A Three Axis Magnetometer For use in a Small Satellite

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***Abstract* – This paper deals with a construction of a three axis magnetometer for use in a small satellite. It is necessary to know the magnetic field around the satellite for an attitude stabilisation and for propulsion. A minimal weight, size and power consumption are the most critical properties of this construction. The magnetic flux has to be measured in an 8-bit resolution. Two small packages with magnetoriesistive sensors from HONEYWELL are used. One package measures magnetic flux in the axis X and Y, and second in the axis Z. The microcontroller is used for data processing, sensors setup and for communication over central bus. Other units in the satellite are able to read the results of the magnetic field measurement over this bus. The software in the microcontroller has to remove any noise and electrical offsets from the data, improves the immunity to an impulse disturbances and a magnetic offsets caused by other electric circuits in the satellite. Construction of this magnetometer is one part of a large project, whose aim is to build Czech amateur satellite compatible with the CubeSat technology.**

ATTITUDE STABILISATION

CubeSat satellites are built in aluminium cubes with dimensions 100 x 100 x 113 mm. They have to orbit on a low-altitude polar track between 500 and 700 km above ground. This track is sun-synchronous, that means the satellite reach one place on Earth in approximately the same part of the day. For the radio contact between the satellite and the ground station, a correct orientation of the satellite is necessary. The satellite has to turn the bottom side with antennas to the ground in the shortest time as possible from the launch. The spin of the satellite around its all axes must be stopped.

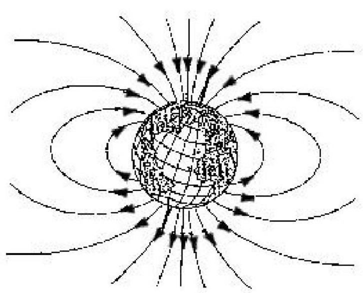

Fig.1 The magnetic field of Earth

It is possible to use a magnetic field to determine the position of the satellite. The strength of this field in a high altitudes is known and its mathematic model exists. The attitude stabilisation algorithm can request magnetometer for an immediate value of the magnetic flux, its direction or strength, or a history of its direction. Then it calculates a correction angles. The orientation of the satellite is set by a current pulses into a special coils whose magnetic field interacts with the field of Earth.

PROPULSION OF THE SATELITE

Another task of this satellite is to test a new method of the satellite propulsion, which is called electrodynamic tether. Its principle is based on the Earth's magnetic field too. To obtain a force in a correct direction, the propulsion must be switched on and off in a correct parts of orbit. To determine these intervals, we can use data of Earth's magnetic field and calculate the latitude of the satellite.

At first, we need to recognise a fly over the Earth's pole or over the equator. At the pole, the magnetic field will be strong and it will be concentrated in the axis Z. The magnetic field in the axis X or Y will be near zero. At the Earth's equator, the magnetic filed will be weak (It will be spread in a large space.) and it's component Z will be near zero. The magnetic filed will be distributed between the axis X and Y.

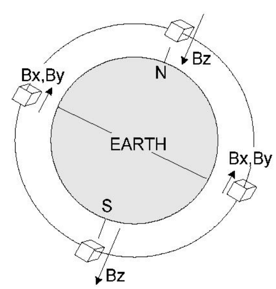

Fig.2 The vector of the magnetic flux at pole and equator

The latitude can be calculated from the time of fly between the pole and the equator. Correct intervals for switching the propulsion can be determined from it.

SENSORS

The magnetic flux density could be 10 to 50 μT in altitudes 500 to 700 km. For the tasks described here the 8-bit resolution is usable. Due to a minimal weight, size and power consumption, the HMC 1052, magnetic sensor from HONEYWELL was chosen.

These sensors are based on AMR, an anisotropic magnetoresistivity. Single sensor consists of the four resistor straps connected to a Wheatstone bridge. If the sensor is exposed to magnetic field, the bridge is unbalanced. Each resistor is made from a permalloy (Ni-Fe) film.

$$R(\varphi) = \rho_o \frac{l}{b \cdot d} + \Delta\rho \frac{l}{b \cdot d} \cdot \cos^2 \varphi \qquad (1)$$

The resistance of the strip depends on the angle φ between the current density in the film and an internal magnetisation vector. It can be calculated using equation 1 from the strip dimensions (b, d, l; l>b>>d). A magnetisation independent resistivity is ρ0 and a minimal resistivity change is Δρ.

$$\left|\frac{H_y}{H_0}\right| \begin{cases} <1 \ldots \sin\varphi = \frac{H_y}{H_0} \\ >1 \ldots \sin\varphi = \mathrm{sign}\frac{H_y}{H_0} \end{cases} \qquad (2)$$

If the strip is exposed to an external magnetic field H_Y, the magnetisation vector will rotate and the resistance will change. (See the equation 2, where H_0 represents an internal magnetisation M.)

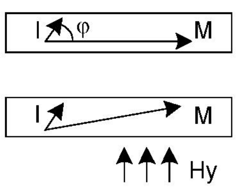

Fig.3 Permalloy (Ni-Fe) resistor strap with and without external magnetic field

The permalloy strip resistance as a function of the external magnetic flux (He) is in Fig.4. This function is even and non-linear. The direction of the magnetic filed cannot be recognised due to that.

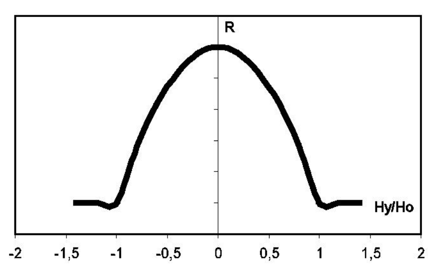

Fig.4 The resistance of the permalloy resistor while an external magnetic field applied

For better properties of the sensors, the barber-pole structure is used. The sensor has the best sensitivity, if the angle between current and internal magnetisation is near 45°. The bridge configuration of this structure brings a better linearity, a low temperature and time drift and the direction sense ability. However, there is still dependency on the supply voltage (Vs).

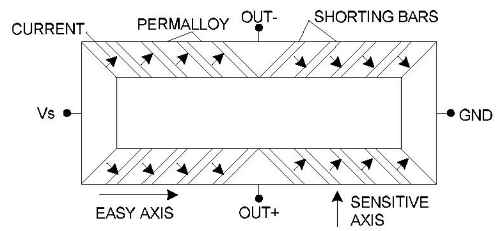

Fig.5 The barber-pole structure

The shorting bars, made from aluminium, causes the current flow in 45° angle to the internal magnetisation of strips.

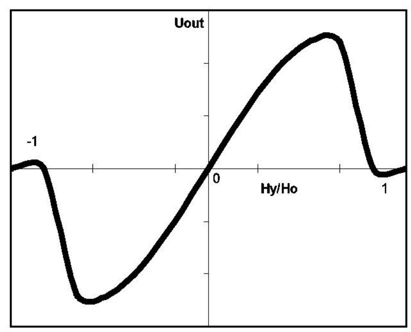

Fig.6 The output voltage of the barber-pole structure as a function of external magnetic field

The sensitivity of this sensor, depends on its internal magnetisation. If the sensor is exposed to a strong magnetic field for a short time, the internal magnetisation will change and the sensitivity will be lost. Due to that, the internal magnetisation has to be recovered. The HMC1052 sensors are equipped with a SET/RESET (magnetisation) strap. The current pulse through this strap recovers the magnetisation and the sensitivity of the sensor. The pulse in the opposite direction causes sensor flip and its sensitivity will have the negative sign.

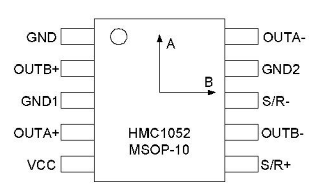

Fig.7 The HMC1052 sensor package

The HMC 1052 sensor package contains two independent sensors A, B, 90° to each other and one SET/RESET strap. It is possible to measure magnetic fields $6 \cdot 10^{-4}$ to $-6 \cdot 10^{-4}$ T with it. A weak magnetic fields around $12 \cdot 10^{-9}$ could be detected.

The sensitivity depends on the supply voltage and could achieve 10 mV/mT/V. The offset voltage could be 1 mV/V. If the magnetic field about 0,1 mT would be measured, the offset voltage is comparable with the output voltage of the sensor. Due to that, a very good offset voltage compensation has to be used.

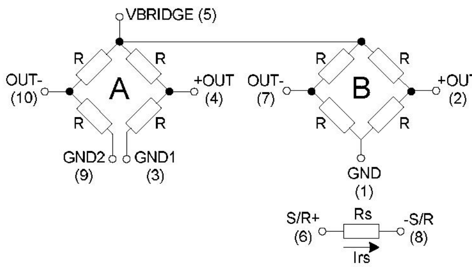

Fig.8 The HMC1052 internal connection

REALISATION OF MAGNETOMETER

The first prototype of the magnetometer contains two sensor packages HMC1052, two independent SET/RESET exciters, three low voltage differential amplifiers and microcontroller ATmega 16L. The communication port of the microcontroller is equipped with an interface for connection to the internal satellite communication bus, called KOMBUS.

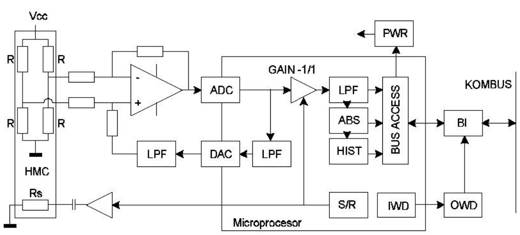

Fig.9 Schematic of single channel measurement

The input voltage measured by ADC depends on the external magnetic field, but is also influenced by the supply voltage, the sensor properties (sensitivity, voltage offset) and the amplifier properties (differential gain, common mode gain). The sensor flipping does the first cleaning of these values. Two measurements are done, where the sensor is magnetised in the correct origin for the fist one (SET) and in the opposite origin for the second one (RESET). These two values are subtracted and in the result, the voltage offset and the common mode amplification is cancelled. The time interval between these two measurements has to be very short to not produce the additional noise voltage. In the first prototype, the time about 1 ms was used and noise voltage below two digits was achieved. The capacitance blocking of sensor's power lines can also decrease the noise voltage.

For bigger offset voltages the digital offset compensation using the DAC channel is used. This offset compensation can by done, once when the new sensor (with new parameters) is put into the magnetometer, or repeatedly during normal operation.

The feedback signal is obtained from the measured signal by a LPF.

This method can be used, if any amplifier or ADC channel is not saturated by the offset voltage. The saturation can rise, due to a strong external magnetic disturb, an incorrect supply voltage or by a big part-to-part dispersion of the sensor parameters.

Three ADC channels are used for magnetic field measurement in axis X, Y, Z. Next two channels are used for the supply voltage and temperature effect cancelling.

SAFETY AND POWER MANAGEMENT

The power consumption of the magnetometer is very low, for voltages 2.7 – 4.2 V it could achieve a few mA. The sleep (low consumption) mode is initiated during all measurement periods due to the noise cancelling and when the magnetometer is not in use. Then the power consumption can fall below 100 μA. The analogue part (the sensors and the amplifiers) can by also switched off.

For a safety operation on the satellite, the magnetometer is equipped with three diagnostic timers. First timer, inside the microcontroller can reset it when the program locks-up. The operation of the microcontroller can be recovered in this way. Next two timers are outside the microcontroller package. They are used for the protection of the KOMBUS form a random or a cyclic transmission which can block the bus. These timers can disconnect the microcontroller from the KOMBUS.

MAGNETOMETER CALIBRATION

The sensitivity of the sensors can differ part-to-part in range 8 – 12 mV/V/mT. Two sensors in a single package can differ too. If a good reliability of measured values is necessary, all sensors have to be calibrated. In low-cost or in space, weight or power consumption limited applications only one calibration procedure may be done, after the sensors are put into this device. When a high precision measurement is needed, the calibration circuit must be inside the device and it is used during normal operation.

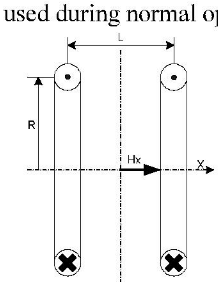

Fig.10 The Helmholtz coil

The weak magnetic fields as field of Earth is, cannot be effectively shielded, but is possible to compensate it to zero using a known magnetic field. The most common configuration for this procedure calls the Helmholtz coil.

It is a configuration of two coils, where a defined magnetic flux is in their centre. The magnetic flux inside the Helmholtz coil can be calculated as

$$B_0 = \left(\frac{4}{5}\right)^{3/2} \frac{\mu_0 NI}{R} \qquad (3)$$

Where ‘B_0’ is the flux in the coil center, ‘μ_0’ is the vacuum permeability, ‘N‘ is number of the each coil turns, ‘I’ is the coil current and ‘R’ is the coil diameter. It is possible to express the Helmholtz coil sensitivity as relation between the magnetic flux and the current. This sensitivity can be measured using a flux meter too.

The calibration of magnetometer can be done inside the Helmholtz coil, when the known current compensates the Earth’s magnetic field to zero.

CONCLUSION

The next versions will use better microcontroller package TQFP instead of DIL. The sensors are put on the same board as other electronics is. It will be better to put them on a separate board connected with the main board using a flexible PCB strip.

Some improvements have to be done on disturbances by a supply voltage change cancellation. The calibration procedure together with temperature and vacuum tests will be more automated.

The calibration of the sensors could be done using active attitude stabilisation coils, during normal operation. The exciter of these coils has to be able work in the linear mode. The current through the coils will compensate the external magnetic flux to zero. However, the constant of these coils will be very hard to calculate.

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MORE INFORMATION

http://www.kosmo.cz/ - The main project page, section “Czech Amateur Satellite”
http://home.zcu.cz/~rlinhart/cubeind.html - The magnetometer module development status