Filtering of Magnetic Noise Induced in Magnetometers by Motors of Micro-Rotary Aerial Vehicle.

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***Abstract*— Avionics systems of micro aerial vehicles (MAV) pose unique problems in system design, sensor signal handling and control. This is evident in micro-rotary aircraft as their whole body rotates with the sensors of the flight control. The precise calculation of attitude and heading from magnetometer readings is complex due to the body rotation. It is made even more difficult by noise induced in the geomagnetic signal by fluctuating magnetic field of the closely positioned motors. Filtering that noise is challenging since the rotation speed of motors and the vehicle can be very close. This paper presents analysis of motor induced noise, based on experimental data of brushless micro motors. A novel time domain filter is proposed, designed, implemented in FPGA hardware, tested and compared to other filters. This filter provides good performance even when the rotational rate of the motor and vehicle are close and traditional frequency domain filters would perform poorly.**

Keywords - magnetic noise, magnetometer, rotary body UAV

I. INTRODUCTION

Rotary body aircraft is unique since it is both a rotary wing and fixed wing aircraft, which produces lift by spinning like a maple seed. The Papin-Rouilly Gyroptère [1] built in 1915 as a manned airplane is the first example of a "monocoptor", a type of rotary body aircraft. While the Gyroptère did not fly it is the basis for contemporary designs of rotary body unmanned micro-aircrafts. Figure 1 shows some of the latest developments of such micro-aircrafts in industry and academia [2], [3], [4],[5].

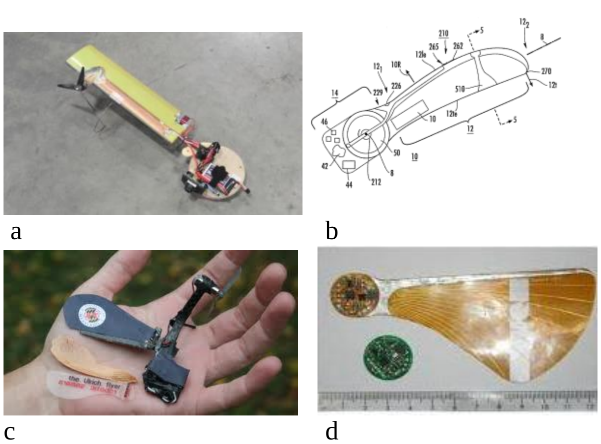

Figure 1. a. Lockheed-Martin Samarai prototype [2], b. Lockeed – Martin patent drawing [3], c. University of Maryland aircraft [4], d. University of Queensland aircraft [5].

The interesting property of the rotary body aircraft is that the core set of sensors of the flight control system, the inertial measurement unit containing magnetometer, is always rotating as it is affixed to the body of the aircraft. While this is not a problem for the sensors, it is an issue for calculation of the attitude and heading of the vehicle since this rotation must be filtered out of the geomagnetic signal. This is compounded by the relatively high rotation rate of these vehicles of up to 10Hz [6], [7].

As the scale of a monocoptor decreases, the speed at which it rotates needs to increase if efficiency of flight is to be maintained [7], [8]. In a fast spinning and small aircraft the on-board magnetometer placed close to the motors is exposed to high level of magnetic noise generated by the motors which rotate with speed close to the spin. Filtering that noise with traditional frequency domain filters is difficult since frequency separation between noise and signal is small, necessitating a complex high order filter, and raising a question if a standard frequency based filter could be effective at all.

This paper presents an alternative: using a recoded or constructed signal to null the signal generated by the motor.

The most widely used motor for micro aerial vehicles is the BrushLess Direct Current (BLDC) motor. The brushless DC motor is a permanent magnet synchronous motor designed to be used with a square wave input generated by a DC powered speed controller [9]. The motor is comprised of a permanently magnetised "rotor" that rotates and the electro-magnetic "stator" that remains stationary. This paper focuses on the most popular out-runner motor type where the rotor is positioned around the outside of the stator as shown in Figure 2.

The out-runner motor has a number of magnets arranged with the poles alternating on the faces of a ring outside the stator, the ring is then connected to a centre shaft that runs inside the stator (stator sandwiched between the rotor and shaft) [10], [11].

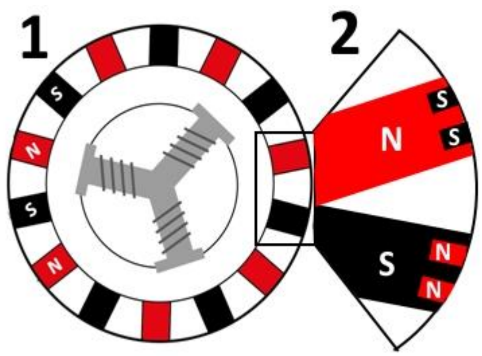

Figure 2. 1. BLDC simplified configuration. 2: Illustration of localised demagnetisation (not to scale).

As the motor rotates, the magnets are presented to different parts of the stator. By energising the windings to pull the magnet towards the winding or inverting the power to winding to push the magnet away, torque is applied to the rotor [12].

The same movement of the magnets generates an alternating field outside the rotor. This field is used by some speed controllers to sense the position of the rotor to determine the optimum way to energise the stator at that instant. This field also is measured by magnetometers as noise superimposed on the geomagnetic measurements.

The strength of the field is dependent on the construction of the magnet, size of the magnet, construction around the magnet and distance to the magnet.

Permanent magnets exhibit a tendency to demagnetise over time. Demagnetisation exhibits relationships with temperature, time and subjected magnetic fields [13], [14]. However it has been noted that there is behaviour where regions of the magnet will demagnetise in preference to surrounding regions resulting in poles with non-uniform strength within the pole region.

Localised demagnetisation is of interest for sensing applications as it adds higher frequency components to the signal generated by the rotation of the motor. Frequencies of these components are approximately odd multiples of the number of poles. As each magnet may not deteriorate identically, the frequency multiple may not be an integer value (but as it is a periodic signal, will be a waveform with an even number of poles).

This paper is structured as follows: in Section 2 analysis of the noise generated by motors is provided, in Section 3 we analyse options for filtering and outline the design of time domain inverse filter, in Section 4 filter performance is discussed, in Section 5 design options and limitations are examined, and finally in Section 6 we conclude and outline possible extensions to this work.

II. EXTERNAL MAGNETIC FIELD OF PERMANENT MAGNET SYNCHRONOUS MOTORS

Before a method of correction could be attempted, the properties of the interference due to the motors needed to be determined. To do this a motor was operated with a moderate load and the resulting magnetic interference

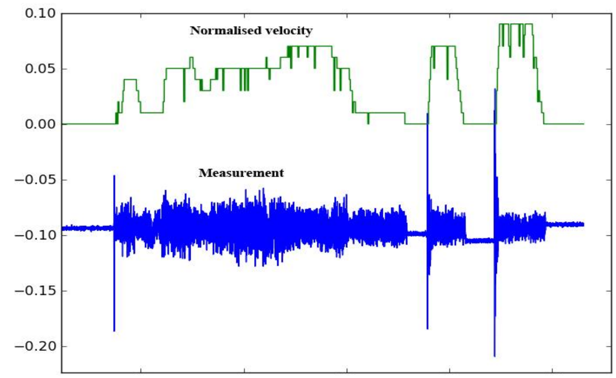

Figure 3. Raw measured magnetic field of rotating motor

recorded by a magnetometer in close proximity. The experiments were conducted on a number of small motors of different types such as Cyclone 440, Scanner RC SCM3213-1750, Turnigy C2826-1650, Turnigy C3542-1100, and a wear ranging from brand new to a few hours of continuous load (typical for micro-aerial vehicles). The effects of the motor were measured at various speeds. During this test it was noted that the noise was fairly constant across the different speeds. The representative results of measurements are shown in Figure 3.

The external magnetic field with the motor running (for the tested motor) is approximately 0.05 gauss. The field generated purely due to permanent magnetic field is also approximately 0.05 gauss for this motor. The above observation indicates that the field measurements can be performed with the motor rotated by an external drive e.g. a stepper motor. Such an arrangement allows for much better control and more precise measurements.

The result of the magnetic field measurement is a periodic waveform presented in Figure It can be observed that the motor appears to have a higher and lower frequency components.

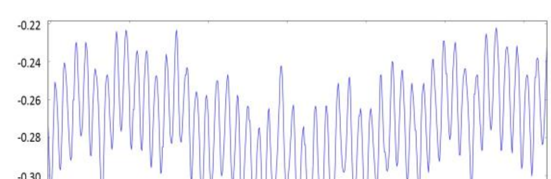

Figure 4. Example magnetic field measurement with a rotating motor

Closer analysis using the Fast Fourier Transform identifies three dominate frequency components, as shown in Figure 5.

The lowest frequency component f_1 corresponds to the speed of the motor. From this it can be established that the motor forms a pair of strong poles, possibly due to imbalances in the magnets. This pair of poles forms the strongest field present in the motor when considering only the permanent magnetic field.

The medium frequency component f_7 corresponds to the magnets embedded inside the rotor of the motor: The motor under this test was a 14 pole motor, with each poll corresponding to either a north or south orientation. As the motor is rotated the polls will result in a waveform with a number of peaks equal to the number of poles and a frequency equal to half the number of poles.

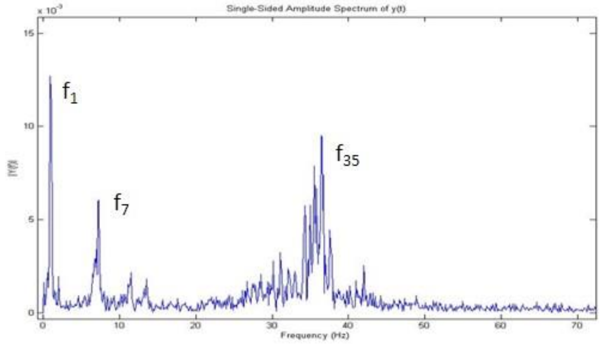

Figure 5. FFT analysis of magnetic field of rotating BLDC

The high frequency component f_{35} is due to localised demagnetisation. Owing to the fact that the demagnetisation is not the same for all magnets, the spectrum had a wider distribution. Different motors exhibited different centre frequencies and distributions, but were all around the 35 times rotation rate.

III. Selection and Design of Filters

A. Frequency domain Filters

Frequency domain filters are the current choice for filtering noise for sensors on UAVs.

The low pass filter is almost universally used on all sensors (typically 2nd or 5th order) to remove high frequency noise from the desired signal. Low pass filters perform poorly when the desired signal is close to the noise and unfortunately, that is the case when the vehicle rotational speed is close to the motor speed.

A more sophisticated method to allow the speed of the vehicle to approach the speed of the motor is to use a combination of tracking notch filter and a low pass filter. Assuming that the motor and vehicle rotation speed don't overlap for long periods, tracking the motor speed, and centring a notch filter on the motor speed may provide a filter of superior performance. A low pass filter would remove high frequency noise outside the maximum vehicle dynamics.

We developed and tested a novel method based on combination of the notch filter tracking the motor and the band pass filter tracking gyroscope measurements of the vehicle. This is based on the observation that if the gyroscope signal is approximately correct then the gyroscope data can be used to estimate the frequency of changes in the geomagnetic field directly related to the motion of the vehicle. We used a notch filter tracking motor speed (4th order Butterworth) and a band pass filter tracking gyroscope measurements (4th order Butterworth).

B. Inverse filter in time domain

The principle of inverse filter is that for periodic noise signals, such as generated by motors, a period of noise signal known not to contain the desired signal is recorded and applied as an inverse signal super-positioned with the measured signal in time domain. The expected result should be the desired signal with only residues of the noise components. This approach has been used in magnetic tape playback [15].

In our application, this method has the potential of providing optimal results assuming that the noise is only dependent on the angular position of the motor's rotor. The noise signal can be divided into position dependent elements that are stored in a look up table. Each element corresponds to a small arc of the motors motion; as the motor rotates, successive elements in the table are used to provide a correction. As this method requires accurate position of the rotor, an optical encoder is added to the motor. The encoder used for experiments generates a signal twice every 1/800th of a rotation (two edges, spaced apart by 1/1600th of a rotation). This signal is used to estimate the position of the rotor and to step to the next element in the look up table.

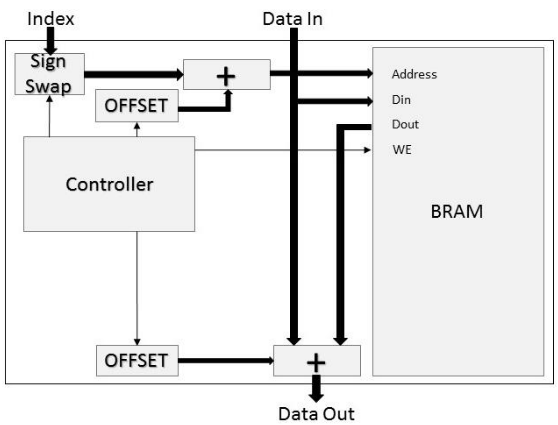

Figure 6. Inverse filter structure

The design shown in Figure 6 is the core of the filter. The index is the current lookup location, Din is the sensor input and Dout is the corrected output. The filter was implemented on an FPGA, and is optimised to make use of the available resources. The BRAM (Block RAM) acts as the look up table and is loaded with the correction values.

Half wave and Quarter wave symmetry were applied to reduce the BRAM usage. Symmetry requires that the index value needs to be folded into a subset of ranges and an offset is needed to shift the waveform. This makes the control part of the design more complex and taking into account the looming accuracy issue in case of asymmetry of the waveform, as shown in Figure 7, makes the approach less attractive.

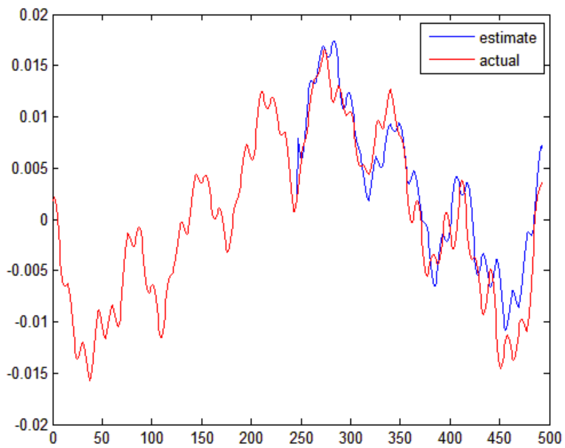

Figure 7. Waveform of half wave symmetric table

Table 1 shows that the logic size doubles when symmetry is used, however as the filter is a very light design, the utilisation of FPGA resources is very small.

TABLE 1. FPGA IMPLEMENTATION RESOURCES

	Used	Spartan 3e500 total available
Logic Slices (no symmetry)	33	4656
Logic Slices (symmetry)	61	4656
Block Ram (1024x16bit)	1	20

The throughput of the filter is very high, requiring only 5 clock cycles to perform a correction. The correction time is as follows:

- 1 cycle to load in the sensor data and index address
- 1 cycle to convert the index address to LUT address
- 1 cycle to fetch the correction from the LUT
- 1 cycle to add the correction and sensor data
- 1 cycle to output the result

This filter is comparable to the simplest frequency domain filter (2 point window filter) in both speed and implementation size. Compared to the band stop/pass filters the implementation size is significantly smaller as it requires at most 3 addition operations rather than iterative addition and multiplication operations. Given a moderate 50HMz clock speed the latency is 100 nanoseconds, which is more than adequate for this application, where filtering in the range of kilohertz is required.

IV. FILTER PERFORMANCE

For all filter designs except the look up table approach, the frequency separation between signal and noise is important. The performance was compared for several conditions:

1. "Traditional" separation that could be expected for most vehicles; vehicle rotation is significantly slower than the motor speed(Typically Fn/Fs > 10)
2. Narrow separation where the vehicle rotation is still slower than the motor, but they are with in an order of magnitude. (10>Fn/Fs > 1)
3. Reversed separation where the motor speed is slower than the vehicle rotational velocity. This would only likely be seen if the motor power was reduced to slow the vehicle (Fn/Fs < 1)

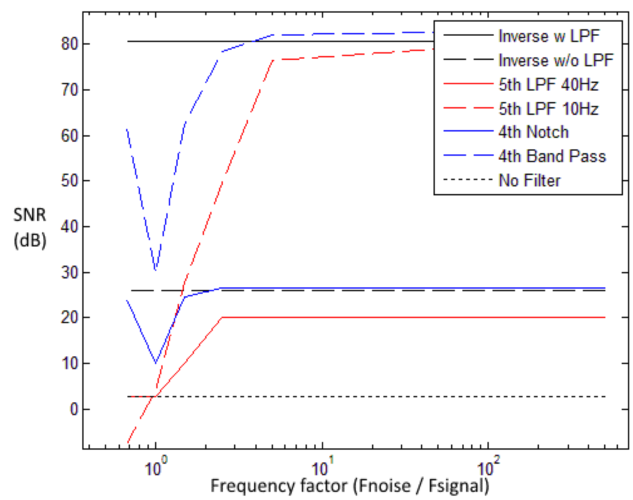

Figure 8. Results of filters at different noise to signal frequency factors

The results in *Figure* 8 show that the low pass filters perform poorly when vehicle and motor rotation speeds are close. Both the band pass and notch filters worked well. Their difference in performance, as shown in Figure 8, is explained by the fact that the notch filter handles motor rotations which have some variance while the band pass filters vehicle rotations which are much more stable due to larger inertia. Their main disadvantage is much larger cost of implementation than the inverse filter.

The look up table based inverse filter has showed good performance and the exceptional performance was achieved with the addition of a low pass filter for filtering the f_{35} component.

Another advantage of the look up table based method is constant latency and linear phase delay, which would be achievable with standard FIR filter but at much higher implementation cost.

V. INVERSE FILTER CONSIDERATIONS

As Figure 5 shows, the spectrum of magnetic noise from the motor contains high frequency component f_{35}. In a straightforward approach the look up table of inverse filter would need to have sufficient number of samples/elements to cover that spectrum. A more efficient method is to augment inverse filter with a simple 2nd order low pass filter (LPF in Figure 8) to filter out that part of the spectrum.

Results presented in Figure 8 were obtained with the highest resolution implemented for the inverse filter, however depending on the platform it may be desirable to decrease the number of elements in the look up table. Tables with 800, 400, 200, 100 and 50 element were tested to determine the impact.

The results in Figure 9 show that for 800 to 200 look up elements the deterioration of performance is limited, while 100 and 50 element table causes significant decrease in effectiveness. The x axis is the rotor position error measured in the number of elements miscounted by the rotor position encoder. The larger the number of samples, the lesser is the impact of the position error since the angle which each sample represents is smaller. FPGA BRAMs make implementation of look up tables very efficient, even if large number of elements is required.

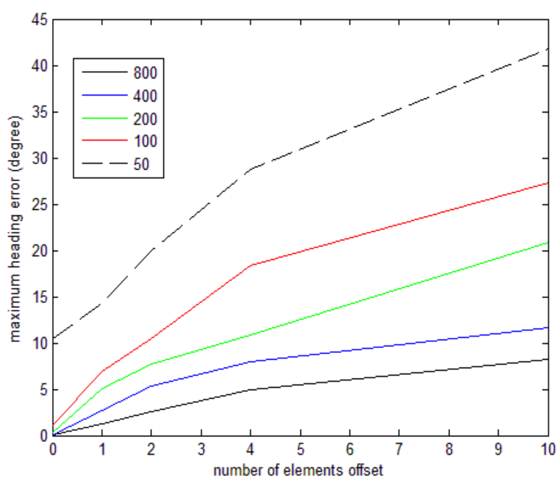

Figure 9. Heading error due to rotor encoder miscounts

Our experiments with a number of motors show significant variations in the rotating magnetic field patterns, even for the same type of motor. This is caused by manufacturing imperfections, demagnetisation and/or wear and tear. The magnets vary in strength (or over time loose strength at differing rates) resulting in the waveform being compressed for a portion of cycle and expanded for another portion, and the individual peaks having varying magnitude. The localised demagnetisation effect adds a high frequency component that is not instantaneously constant, when the motor starts.

The above phenomena means that the look up table must be prepared for a specific motor and updated with the aging of the motor. This can be done automatically with help of an additional calibration module in the aircraft control system that is activated in the start when the vehicle is stationary.

VI. CONCLUSIONS AND FUTURE RESEARCH

We analysed and experimented with the motor induced noise in magnetometer measurements on board micro body rotate aircraft. Methods of filtering that noise were investigated and properties of various filters assessed for this application. An inverse filter in time domain, based on look up table principle, has been designed on FPGA. The filter was tested and proven to have superior performance in filtering signals and noise of very close frequencies. This filter demonstrates a small implementation cost while offering speed either matching or exceeding the performance of optimised frequency domain based filters.

The research presented in this paper focused on steady state operation of the motor. This was justified as the motor speed of a rotary body vehicle does not vary significantly during operation. However for some applications where the motor speed need to change rapidly, further research is needed to assess applicability of our filtering method.

A possible application of our research is also for assessing the health of a motor by monitoring the spectrum of motor induced noise in magnetometer readings. It has been demonstrated that as a motor ages or is subjected to high loads, the localised demagnetisation increases, changing its noise spectrum. This relationship could be possibly used to estimate the health of the motor.

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