output will not make a clean transition from zero voltage to the reference voltage. Therefore, to ensure a clean square wave output by the flip-flop, the signal slope must be steep enough so that the comparator is triggered consistently.

3.4.1.2 Duty cycle

With reference to Figure 3-7, the times in Equation 2-1 can easily be extracted from the processed square wave. The time between consecutive up-going pulses (or down-going pulses) is simply the period of the square wave signal. Also, the pulse width of the square wave corresponds to the time between up and down-going pulses. The ratio between these numbers is the duty cycle of the square wave and can be expressed mathematically as:

$$DC = \frac{t_A}{t_{AB}} \quad [3-34]$$

where t_A and t_{AB} are defined in Equation 2-1.

The duty cycle will be greater than 0 but less than 1 with the extreme values corresponding to the extreme tilt angles.

3.4.1.3 Difference Ratio

As was mentioned in previous sections, subtracting the output of opposing sensors eliminates many errors. If one of the two duty cycles is subtracted from the other, the resultant is a value that can be called the Difference Ratio or DR. This value is expressed mathematically as:

$$\begin{aligned} DR &= \left(\frac{\text{Pulse Width}}{\text{Period}} \right)_{\text{Sensor 1}} - \left(\frac{\text{Pulse Width}}{\text{Period}} \right)_{\text{Sensor 2}} \\ &= \left(\frac{t_A}{t_{AB}} \right)_{\text{Sensor 1}} - \left(\frac{t_A}{t_{AB}} \right)_{\text{Sensor 2}} \end{aligned} \quad [3-35]$$

The difference ratio is greater than -1 but less than 1 . When the DR is zero, both sensors are reading the same tilt and the rotor is at a zero tilt angle. In this way, the DR automatically finds the null position.

3.4.1.4 Signal Calibration

With the pattern defined in Section 3.3, the relationship between the tilt and the DR should be linear. In which case, the calibration of the sensor should be straightforward. The rotor can be set at various angles and the resulting DR values can be

tabulated. A linear fit can be applied to the tabulated data to get a calibration curve. If need be, a quadratic or a cubic fit can be applied to account for mild non-linearity that may occur as the rotor tilts away from the null position.

However, to set the angles in the calibration procedure, an independent angle measurement must be employed. This independent measurement must be very accurate in order to get an accurate calibration. Tilt angle measurement of a spinning rotor is difficult to achieve and even more difficult when the rotor is gimballed. For direct measurement of a tilting rotor, an autocollimator can be used over a small tilt range to get a very accurate tilt reading. An autocollimator is a telescope that looks at a mirrored surface on the spinning rotor. Through the telescope one can see a reflection of a target on the end of the telescope and compare the reflection with the actual target to obtain a very accurate angular measurement. An alternative arrangement that makes angle measurement simpler is to spin the rotor on a fixed gimbal and then tilt the sensors around the rotor on a non-spinning platform that is aligned with the centre of tilt of the rotor. In this way, the tilt of the platform can be measured with an inclinometer accurately over the full range of tilt motion. See Sections 4.5.3 and 4.5.4 for examples of this type of calibration procedure.

3.5 Error

3.5.1 Cross Dependencies due to Sensor Position

In order for many rotation dependent effects involving the sensors along the rotation axis to be cancelled out (in theory), the line joining the two points on the surface of the rotor where the sensor pair track (sensor line) must intersect the gimbal centre of

tilt and be perpendicular to the rotor shaft spin axis. There are several modes that the misalignment can take that differ from this ideal. Figure 3-9 illustrates these different modes. The sensor tracks in this figure are showing the paths of the sensors when the frame of reference is the tilting rotor.

Figure 3-9: End View of Gimbal Tilt Axis Showing Locus of Tilt Axis End-points of Various Misalignment Modes as Rotor Tilts

3.5.1.1 Offset Misalignment

The first and least dominant of these is offset misalignment. This mode consists of the sensor line being perpendicular to the rotor shaft spin axis but offset from the centre of gimbal tilt. Two sensor points overlapping at point A on Figure 3-9 represent this misalignment. This offset can be introduced intentionally in the design in order to take advantage of the space that is available. The sensors can be brought closer to the rotation axis because the rotor is curved and consequently decrease the overall diameter of the MMS footprint. Due to this offset, the distance from the sensor tip to the surface of the

rotor will vary slightly with a change in tilt due to the flexure rotation centre displacement. This will cause the magnitude of the peaks of the sensor signal output to vary with angle around the axis not directly measured by the sensors. This effect will cancel out since it will affect equally both sensors in a tilt pair. If the offset causes the sensor line not to intersect the shaft spin axis (as would be represented on Figure 3-9 by two sensor points at point D), the result will be a decrease of the calibration factor. This will be a loss in the sensitivity of the sensor pair but will be calibrated out and does not represent a cross dependency. However, while this misalignment does not cause a dominant cross dependency, it does affect the misalignments that follow.

3.5.1.2 Tilt Misalignment

Tilt misalignment is produced when the sensor line is rotated by some angle around the gimbal axis of rotation orthogonal to the axis that is parallel to the sensor line. However, when both an offset and tilt misalignment are present, the tilt misalignment introduces a parabolic cross dependency. The condition where an arbitrary offset misalignment is combined with a tilt misalignment is represented in Figure 3-9 by the two sensor points located at points A and B. An example of this effect is illustrated in Figure A-2 in Appendix A. There is an initial value at a tilt equal to zero on this graph. This effect is simply due to the fact that a tilt misalignment represents an initial tilt. Therefore, the zero latitude, which is normally represented by a zero difference ratio, needs to be set to a non-zero difference ratio in the calibration. This does not effect the illustrative nature of this example.

3.5.1.3 Phase Misalignment

Phase misalignment is produced when the sensor line is rotated by some angle about the rotor shaft spin axis. When combined with offset misalignment, it produces a roughly linear cross dependency. The condition where the offset misalignment at point A is combined with a phase misalignment is represented in Figure 3-9 by the two sensor points located at points C and D. An example of this effect is illustrated in Figure A-1 in Appendix A.

A combination of tilt, phase and offset misalignments is shown in Figure A-3 in Appendix A.

3.5.2 Error due to Sensor Mounting

3.5.2.1 Repeatability

The positioning of the sensors after removing and replacing them in the MMS case should not change significantly. As can be seen in Section 3.5.1, the output of the sensors is sensitive to misalignments relative to one another and relative to the gimbal pivot centre. For this reason, it is best to mount the sensors in some precisely machined fixture. This fixture should be easily removable without disturbing the relative position of the sensors. One should also be able to replace the fixture so that the sensors are properly indexed and centred.

3.5.2.2 *Stiffness*

Since the MMS is a rotating system, there will be vibration forces present that will cause perturbances in the sensors. The periodic forces may lead to instantaneous misalignments as described in Section 3.5.1. Also, relative motion between the sensors and the ferromagnetic surface of the rotor will cause voltage output (this is the effect of which the sensor is taking advantage). Therefore, stiffness in the sensor mounting and the sensor itself is very important. Flexing can be avoided by using stiff materials and structures where possible. The structures of the sensor should not contain long cantilevered beams or elements with small cross-sectional areas.

3.5.3 Noise

3.5.3.1 *Electromagnetic (EM)*

Since the sensors are basically inductive coils, they will likely work quite well as antennae to pick up EM radiation. Some shielding can be provided through the use of a mu-metal case for the MMS but it will be difficult to completely isolate the sensors from external EM fields and still have them sense the changing magnetic flux in order read the tilt of the rotor. Fortunately, the sensors have a low inductance and capacitance and this results in a very high resonant frequency of the sensors. Therefore, the EM signal detected will be at a much higher frequency than that of the patterns passing by the sensor. Consequently, the EM noise in the signal can be readily removed by using a low pass filter.

3.5.3.2 *Vibrational*

Vibrational noise should not pose a severe problem. There are two modes of vibration that are of importance: axial and lateral vibration. Axial vibration results from oscillating forces in the axial direction of the rotor. As was mentioned in Section 2.2.4.4, using two sensors to measure tilt around each axis compensates for axial displacement. In this way, the tilt sensor will remain insensitive to axial vibration. Transverse vibration results from forces in the axes perpendicular to the spin axis. If this type of motion was permitted, it could affect the tilt sensor accuracy since the displacement of the rotor relative to each sensor is not in the same direction. In addition, displacement in this direction of a spinning rotor would set up further imbalances that would have unusual dynamic effects. It is fortunate that, as described in Section 1.3.2, the stiffness of the flexures in the transverse direction is very high. Therefore, any resonance that occurs in this mode will be high frequency and can be easily filtered out in the same manner as the EM noise described in Section 3.5.3.1.

Since the rotor is to be statically and dynamically balanced, neither axial nor transverse vibration should translate into dynamic torque vibration around the gimbal axes. The more out of balance the rotor is, the more that these vibrations will be a problem for the tilt sensors and the rotor tilt control system in general.

3.5.4 Other Error Sources

3.5.4.1 *Pattern End Effects*

When the tilt of the rotor reaches either extreme, the tilt sensor will begin to encounter influences that will create non-linearities in the tilt angle to DR relation. The first of these effects is due to the proximity of the two edges to one another. As was mentioned in Section 3.4.1.1, the signal pulses coming from the tilt sensor have a finite width. When the pulses from the two edges are too close together, they begin to interfere with one another. At one extreme, the tail of the down-going pulse decreases the magnitude and shifts the phase of the up-going pulse. At the other extreme, the up-going pulse decreases the magnitude and shifts the phase of the down-going pulse. These effects translate into deviations from the linear relationship between tilt and DR.

The second of these end effects is the fact that the characteristics of the magnetic circuit change due to the proximity of a region with no pattern at one extreme and a region off the rotor at the other. Both of these effects will change the magnitude of the sensor signal so that the electronics may not trigger cleanly as described in Section 3.4.1.1.

3.5.4.2 *Rotation Speed Variation*

The dynamics of the rotor dictate that as the tilt departs from null, there will be an oscillation of the rotation speed that is twice the frequency of the rotation speed. This variation will affect the tilt reading since the speed of the rotor changes as the sensor passes through the pattern. This effect will become more pronounced with fewer patterns.

It will not affect the rotation average of the tilt angle provided an even number of patterns are used. A notch filter tuned to this frequency can be employed but it would have to be digitally implemented since this frequency will vary during normal operation of the MMS since the spin speed is expected to vary from the tuned condition. This only presents a problem if the control system requires the tilt reading frequency to be higher than the rotor spin frequency.

3.5.4.3 *Pattern Symmetry*

The pattern symmetry will have an impact on the accuracy of the tilt sensor system. In theory, if one edge of the pattern is machined with a different magnitude of slope than the other, the system will still work. There will still be a linear relationship between the tilt and the times between pattern edges. However, the sensor will likely be sensitive to the angle between the path of the sensor and the edge. If this angle is 90° , the sensor will pass by the edge as fast as a point on the rotor's circumference can travel through the distance of one core diameter. When the edge is inclined away from this point, the angular distance over which the edge is under the sensor core increases. While a 90° angle with the edge will give the sharpest signal pulse, there will be no dependence of edge times to tilt angle. Therefore, a compromise must be made that will sacrifice some pulse sharpness for a strong dependency of edge times to tilt. However, in order to avoid non-linearities from being introduced by the edge angle effect, a symmetric pattern will be used. In this way the up-going pulse of the signal will be affected in exactly the same way as the down-going pulse and the effects will cancel.

All of these errors will combine to limit the accuracy of the tilt sensor. The only way to determine these limitations is to physically test a prototype. This is the focus of the following chapter.

3.5.4.4 Correlation

A measure of the correlation of the data with the fit function is a useful number to have. The R-squared value of the curve fit is displayed on the final calibration data. This value represents the change in the y-axis value due to a change in the x-axis value. A R-squared value of 0.9999993 represents a fit that is accurate to within ± 15 arcseconds.

4. Testing Iterations and Results

4.1 Proof of Concept Prototype – Carleton University - Electromagnet Excitation

4.1.1 Overview

The goal of this series of tests was to indicate whether or not the inductive method of pattern sensing would yield a useable signal. This was done with a rudimentary test rotor and different pattern types.

4.1.2 Apparatus

4.1.2.1 Test Rotor Description

The simple test rotor consisted of a 152 mm (6 inch) diameter ferromagnetic steel cylinder mounted on a 38 mm (1-½ inch) hollow shaft. The cylinder was machined after it was mounted on the shaft in order to ensure concentricity. The pattern on the rotor was first applied by masking off the pattern area and painting on various patterns using “nickel print” (a conductive nickel based paint used on printed circuit boards).

There are several fundamental differences between the proof of concept test rotor and the actual MMS rotor. The primary difference is that the test rotor will have straight sides. The MMS rotor has a spherical shape in order to ensure an even gap length with changing rotor tilt. The cylindrical shape of the test rotor was used in order to facilitate manufacturing of the test rotor. Since there were not gimbals in the test rotor, it did not

need to be spherical shaped in order to prove the sensing concept. Secondly, the test rotor was made of a solid cylindrical block of steel. It has mass and magnetic properties that are very different from the MMS rotor. The actual MMS rotor will be a spherical shaped shell in order to maximize the rotational inertia while minimizing the rotor mass. This means that the test rotor will have very different vibrational properties from the MMS rotor. A schematic of the proof of concept test rotor is shown in Figure 4-1.

Figure 4-1: Schematic of Proof of Concept Test Rotor

4.1.2.2 Sensor description

The excitation magnetic field could be supplied by two sources: a permanent magnet or an electromagnet. A large electromagnetic sensor 88.9 mm (3 ½ inch) long and 25.4 mm (1 inch) in diameter was produced out of ferromagnetic steel. This sensor had a core diameter of 6.35 mm (¼ inch) and it contained 600 windings for magnetic field production and 600 windings for magnetic flux reading.

4.1.3 Method

The method of sensor testing was to replace the lathe tool with magnetic tilt sensor and use cutting tool controls (accurate to ± 0.001 inch) to determine the following testing parameters:

- pulse magnitude with respect to:
 - radial gap distance
 - pattern angle
 - rotor speed
 - electromagnet current

4.1.4 Results

4.1.4.1 Pattern Modification

It was found that the nickel print did not provide enough change in flux to be detected. Therefore, instead of the painted-on pattern, a series of grooves 9.525mm (3/8 inch) wide and 0.508 mm (0.020 inch) deep were cut longitudinally into the cylindrical test rotor to provide the change in flux necessary for sensor excitation.

4.1.4.2 Tilt Sensor Modification

It was found that the electromagnet (combined with the improved pattern) could produce a field strong enough to provide a signal as the patterns passed by the tip of the sensor with a 5 VDC excitation voltage. However, the signal was not strong (only 125 mV peak to peak) and was extremely unsymmetrical. Additionally, the signal had a very high pulse width and a virtually non-existent negative pulse (see Figure 4-2). These signal characteristics were likely generated by the fact that the changing magnetic flux would establish a back EMF in the source voltage circuit that is powering the excitation electromagnet. This back EMF would cause a fluctuation in the source current that essentially causes a feedback loop that interferes with the establishment of a steady electromagnetic magnetic source. The effect is that an unacceptable signal results.

Another factor in the degradation of the signal was likely the size of the sensor itself. The sensor was quite large. It has a large core and a large pole piece that would have had the effect of damping the signal and giving the widely spread pulses that were observed.

A brief attempt at decreasing the size of the coil, eliminating the ferrous core and changing the orientation of the sensor so that the coil normal was tangent to the surface of the test rotor (rather than pointing in the radial direction) produced no measurable signal at all.

These results indicated that a magnetic field established by an electromagnet was likely not the route to follow and also that a tangent orientation of the coil produced unacceptable results. Since there was no clear signal from the sensor, none of the testing parameters could be evaluated.

Figure 4-2: Sensor Output from Electromagnetic Excitation Testing at 1200 RPM

4.2 Second Iteration – Carleton University - Ferrite Magnet Pole-driven Sensor

4.2.1 Overview

The goal of this series of tests was to evaluate the effectiveness of a permanent magnet to drive the sensor. Also, both the rotor that was used in the last iteration and a rotor that was milled with 12 patterns as defined in Equation 3-17.

4.2.2 Apparatus

This testing iteration began with the use of the cylindrical rotor that was utilized in the first test iteration. The rotor was spun in a lathe as in the first iteration. A spherical rotor was machined at Carleton University at the Science Technology Centre. This was used in the testing once it was available. The spherical rotor had machined into it 12 patterns as defined in Equation 3-17. The patterns spanned from the equator to the edge of the rotor and the pattern edges intersected at the equator and at the edge of the rotor.

The sensor used was a ferrite ceramic magnet, pole-driven sensor. The coil was 12.7 mm ($\frac{1}{2}$ inch) long and 12.7 mm ($\frac{1}{2}$ inch) in diameter. The core was 3.175 mm ($\frac{1}{8}$ inch) in diameter and contained 218 windings. The sensor signal was acquired with a Nicolet digital oscilloscope.

4.2.3 Method

The digital oscilloscope had the ability to store a binary file containing the data that was displayed on the screen. This binary file could then be post-processed to be

imported into a spreadsheet program for graphing. These graphs were examined to evaluate the effectiveness of the permanent magnet driven configuration over the electromagnet driven configuration. Also, the effect of speed variation on the output signal was confirmed by taking data at two speeds. The speeds chosen were 760 RPM and 1200 RPM. Since the rotor was spun in a metal lathe, the maximum speed (1200 RPM) of the lathe governed the maximum speed of the tests.

4.2.4 Results

The results of these tests can be seen in Figure 4-3 through Figure 4-5.

The signal from the ferrite driven sensor is significantly clearer than that from the electromagnet driven sensor. This is the case even though the number of windings on the coil was less and the ferrite magnet is not a particularly strong magnet. This means that the permanent magnet excitation is the best method for the tilt sensor.

The effect of speed variation can be seen by comparing Figure 4-3 and Figure 4-5. The ratio between the two rotor speeds almost exactly matches the ratio between the two peak voltages. This confirms the direct relationship between speed and sensor output voltage predicted by Equation 3-12.

An unexpected result occurred due to the fact that the rotor was extremely difficult to align with the lathe spin axis. This meant that there was always some transverse wobble associated with the rotor as it spun. This wobble is seen clearly in Figure 4-4 as a modulation of the signal voltage peaks with the modulation frequency

equal to the spin frequency. The eccentricity required to cause this amount of variation was measured and was found to be ± 0.127 mm (± 0.005 inch).

Figure 4-3: Sensor Output from Second Iteration Testing at 1200 RPM

Figure 4-4: Sensor Output from Second Iteration Testing Showing Effect of ± 0.005 Inch Lathe Imbalance

Figure 4-5: Sensor Output from Second Iteration Testing at 760 RPM

4.3 *Third Iteration - Bristol - November 1997*

4.3.1 Overview

The goal of this series of tests was to further refine the permanent magnet driven sensor. Many different sensors with the same physical dimensions but with different winding counts and driving magnets were tested. Also, a sensor using the core-driven configuration defined in Section 3.2.1 was tested. The effects of various sensor parameters on the signal shape were examined.

4.3.2 Apparatus

This iteration was not performed using a metal lathe as a base for the rotor. A Tilt Ring Apparatus was used to mount the sensors so that they could tilt freely around the spinning rotor. The rotor was spun using the electric motor that is used in the actual MMS system. The rotor used was the STC-Carleton spherical rotor that was used in the second testing iteration. Figure 4-6 shows a schematic of the tilt ring apparatus. This figure shows the rotor that was used in the fourth and fifth testing iteration. An HP digital oscilloscope was used in this iteration. This scope had the ability to output the signal data shown on the screen in a number of different formats that could be imported directly into a spreadsheet program.

Figure 4-6: Drawing of the Tilt Ring Test Apparatus

Several different sensors were tested. All of the sensor coils were 6.35 mm ($\frac{1}{4}$ inch) long and 12.7 mm ($\frac{1}{2}$ inch) in diameter. One of the sensor cores was 6.35 mm ($\frac{1}{4}$ inch) in diameter and housed a 6.35 mm ($\frac{1}{4}$ inch) diameter ferrite magnet that ran through the core. This sensor core contained 832 windings. A second sensor was tested that had a 3.175 mm ($\frac{1}{8}$ inch) core diameter. This sensor core contained 1180 windings. A third sensor was tested that had a 1.397 mm (0.055 inch) core diameter. The same number of windings were placed on this sensor (1180 turns) in order to easily compare the different configurations. Both the second and the third sensor were driven by a 3.175 mm ($\frac{1}{8}$ inch) thick, 12.7 mm ($\frac{1}{2}$ inch) in diameter cylindrical ferrite magnet and by a $6.35 \times 25.4 \times 25.4$ mm ($\frac{1}{4} \times 1 \times 1$ inch) square rare-earth magnet. A fourth sensor configuration was tested that had 1600 windings. Other than the winding count, this sensor was identical to the third sensor listed and was driven by the rare-earth magnet.

4.3.3 Method

The signal was taken for all of the sensor configurations mentioned in Section 4.3.2. The signal was normalized with respect to peak voltage. The slope of each signal was also calculated and graphed as a function of time. The effect of sensor configuration was examined by comparing the output from the Ferrite Ceramic Core-driven Sensor with that from the Ferrite Ceramic Pole-driven Sensor. The effect of core size on slope and peak output was examined by comparing the output from the Ferrite Ceramic Pole-driven Sensor with that from the Ferrite Ceramic Pole-driven Sensor with the smaller core diameter. The effect of the magnet strength on the slope and peak output was examined by comparing the output from the Ferrite Ceramic Pole-driven (Small Core) Sensor to that from the Rare-Earth Pole-driven (Small Core) Sensor. Also, the effect of speed on slope was examined by comparing the signal from the Rare-Earth Pole-driven (Small Core) Sensor at speeds ranging from 750 to 5000 RPM.

4.3.4 Results

The results of the third testing iteration can be seen in Figure 4-7 through Figure 4-12.

4.3.4.1 Core Configuration

While there was a slight difference in the number of windings between the two sensors compared, there was a larger percentage difference in the slope and the peak voltage. The pole-driven configuration was shown to have far superior performance. The amount of magnetic material in the core is limited by the core diameter.

4.3.4.2 Core Diameter

The two sensors compared were identical except for the core diameter. The larger core diameter was 2.4 times larger than the smaller core diameter. This led to the 2.3 times larger peak signal observed for the larger diameter core. This effect is predicted in Equation 3-12. However, the slope of the signal is only 1.4 times greater for the larger core. This indicates that the shape of the signal is changed with core diameter. The signal pulse width becomes narrower with respect to the pulse height with a decrease in core diameter. This can be observed by the fact that when the drop in peak voltage is compensated for by adding windings (as in Figure 4-11), the slope exceeds that of the larger diameter core. This is an important result since it will make the comparators trigger cleaner (see Section 3.4.1.1) and also it will reduce the end effect error due to pulse interference (see Section 3.5.4.1).

4.3.4.3 Driving Magnet

By examining Figure 4-8 and Figure 4-9, the effect of magnet strength can be observed. The stronger magnet amplifies the peak voltage. However, the maximum slope of the signal is virtually unaffected. This has a negative effect on the end effect error introduced by pulse interference, contrary to the decreasing of the core diameter mentioned above. This is likely due to the spread of the magnetic field introduced by the fact that the driving rare-earth magnet has a much larger cross-section than the sensor it is powering.

4.3.4.4 Rotor Speed

The effect of the rotor speed on the pulse slope is summarized in Figure 4-12. The slope increases exponentially with an increase in speed. This is a good trend that will counteract the growing pattern interference that will inevitably occur when the rotor speeds up. As the rotor speeds up, the pulses become closer together in time (increase in frequency) and will begin to bunch up. This trend in the slope will extend the maximum speed at which the sensor will operate accurately over a set tilt range.

Figure 4-7: Normalized Voltage and Slope vs. Time for 832 Winding Ferrite Core-driven Sensor

Figure 4-8: Normalized Voltage and Slope vs. Time for 1180 Winding Ferrite Pole-driven Sensor

Figure 4-9: Normalized Voltage and Slope vs. Time for 1180 Winding Rare Earth Pole-driven Sensor

Figure 4-10: Normalized Voltage and Slope vs. Time for 1180 Winding Rare Earth Pole-driven Small Core Sensor

Figure 4-11: Normalized Voltage and Slope vs. Time for 1600 Winding Rare Earth Pole-driven Small Core Sensor

Figure 4-12: Rotation Speed vs. Slope at 1/2 Peak for 1600 Winding Rare Earth Pole-driven Small Core Sensor

4.4 *Fourth Iteration – Bristol - March 1998 - Rare Earth Pole-driven Sensor*

4.4.1 Overview

The goal of this series of tests was to test a Rare-Earth Pole-driven Sensor with the actual rotor to be used in the MMS lab model.

4.4.2 Apparatus

The sensor used in this iteration was a NbFeB pole-driven sensor. Four sensors were manufactured and all of the coils were 15.24 mm (0.600 inch) long and 15.24 mm (0.600 inch) in diameter. Each coil contained 1225 windings. The electrical resistances of the four coils are 27.6, 28.9, 26.3 and 28.4 Ω . The tilt ring apparatus was used to tilt the sensors around the rotor. The rotor used was the real lab model MMS rotor. This rotor has 6 trapezoid patterns around the circumference. These patterns were erroneously manufactured off-centre by the sink-EDM method. The magnets used to create the tilt control torque were installed.

4.4.3 Method

The sensors were tilted around the rotor using the tilt ring apparatus. Only one sensor was tested at a time and the outputs were compared to see if they were consistent. This was done to prepare the sensors for the final calibration testing (see Section 4.5) by ensuring that the sensors were functioning properly and there were no shorts or breaks in

the coil windings. Also, the effect of the torque magnets on the signal output was examined.

4.4.4 Results

At a fixed tilt, the signals from the sensors were found to match quite well. However, when the tilt was varied, there was a very large dependency observed in the magnitudes of the up-going and down-going pulse on tilt angle. The dependency was such that the signal peak of the up-going pulse remained quite stable while the peak of the down-going pulse reduced to $\frac{1}{4}$ the size it was at one extreme. At first this effect was attributed to the slight offset in the rotor pattern causing a different pattern depth at one end of the tilt range than the other. However, when the driving magnet was reversed, the dependency also reversed. The down-going pulses were then stable while the up-going pulse varied with tilt. This indicated that there was interplay between the poles of the sensor driving magnet and the poles of the tilt torque magnet in the rotor. The sensor was then tested without any driving magnet and the sensor functioned properly. This indicated that the stray magnetic field of the rotor torque magnets was strong and could be used as a tilt sensor flux source. Examination of the 2D electromagnetic FEM simulation done by Infolytica Corporation confirmed the existence and uniformity of this stray flux. The illustration of the rotor magnet and the corresponding flux can be found in Figure 4-13.

Figure 4-13: Flux Plot Showing the Uniform Flux Leakage at Pattern Region (from Report Titled "Revised Analysis of Permanent Ring Device With Modified Hub: For Bristol Aerospace Ltd." by Infolytica Corporation)

4.5 Fifth Iteration – Bristol Aerospace - Ambient Rotor Magnetic Field Pole-driven Sensor

4.5.1 Overview

Several tests were performed to calibrate the current version of the magnetic tilt sensors. The calibration tests were performed on the same tilt table as the third iteration tests and also on a modified version of that tilt table to enable determination of the cross axis properties. A data acquisition counter card in an IBM Compatible computer driven by Labview software collected the tilt sensor readings. Calibration curves were fit to the resulting output to get first, second and third order calibration constants. These coefficients were used in an iterative calibration routine used to convert the output of the tilt sensors into an angle between the rotor normal and the shaft axis. This angle was decomposed into its components in the x-z and the y-z planes.

4.5.2 Data Acquisition (DAQ) Algorithm Design

4.5.2.1 Labview Data Acquisition Methods

The Labview DAQ application was used at Bristol to perform data acquisition and processing. Using Labview, the counters were read on a PC-TIO-10 counter card that uses an AM9513 Counter chip. For each tilt sensor there was one counter on this card set to output counts between consecutive rising edges (period) and another counter set to count between consecutive rising and falling edges (pulse width) of the square wave output from the sensor electronics. This was done for each tilt sensor resulting in eight

counter inputs. There were two techniques tested for reading the counter data from the registers: polling and interrupts.

4.5.2.1.1 Technique 1: Polling the Counter Card

The first method used was the polling method. This method simply consisted of reading the counters at a fixed sampling rate. The sampling rate was chosen to be faster than the expected pattern rate of 6 times the rotor rotation speed. This method of reading the counters was employed for the testing using the tilt ring apparatus.

This method of reading the counters was ineffective at reliably reading counts from consecutive patterns as the rotor spun around. The required polling rate was dependent on the speed of the rotor. Therefore, the sample rate would have to be changed for different rotor speeds. Also, if the sample speed was too fast, there was no way of determining if the counter value had been read twice for the same pattern. Alternatively, if the counter sample rate was set too low, there was no way of determining if the counter was missing patterns. Another problem with this technique was the tendency of the polling to freeze when the tilt was set past 4° away from null. This made it difficult to take counter readings over the intended full range of $\pm 7^\circ$. The reason for this counter freeze was undetermined but it is suspected that at high tilts, the narrow pulse widths may cause problems with this technique since the polling must read the counter in a very short allotted time period. This method is also processor intensive since the computer must poll the counter card regardless whether there is a reading waiting or not.

4.5.2.1.2 Technique 2 Hardware Interrupts Triggering Occurrences

In light of the results of the polling method of reading the counters, it was apparent that an alternative method must be used to enable more controlled and reliable counter reading. It was possible to set up the counter card to produce a hardware interrupt on every falling edge. This interrupt triggered a portion of the Labview code to execute (an Occurrence). This ensured that the counter reading process would be triggered no more than once per pattern and that the Labview application was free to perform other duties in between interrupts. This method of counter acquisition was utilized in the testing using the tilt platform apparatus.

This method of reading the counters was much more effective at capturing the counter data. The full range of the tilt platform apparatus could be sensed reliably with this method. There remained no assurance that this method captured every consecutive pattern data but procedures built into the Labview application increased the likelihood of this occurring. Also, using this method allowed the ability to ensure that the same pattern data was not being read twice in a row as well as making sure that paired tilt sensors are being read at the same time. The later assurance is important when dynamic tilts need to be measured on a rotor with a gimbal with free flexures. In later tests it was discovered that the counter card was interrupting the Labview process only once every 48 - 49 milliseconds which represents a sample frequency of 20.6 Hz. This sample rate is slower than the rotor rotation speed of 25 Hz. Therefore, Labview produced captured counter values every 7 - 8 patterns which led to the impression that it was counting patterns regularly when the output waveform was viewed with no time reference. When the

occurrences were disconnected from the counter read control loop in the Labview application, allowing the counter to be read as fast as possible, the counter values remained at an output frequency of 20.6 Hz. This may indicate that the counter reading may have been triggered by a regular event other than the hardware interrupts generated by the tilt sensor signal. Upgrading the Labview software to version 5 helped the data acquisition speed marginally up to 25 Hz but this speed still remains too slow to capture every pattern.

4.5.2.2 Sequential Pattern Capture

It is important to the sub-rotation tilt angle analysis (detection and characterisation of the $2\times\omega$ rotor wobble) and the averaging of machining errors between patterns to capture sequential pattern data around a complete rotation of the rotor. An algorithm was implemented that facilitated the performance of this task. By capturing data from one interrupt and then processing it, there is a chance that another interrupt will be missed while the previous signal is processed into an angle reading and the program returns to data acquisition mode. For this reason, the algorithm used captures data into an array (software buffer) and only after it fills a predetermined sized array does it process the patterns. This method has a good chance of capturing consecutive patterns during the software buffering stage but does not ensure this. The speed of the interface between the computer and the DAQ card and the speed of the computer itself will limit this ability. Other processes may be running in other applications that may also disrupt consecutive pattern gathering. However, this method will reduce the occurrence of these missed patterns compared to processing the patterns one at a time.

4.5.2.3 Damped Signal with Software Low-Pass Filter

Implementing a low-pass filter on the signal output can reduce the effect of certain higher frequency disturbances of the tilt reading (machining errors, rotor wobble, and sporadic signals). This will introduce a time constant into the system but if the damping factor is chosen properly with respect to the required output frequency of the tilt readings, one can ensure that the signal is responsive enough for the requirements of control system. This is implemented with the discretized formula:

$$DR_{N+1} = DR_{N-1} + DF \cdot (DR_N - DR_{N-1})$$

where DR_N = Current Difference Ratio Reading [4-1]
 DF = Damping Factor

This will lead to a time constant, τ , given by the equation:

$$\tau = \frac{2 \cdot \pi}{DF \cdot f_{pattern}}$$

where $f_{pattern}$ = frequency of the pattern readings [4-2]

This leads to a corner frequency, ω_c , given by:

$$\omega_c = \frac{f_{pattern} \cdot DF}{2 \cdot \pi}$$

[4-3]

4.5.2.4 Counter Error Filtering

Due to a hardware error in the DAQ card, the pulse width counters occasionally count the pattern period. This leads to a duty cycle of 1 in the output of the misbehaving counter pair. This effect seems to happen randomly and on all channels counting pulse width and does not favour one counter over another. The solution implemented was to limit duty cycle of each counter pair to the range 0.2 to 0.8. If the counter pair should fall outside this ratio, the current flawed value is replaced with the previous value. Since this miscount seems to never occur in back to back counts, the replacement value will be much closer to the average for that rotation than the flawed value. This limit value will also eliminate other counter errors that may occur which give duty cycles corresponding to angles which cannot be reached with the current stops in place (e.g. a zero count on a counter). The limiting values of 0.2 to 0.8 correspond to a tilt angle of $\pm 9^\circ$ on a rotor that is limited to $\pm 7^\circ$.

4.5.2.5 Calibration Routine

In the calibration process, a combination of the various filtering techniques was used to obtain a stable difference ratio reading. The basic counter acquisition was performed using the interrupt-occurrence method. After the readings were collected 6 at a time, the averages of the 6 readings were run through the low-pass filter with a damping factor of 0.001. This was done to give a stable reading of the difference ratio down to 6 decimal places. A cubic least squares fit was then found for the data for the L1 and L2 tilt sensor pair for tilt around the y axis and L5 and L6 tilt sensor pair for tilt around the x axis (see Figure A-4 for locations of L1, L2, L5 and L6). It was found that there was a

cross dependency of the tilt sensors. This cross dependency was characterised by a variation of the L1 and L2 tilt sensor pair with a variation of tilt around the x axis and a variation of the L5 and L6 tilt sensor pair with a variation of tilt around the y axis. The cross dependency data was also collected and a linear fit was found for both tilt sensor pairs. With the two direct dependency cubic fits and the two cross dependency linear fits, an iterative approach was used in converting the difference ratios to tilt in the x and y directions. The iterative calibration method was developed by NASA Langley Research Centre for the calibration of their load cells on wind tunnel stings. Bristol Aerospace Ltd. also used this technique for the calibration of the load cells used in the OEDIPUS-C Tether Dynamics Experiment [7]. The basic relationship between tilt and difference ratio is:

$$\bar{\theta} = f(\psi_x, \psi_y)$$

$$\text{where } \bar{\theta} = \begin{bmatrix} DR_{56} \\ DR_{12} \end{bmatrix} = \begin{bmatrix} DR_x \\ DR_y \end{bmatrix}$$

ψ_x = Tilt around the x axis

[4-4]

ψ_y = Tilt around the y axis

DR_{12} = Difference Ratio measured at L1 and L2

DR_{56} = Difference Ratio measured at L5 and L6

This can also be expressed in the following matrix form:

$$\bar{\theta} = \begin{bmatrix} k_{\psi_x, \psi_x} & k_{\psi_x^2, \psi_x} & k_{\psi_x^3, \psi_x} & k_{\psi_y, \psi_x} & k_{\psi_y^2, \psi_x} & k_{\psi_y^3, \psi_x} \\ k_{\psi_x, \psi_y} & k_{\psi_x^2, \psi_y} & k_{\psi_x^3, \psi_y} & k_{\psi_y, \psi_y} & k_{\psi_y^2, \psi_y} & k_{\psi_y^3, \psi_y} \end{bmatrix} \begin{bmatrix} \psi_x \\ \psi_x^2 \\ \psi_x^3 \\ \psi_y \\ \psi_y^2 \\ \psi_y^3 \end{bmatrix} \quad [4-5]$$

Where,

k_{ψ_x, ψ_x} = First order interaction coefficient of ψ_x for DR_x as rotor was tilted about x axis,

k_{ψ_y, ψ_x} = First order interaction coefficient of ψ_y for DR_x as rotor was tilted about x axis,

k_{ψ_x, ψ_y} = First order interaction coefficient of ψ_x for DR_y as rotor was tilted about y axis,

k_{ψ_y, ψ_y} = First order interaction coefficient of ψ_y for DR_y as rotor was tilted about y axis,

and the higher order interaction coefficients are defined similarly.

Equation 4-5 can then be expanded in the following way:

$$\begin{bmatrix} DR_x \\ DR_y \end{bmatrix} = \begin{bmatrix} k_{\psi_x, \psi_x} \cdot \psi_x & k_{\psi_x^2, \psi_x} \cdot \psi_x^2 & k_{\psi_x^3, \psi_x} \cdot \psi_x^3 & k_{\psi_y, \psi_x} \cdot \psi_y & k_{\psi_y^2, \psi_x} \cdot \psi_y^2 & k_{\psi_y^3, \psi_x} \cdot \psi_y^3 \\ k_{\psi_x, \psi_y} \cdot \psi_x & k_{\psi_x^2, \psi_y} \cdot \psi_x^2 & k_{\psi_x^3, \psi_y} \cdot \psi_x^3 & k_{\psi_y, \psi_y} \cdot \psi_y & k_{\psi_y^2, \psi_y} \cdot \psi_y^2 & k_{\psi_y^3, \psi_y} \cdot \psi_y^3 \end{bmatrix}$$

$$\begin{bmatrix} DR_x \\ DR_y \end{bmatrix} = \begin{bmatrix} k_{\psi_x, \psi_x} \cdot \psi_x \\ k_{\psi_y, \psi_y} \cdot \psi_y \end{bmatrix} + \begin{bmatrix} 0 & k_{\psi_x^2, \psi_x} \cdot \psi_x^2 & k_{\psi_x^3, \psi_x} \cdot \psi_x^3 & k_{\psi_y, \psi_x} \cdot \psi_y & k_{\psi_y^2, \psi_x} \cdot \psi_y^2 & k_{\psi_y^3, \psi_x} \cdot \psi_y^3 \\ k_{\psi_x, \psi_y} \cdot \psi_x & k_{\psi_x^2, \psi_y} \cdot \psi_x^2 & k_{\psi_x^3, \psi_y} \cdot \psi_x^3 & 0 & k_{\psi_y^2, \psi_y} \cdot \psi_y^2 & k_{\psi_y^3, \psi_y} \cdot \psi_y^3 \end{bmatrix} \quad [4-6]$$

The main linear coefficients ($k_{\psi_x, \psi_x}, k_{\psi_y, \psi_y}$) can be used to normalize the k matrix by dividing them into their respective rows. The main linear matrix can then be separated out of the normalized k matrix.

If we define the following:

$$K_{\psi_x, \psi_x} = \frac{1}{k_{\psi_x, \psi_x}}; K_{\psi_x^2, \psi_x} = \frac{k_{\psi_x^2, \psi_x}}{k_{\psi_x, \psi_x}}; K_{\psi_x^3, \psi_x} = \frac{k_{\psi_x^3, \psi_x}}{k_{\psi_x, \psi_x}};$$

$$K_{\psi_y, \psi_x} = \frac{k_{\psi_y, \psi_x}}{k_{\psi_x, \psi_x}}; K_{\psi_y^2, \psi_x} = \frac{k_{\psi_y^2, \psi_x}}{k_{\psi_x, \psi_x}}; K_{\psi_y^3, \psi_x} = \frac{k_{\psi_y^3, \psi_x}}{k_{\psi_x, \psi_x}}$$

and

$$K_{\psi_y, \psi_y} = \frac{1}{k_{\psi_y, \psi_y}}; K_{\psi_y^2, \psi_y} = \frac{k_{\psi_y^2, \psi_y}}{k_{\psi_y, \psi_y}}; K_{\psi_y^3, \psi_y} = \frac{k_{\psi_y^3, \psi_y}}{k_{\psi_y, \psi_y}};$$

$$K_{\psi_x, \psi_y} = \frac{k_{\psi_x, \psi_y}}{k_{\psi_y, \psi_y}}; K_{\psi_x^2, \psi_y} = \frac{k_{\psi_x^2, \psi_y}}{k_{\psi_y, \psi_y}}; K_{\psi_x^3, \psi_y} = \frac{k_{\psi_x^3, \psi_y}}{k_{\psi_y, \psi_y}}$$

Then Equation 4-6 becomes:

$$\begin{bmatrix} DR_x \\ DR_y \end{bmatrix} = \begin{bmatrix} k_{\psi_x, \psi_x} & 0 \\ 0 & k_{\psi_y, \psi_y} \end{bmatrix} \begin{bmatrix} \psi_x \\ \psi_y \end{bmatrix}$$

$$+ \begin{bmatrix} k_{\psi_x, \psi_x} & 0 \\ 0 & k_{\psi_y, \psi_y} \end{bmatrix} \begin{bmatrix} 0 & K_{\psi_x^2, \psi_x} & K_{\psi_x^3, \psi_x} & K_{\psi_y, \psi_x} & K_{\psi_y^2, \psi_x} & K_{\psi_y^3, \psi_x} \\ K_{\psi_x, \psi_y} & K_{\psi_x^2, \psi_y} & K_{\psi_x^3, \psi_y} & 0 & K_{\psi_y^2, \psi_y} & K_{\psi_y^3, \psi_y} \end{bmatrix} \begin{bmatrix} \psi_x \\ \psi_x^2 \\ \psi_x^3 \\ \psi_y \\ \psi_y^2 \\ \psi_y^3 \end{bmatrix}$$

If we define:

$$K = \begin{bmatrix} K_{\psi_x, \psi_x} & 0 \\ 0 & K_{\psi_y, \psi_y} \end{bmatrix}, \quad \bar{\theta} = \begin{bmatrix} DR_x \\ DR_y \end{bmatrix}$$

$$\hat{K} = \begin{bmatrix} 0 & K_{\psi_x^2, \psi_x} & K_{\psi_x^3, \psi_x} & K_{\psi_y, \psi_x} & K_{\psi_y^2, \psi_x} & K_{\psi_y^3, \psi_x} \\ K_{\psi_x, \psi_y} & K_{\psi_x^2, \psi_y} & K_{\psi_x^3, \psi_y} & 0 & K_{\psi_y^2, \psi_y} & K_{\psi_y^3, \psi_y} \end{bmatrix},$$

$$\hat{\bar{X}} = \begin{bmatrix} \psi_x \\ \psi_x^2 \\ \psi_x^3 \\ \psi_y \\ \psi_y^2 \\ \psi_y^3 \end{bmatrix} \text{ and } K^{-1} = \begin{bmatrix} k_{\psi_x, \psi_x} & 0 \\ 0 & k_{\psi_y, \psi_y} \end{bmatrix}$$

then:

$$K^{-1} \bar{X} + K^{-1} \hat{K} \hat{\bar{X}} = \bar{\theta}$$

$$K^{-1} [\bar{X} + \hat{K} \hat{\bar{X}}] = \bar{\theta}$$

$$K = \begin{bmatrix} \frac{1}{k_{\psi_x, \psi_x}} & 0 \\ 0 & \frac{1}{k_{\psi_y, \psi_y}} \end{bmatrix} = \begin{bmatrix} K_{\psi_x, \psi_x} & 0 \\ 0 & K_{\psi_y, \psi_y} \end{bmatrix}$$

since $KK^{-1} = I$

Therefore,

$$\bar{X} + \hat{K} \hat{\bar{X}} = K \bar{\theta}$$

$$\bar{X} = K \bar{\theta} - \hat{K} \hat{\bar{X}}$$

[4-7]

In recursive form the above expression can be written as:

$$\bar{X}_n = K\bar{\theta} - \hat{K}\hat{X}_{n-1} \quad [4-8]$$

where $\hat{X}_0 = 0$

Recursion of the above expression causes the angle value to converge to an accuracy of 6 decimal places within 5 iterations. It is advised that while 5 iterations may not be many, it will make the conversion run quicker if the iterations were run for various difference ratios before hand and then least squares fit a multi-variable function to the resulting matrix and then use the result for the conversion.

The latest calibration with the tilt platform (see Figure 4-26 to Figure 4-29) gave the following matrices:

$$k = \begin{bmatrix} 66.16657 \times 10^{-3} & -39.75299 \times 10^{-6} & 10.56276 \times 10^{-6} & -580.2893 \times 10^{-6} & 0 & 0 \\ 110.0500 \times 10^{-6} & 0 & 0 & 66.98929 \times 10^{-3} & 31.99378 \times 10^{-6} & -4.456616 \times 10^{-6} \end{bmatrix}$$

This basic coefficient matrix, when normalized and separated as described previously, leads to the matrices to be used in the iterative formula:

$$K = \begin{bmatrix} 15.11337 & 0 \\ 0 & 14.92776 \end{bmatrix}$$

$$\hat{K} = \begin{bmatrix} 0 & -600.8017 \times 10^{-6} & 159.6389 \times 10^{-6} & -8.770128 \times 10^{-3} & 0 & 0 \\ 1.642800 \times 10^{-3} & 0 & 0 & 0 & 477.5954 \times 10^{-6} & -66.52729 \times 10^{-6} \end{bmatrix}$$

4.5.2.6 Rotation Average of Patterns

Provided that every pattern around the rotor is captured, a stable average tilt angle should be able to be obtained by averaging over an entire rotation of patterns (6 in the

current design). This would average out the machining inconsistencies, $2 \times \omega$ dynamic effects and other sources of error that are associated with the rotation speed of the rotor. This averaging must be taken carefully. One cannot find the average of the indicated pattern angles by simply adding all of the pulse widths together and then dividing by the total period of the rotation.

The average of the patterns, ψ_{avg} , is represented mathematically as:

$$\psi_{avg} = \frac{\left(\frac{t_w}{t_p}\right)_1 + \left(\frac{t_w}{t_p}\right)_2 + \left(\frac{t_w}{t_p}\right)_3 + \left(\frac{t_w}{t_p}\right)_4 + \left(\frac{t_w}{t_p}\right)_5 + \left(\frac{t_w}{t_p}\right)_6}{6}$$

$$= \frac{\left(\frac{t_{w1} \cdot t_{p2} \cdot t_{p3} \cdot t_{p4} \cdot t_{p5} \cdot t_{p6} + t_{w2} \cdot t_{p1} \cdot t_{p3} \cdot t_{p4} \cdot t_{p5} \cdot t_{p6} + t_{w3} \cdot t_{p1} \cdot t_{p2} \cdot t_{p4} \cdot t_{p5} \cdot t_{p6} + t_{w4} \cdot t_{p1} \cdot t_{p2} \cdot t_{p3} \cdot t_{p5} \cdot t_{p6} + t_{w5} \cdot t_{p1} \cdot t_{p2} \cdot t_{p3} \cdot t_{p4} \cdot t_{p6} + t_{w6} \cdot t_{p1} \cdot t_{p2} \cdot t_{p3} \cdot t_{p4} \cdot t_{p5}}{t_{p1} \cdot t_{p2} \cdot t_{p3} \cdot t_{p4} \cdot t_{p5} \cdot t_{p6}} \right)}{6}$$

$$= \frac{t_{w1} + t_{w2} + t_{w3} + t_{w4} + t_{w5} + t_{w6}}{t_{p1} + t_{p2} + t_{p3} + t_{p4} + t_{p5} + t_{p6}} \quad [4-9]$$

where t_{wn} = pulse width of pattern n
 t_{pn} = period of pattern n

This is true if:

$$t_{p1} = t_{p2} = t_{p3} = t_{p4} = t_{p5} = t_{p6} \quad [4-10]$$

In this case, the pattern periods are not equal due to pattern inconsistencies and dynamic effects and therefore the duty cycles of the each pattern must be calculated before they are averaged.

4.5.3 Tilt Ring Testing

4.5.3.1 Apparatus

The first round of calibration testing was performed using the test apparatus from the previous tilt sensor testing that was performed in November 1997. This set-up is shown in Figure 4-6.

4.5.3.2 Method

With this set-up it was possible to find a calibration curve to relate the readings from the tilt sensors to the set angle of tilt in one axis only. The testing was done from 4° to -4° of tilt due to the limitation, mentioned previously, of the polling method of data acquisition used. The tilt angle was measured to the nearest arcminute due to the limitation in the accuracy of the inclinometer used. The calibration curves for both axes were assumed at this point to be equal. The expected results from this test were to obtain a basic calibration curve fit to the acquired data and check the accuracy of curve in deriving angular data from counter values.

4.5.3.3 Results

The results are shown in Figure 4-14 through Figure 4-16.

Figure 4-14: $\pm 1^\circ$ Region of Difference Ratio vs. Angle for Tilt Ring Testing

Figure 4-15: Difference Ratio vs. Angle for Tilt Ring Apparatus Testing

Figure 4-16: Angle vs. Error for Tilt Ring Apparatus Testing

4.5.4 Tilt Platform Testing

4.5.4.1 Apparatus

The intermediate and final round of calibration testing was performed on a modified test apparatus that enabled both sets of tilt sensors to be evaluated at one time.

This set-up is shown in Figure 4-17.

Figure 4-17: Drawing of the Tilt Platform Test Apparatus (Inclinometer not Shown). Note sensors located at cardinal points around the rotor.

It also had the benefit of using the actual tilt sensor mounting ring to hold the sensors in place so that after the calibration testing was done, the mounting ring could be affixed to the actual MMS lab model without having to disturb the position of the tilt sensors. The tilt platform set up also had an adapter to allow direct control of the tilt by adjusting the inclinometer.

4.5.4.2 Method

The calibration curves were determined by recording the tilt sensor readings from the sensors perpendicular to the rotation axis as well as from the sensors inline with the rotation axis. The interrupt method was used so that the platform could be rotated about the axis in the $\pm 7^\circ$ tilt range. This allowed the determination of the direct angle sensing properties on one set of sensors and the cross axis properties of the other set of sensors. The tilt ring was then indexed on the platform 90° and the properties of the other axis were determined. The tilt sensors were fixed in the tilt sensor ring the entire time. The gap between the tilt sensors and the rotor was set with four pieces of 0.010 inch shim stock that allowed the tilt ring to be secured in the proper spot to ensure that all tilt sensors were the same distance away from the rotor. The intermediate tests were done at 1500 RPM and 2250 RPM to show sensitivity of the calibration to speed. The final tests were only performed at 1500 RPM.

4.5.4.3 Results

The results of the intermediate calibration testing are shown in Figure 4-18 through Figure 4-25. The results of the final calibration testing are shown in Figure 4-26 through Figure 4-31.

Figure 4-18: Y Axis Angle vs. L1L2 Tilt Sensor Pair at 1500 RPM

Figure 4-19: Y Axis Angle vs. L1L2 Tilt Sensor Pair Error at 1500 RPM

Figure 4-20: Y Axis Angle vs. Difference Ratio from L1L2 Tilt Sensor Pair at 2250 RPM

Figure 4-21: Y Axis Angle vs. Error at 2250 RPM

Figure 4-22: -X Axis angle vs. Difference Ratio from L1L2 Tilt Sensor Pair at 1500 RPM (Cross Axis)

Figure 4-23: -X Axis Angle vs. Difference Ratio from L5L6 Tilt Sensor Pair at 1500 RPM

Figure 4-24: -X Axis Angle vs. L5L6 Tilt Sensor Pair Error at 1500 RPM

Figure 4-25: Y Axis Angle vs. Difference Ratio from L5L6 Tilt Sensor Pair at 1500 RPM (Cross Axis)

Figure 4-26: Graph of X Axis Tilt vs. Difference Ratio from L5L6 Tilt sensor Pair (Final Calibration)

Figure 4-27: Graph of X Axis Tilt vs. Difference Ratio from L1L2 Tilt sensor Pair (Final Calibration)

Figure 4-28: Graph of Y Axis Angle vs. Difference Ratio from L1L2 Tilt sensor Pair (Final Calibration)

Figure 4-29: Graph of Y Axis vs. Difference Ratio from L5L6 Tilt sensor Pair (Final Calibration)

Figure 4-30: Angle vs. Error for Tilt Around Axis +30° from X Axis (Final Calibration)

Figure 4-31: Angle vs. Error for Tilt Around Axis +60° from X Axis (Final Calibration)

4.5.5 Testing Discussion

It was found that the cross dependency of the tilt sensors caused a great deal of complication in the calibration. The cross dependency is suspected to be linked to a misalignment of the tilt sensor axis with the tilt axis (see Section 3.5.1). The dependency was found to be quite sensitive to small errors so while this effect can be minimized with careful alignment of the sensors, it is doubtful that this effect can be eliminated so that arcsecond accuracy is maintained with a simple calibration.

The greatest accuracy observed was ± 1 arcminute. This was likely due to the fact that the angle during the tilt calibration could only be set to that accuracy. In order to decrease this error, a reliable, independent method of measuring the angle of the rotor within one arcsecond would have to be used. To make this independent measurement more useful, it would have to be made over a large range (i.e. the range of the rotor tilt, $\pm 7^\circ$). A method using laser reflection to track this angle accurately could be employed.

The Labview application is not able to actively sample the counter card reliably at the frequencies that would be useful for filtering and response time. One way to overcome this impasse is to find a card that has circular hardware buffering and obtain a Labview version that has the capability of utilizing these structures (Labview v.4.1 cannot read these buffers properly, Labview v.5 may be able to). This would allow Labview to capture consecutive patterns over a range useful enough to get accurate sub-rotation data to use for filtering techniques.

The sampling frequency of the counter card is not immediately apparent when the data is collected. This may be an issue with other signal inputs also. It is recommended that a timestamp of the input signal be associated with the value to more readily keep track of sampling rate and synchronicity of various input channels. This would allow for detection of slow processes and perhaps interpolation of lost data. This compensation might remove artefacts in the output of filters that depend on frequencies close to sample rate.

The calibration was found to be relatively sensitive at off null tilt values to variation of rotor speed. The error in a calibration curve from the 1500-RPM test applied to a 2250-RPM data set increases from about 1 arcminute to about 4 arcminutes at 7° tilt. Since the rotor is expected to operate close to its nominal speed, this should not introduce unreasonable error. If the error under normal operation conditions exceeds what is deemed acceptable, the calibration variables could also include rotor speed as a parameter. This would require a set of calibration tests to be run at various speeds. A multi-variable least squares fit could then be applied to the set to get a more accurate conversion. It would also require the rotor speed to be an input into the data acquisition card for the Labview application to use in the calibration procedure.

Considering that both data acquisition methods were found to not capture every pattern, the calibration coefficients may not be as accurate as they could be if the sub-rotation effects were averaged properly. It is recommended that once Labview is enabled to capture consecutive patterns, another calibration be performed to ensure the best accuracy possible.

It was found that the control system requires a slightly higher pattern output frequency. The number of patterns should be raised to 8 for future iterations of the rotor. This would allow for greater rotation averaging and a greater frequency of rotor tilt information (if consecutive patterns could be captured). The greater frequency of rotor tilt information would allow a more accurate assessment of high frequency (i.e. greater than the spin rate) dynamic effects. This small increase should not cause problems with peak-trough interference that is experienced at extreme tilt when the patterns are too close together. The new pattern can be designed to minimize this effect within the operating range of $\pm 7^\circ$.

The choice of eight patterns offers some other benefits as well. Eight patterns allow easier spacing of the gap between the sensors and the rotor. There are points on the rotor rotation where all of the sensors are over the high point in the pattern. This is not the case with six patterns where the spacing of the gaps using shim stock is impossible to do with all four sensors simultaneously. Also, the pattern edges will pass by all four sensors at roughly the same time when there are eight patterns. This may help to balance out the magnetic attraction of the rotor to the sensors so that the sensors do not apply a disturbance torque in the tilt directions.

4.6 Summary of Testing and Design Decisions

4.6.1 Pattern Design Parameters

4.6.1.1 Detection Medium

The method by which the pattern influences the flux passing through the sensor was chosen to be a machined pattern. This choice of this method over the painted pattern method was made with reference to the testing described in Section 4.1.

4.6.1.2 Configuration

The pattern configuration was chosen to be symmetrical. The option of using an unsymmetrical pattern was discarded with reference to Section 3.5.4.3.

4.6.1.3 Slope

The slope of the pattern edges were chosen to be 1° tilt per 1° rotation (i.e. $m=1$ in Equation 3-17). This slope was not the only slope that could have been used but the trade-offs covered in Sections 2.2.4 and 3.3.4 indicated that this selection would offer a balance between two opposing effects. Testing done in Section 4.5 seems to verify the satisfactory function of this pattern slope.

4.6.1.4 Number

The number of patterns suitable for the MMS rotor was found to be 8. The number of patterns was selected with reference to Section 3.3.3. Testing outlined in Section 4.5.5 indicated that a more than six patterns were necessary.

4.6.1.5 Tilt Range

The pattern range is a consequence of the choice of pattern slope and number and was calculated to be 22.5° . The calculations used to determine this number are outlined in Sections 3.3.2 and 3.3.3.

4.6.1.6 Depth

The depth of the pattern was chosen to be 1.27 mm (0.050 inch). The justification for this selection can be found in Section 3.3.2. Testing outlined in Section 4.3 seems to support this pattern depth selection.

4.6.2 Sensor Design Parameters

4.6.2.1 Detection Medium

The selection of an inductive type sensor over other types was made with reference to Sections 2.1.2.1 and 2.2.3.

4.6.2.2 Excitation Source

The magnetic flux was selected to come from a permanent magnet source. The option of using an electromagnet for this purpose was ruled out in testing outlined in Section 4.1. The use of permanent magnets was supported in testing outlined in Section 4.2

4.6.2.3 Magnet Type

The use of a Type II magnet over a Type I magnet was decided to be most suitable for the MMS tilt sensor. The characteristics of both types can be found in Section 3.1.3 and it was found that Type II magnets were more suitable.

4.6.2.4 Configuration

The configuration of the sensor was selected to be a pole-driven configuration over a core-driven configuration. Both configurations are described in Section 3.2.1. Testing outlined in Section 4.3.4.1 indicated that the pole-driven configuration gave the most design flexibility and best signal shape.

4.6.2.5 Magnet Material

The magnets to be used to drive the tilt sensor were chosen to be Rare-Earth magnets. Rare-Earth and Ferrite Ceramic magnets are both Type II magnets and are described in Section 3.1.3. However, testing outlined in Section 4.3.4.3 seemed to indicate that Rare-Earth magnets gave a stronger signal and some of the disadvantages noted in this testing were due to magnet size.

4.6.2.6 Core Diameter

The core diameter selected was a small diameter of 1.397 mm (0.055 inch). The advantages and disadvantages of using small and large diameter cores can be found in Section 3.1.1. Testing outlined in Section 4.3.4.2 supports the use of a small diameter core.

4.6.2.7 Dimensions

The final sensor dimensions are 15.24 mm (0.600 inch) diameter by 15.24 mm (0.600 inch) long. These dimensions were chosen with reference to the limitations given in Section 3.2.3.

4.6.2.8 Coil Parameters

The sensor coils will be wound with epoxy coated, copper, 34 gauge wire. The number of windings will be 1225. These selections were made with reference to Sections 3.2.2 and 3.2.3. Testing with sensor coils having these parameters was performed and outlined in Section 4.4 and their performance was found to be satisfactory.

4.6.3 Signal Processing Design Parameters

4.6.3.1 Acquisition Method

The signal acquisition method was chosen to be the Hardware Interrupt method. This method was chosen over the Polling method with reference to testing that is outlined in Section 4.5.2.1.

4.6.3.2 Filtering

A low pass filter was needed and was implemented digitally. The filter used is outlined in Section 4.5.2.3. Also, since there were errors in the counter card, another layer of error filtering was necessary. This error filter is described in Section 4.5.2.4.

4.6.3.3 Conversion

The method of conversion between sensor signal and tilt angle involved in many steps. The opposing sensor signals were combined for error reduction outlined in Section 2.2.4.4. The method of calculating the Difference Ratio, as outlined in Section 3.4.1.3, was used for further error reduction. This method performed better than a simple Duty Cycle Average. This value was calibrated with respect to tilt angle using principles outlined in Sections 3.4.1.4 and 3.5.1. A Dual Axis Recursive Calibration was chosen over a simple Signal Axis Calibration with reference to the results of testing outlined in Section 4.5.2.5.

5. Conclusion

5.1 Final Design Description

Most of the requirements for the MMS tilt sensor are met by the final tilt sensor design. Testing on the finished sensor with a rotor with six patterns was performed and the sensor was found to have a tilt angle resolution of about 1 arcminute. This is smaller than that required for some of the applications outlined in the introduction but does not meet the requirements set out in the specifications on resolution. However, accurate secondary angle measurement would have to be performed to verify whether 1 arcminute is the best accuracy possible with the current system or if the system actually performs better than that. It would likely meet all of the other requirements specified in the introduction if a rotor with eight patterns was used. However, testing with an eight pattern rotor would have to be done to verify the performance.

5.1.1 Pattern Design Summary

Figure 5-1: Flow Chart Showing Decision Path for Design of MMS Tilt Pattern Including References to Supporting Thesis Material

5.1.2 Sensor Design Summary

Figure 5-2: Flow Chart Showing Decision Path for Design of MMS Tilt Sensor Including References to Supporting Thesis Material

5.1.3 Signal Processing Design Summary

Figure 5-3: Flow Chart Showing Decision Path for Design of MMS Tilt Sensor Signal Processing Including References to Supporting Thesis Material

5.2 Contributions

This thesis outlines a unique method of accurately measuring the angle of a rotating body over a long range. This method is physically non-intrusive which makes it appropriate for observing the dynamics of a rotating mass without introducing various disturbances. It is also flexible such that various sensor-pattern combinations using different detection mediums can be used that may suit other more particular environments. While there are undoubtedly other methods of achieving this measurement, there are few, if any, methods of angle measurement that can match the range-precision characteristics and share the simplicity and low cost (both power consumption and monetary) of the MMS tilt measurement system.

The author performed much of the work presented in this thesis but there are certain tasks that were performed by others who had the expertise and equipment necessary for completion. The circuit design and manufacture for the signal conversion, the manufacture of the tilt ring and tilt platform apparatus and the manufacture of the 6 pattern rotor was all performed by Bristol Aerospace Limited in Winnipeg, Mb. The manufacture of the 12 pattern rotor was performed by the Science and Technology Centre at Carleton University.

5.3 Recommendations for Future Work

While an attempt was made to make the most efficient choice of all the design parameters, a formal optimization of the characteristics of the MMS tilt sensor was not performed. Future work on this project could include a more detailed analysis of the magnetic flux path and its sensitivity to various parameters such as:

- Magnet Size
- Coil Size
- Pattern Depth

Also an optimization of the calibration procedure used could be performed. This would be done to increase the processing speed of the calibration to convert sensor signal into tilt angle in a real-time way.

The sensor and the pattern were found to be time-consuming to manufacture and the manufacturing methods imposed limitations that had to be tolerated. Manufacturing methods for the machining of the rotor pattern, the sensor machining and the coil winding could be developed to make the MMS more suitable for mass-production.

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A Appendix

Figure A-1: Graph of Tilt Cross Dependency due to Sensor Line Misalignment
Phase = 2.8° and Offset = 12.129 mm (0.4775 inch)

Figure A-2: Graph of Tilt Cross Dependency due to Sensor Line Misalignment
Tilt = 3.25° and Offset = 12.129 mm (0.4775 inch)

Figure A-3: Graph of Tilt Cross Dependency due to Sensor Line Misalignment
Tilt = 3.25 ° Phase = 2.8 ° and Offset = 12.129 mm (0.4775 inch)

Notes:

cw current in coil runs clock wise when looking at coil from the outside towards the center

ccw current in coil runs counter clockwise when looking at coil from the outside towards the center

L1 - L8 labels on the schematics for the x and y axis control loops

Figure A-4: Top View of Tilt Sensor Mounting Ring Showing Co-ordinate System and Sensor Labels used in Intermediate and Final Testing

Figure A-5: Cross-section View of MMS Showing Space Constraint of Tilt Sensors

32	REFLECT OBJECT SENSOR	QT OPTOELECTRONICS
31	RING, RETAINER	
30	MIRROR	
29	RTV ADHESIVE	DOW CORNING
28	ADHESIVE	LOCTITE
27	BELL JAR	FISHER
26	PICKOFF ASSEMBLY	
25	NUT .375-24 UNF	
24	MOTOR	KOLLMORGEN
23	CONNECTOR, ELECTRICAL	
22	WASHER $\varnothing$.375 SS	
21	COIL, TORQUE	
20	DISC, MOTOR CLAMP	
19	COIL STAND, MODIFIED	
18	COIL STAND, UPPER	
17	SHAFT ASSEMBLY	
16	TUBE, PICKOFF	
15	RING, PICKOFF REGISTER	
14	RING, PICKOFF	
13	TUBE, SUPPORT	
12	GIMBAL, MODIFIED	
11	KEY, INDEX	
10	ROTOR ASSEMBLY	
9	SLEEVE, BALL CAGE	
8	COVER, BOTTOM	
7	COVER, TOP	
6	BALL, CAGING	
5	CAGE, TOP HAT	
4	HOUSING	
3		
2		
1	MMS ASSEMBLY	
ITEM NO.	PART NAME	MANUFACTURER

Table A-1: Parts List for Exploded View of MMS

IMAGE EVALUATION TEST TARGET (QA-3)

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