SIMPLE MOTOR AND CONTROL CONCEPT RESULTS IN HIGH EFFICIENCY AT HIGH VELOCITIES

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ABSTRACT

The need for high velocity motors in space applications for reaction wheels and detectors has stressed the limits of Brushless Permanent Magnet Motors (BPMM). Due to inherent hysteresis core losses, conventional BPMMs try to balance the need for torque verses hysteresis losses. Cong-less motors have significantly less hysteresis losses but suffer from lower efficiencies. Additionally, the inherent low inductance in cog-less motors result in high ripple currents or high switching frequencies, which lowers overall efficiency and increases performance demands on the control electronics.

However, using a somewhat forgotten but fully qualified technology of Isotropic Magnet Motors (IMM), extremely high velocities may be achieved at low power input using conventional drive electronics. This paper will discuss the trade study efforts and empirical test data on a 34,000 RPM IMM.

1. GENERAL REQUIREMENTS

Avior was approached with a requirement for a proprietary application to provide motor and controller that operates at 34,000 RPM continuously. The system had to achieve synchronous speed within five seconds, and have an internal torque Margin of Safety (MoS) per GEVS [1]. There were no requirements for reversal or ramp-down. The envelope requirements for the motor are 40 mm in diameter by 50 mm long, and operate off supply voltage of 26 to 32 VDC. This program is in the bench-testing developmental stage, which will lead to eventual flight hardware.

2. MOTOR CONTROLLER OPTIONS

To address the challenge of this application, Avior's engineers simulated the performance as a conventional BPMM, a Permanent Magnet Stepper motor, a Hybrid Stepper Motor and finally as an IMM.

2.1 Brushless Permanent Magnet Motor Analysis Results

Brushless Permanent Magnet Motors (BPMMs) are certainly established within the industry as reliable performers. Performing analysis at high velocities, however, yields extremely high inherent core losses in the motor. These losses are referred to as hysteresis or eddy current losses, and are the result of rotating a high-energy-product magnet inside a permeable magnetic material. Hysteresis losses are extremely linear and repeatable. We add these dynamic losses to the zero-speed magnetic coulomb and bearing friction of the rotor assembly. Hysteresis losses are roughly proportional to the cube (third power) of the motor bore size and linear with magnet length. Given this relationship, it makes sense to use the smallest practical motor. The basic performance of Avior's 19 mm motor are as follows [2]:

Table 1 – 19 mm Brushless Motor

Parameter	Symbol	Value	Units
Coulomb Friction	fc	2.3E-04	Nm
Bearing Friction	fb	9.0E-4	Nm
Hysteresis Losses	Bv	2.0E-7	Nm/RPM
Analysis Velocity	ω	34,000	RPM

Our total torque losses at speed (Tv) is represented in Eq. 1, and the Power Loss at speed due to motor frictions (Pv) is represented in Eq. 2

$$Tv = fc + fb + (Bv \bullet \omega) \tag{1}$$

$$Pv = \frac{Tv \bullet \omega}{9.55} \tag{2}$$

Note: Eq. 2 does not include motor I^2R or electrical eddy current losses, which will increase our dynamic power losses further.

When we perform the calculations of the power losses due to hysteresis and frictional losses in our motor, we would realize a power loss of 28 watts. These losses alone would result in a motor temperature rise in a vacuum of over 280º C, given the motor's thermal constant in a vacuum of about 10ºC per watt. This realization is enough to halt our trade study, for this candidate motor. If the power losses were reasonable at this point, we would apply our torque margins per [1] and add our I^2R and electrical eddy current losses to our analysis.

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2.2 Stepper Motor Analysis Results

Low-level logic voltages to control Direction, Step and Enable (DSE) and their extensive application heritage make stepper motors highly desired in space applications. One of the disadvantages of stepper motors, however, is their limitation of operation at high velocities. Permanent Magnet and Hybrid Stepper motors are very similar in their ability to achieve high-speed operation. Our engineers were aware that stepper motors are not an ideal solution for this application, but this analysis sets the stage for our ultimate solution.

A common figure of merit for any Permanent Magnet Motor is the Torque per Square Root Watt, known as the "Km". In order to double the torque, you require four times the power. A similar relationship holds true with a Stepper Motors Response Rate, or No Load Speed. The Response Rate Constant, or K_{RR}, describes the No Load Speed in RPM per Square Root Watt of stall power. In order to double the no load velocity, you must apply four times the stall power to the motor. Intuitively, smaller frame-size motors have higher K_{RR}. Avior's 19mm motor has a K_{RR} of 900 RPM/square root watt. In order to achieve 34,000 RPM velocity, over 1.4 kilowatts of stall power would be required (assuming there would be no saturation, which there assuredly would be). Obviously, stepper motors are not a preferred solution.

2.3 Isotropic Magnet Motor Analysis Results

Isotropic magnets have minimal magnet properties in the absence of a magnetic field. Unlike permanent magnets, their field may be oriented in different directions. In other words: Isotropic magnets create a low energy product magnetic field while in the presence of presence of a magnetic field. The consequences of this characteristic allow for extremely low core losses at extremely high velocities.

IMMs, also known as Hysteresis Synchronous Motors, have typically been controlled with sinusoidal voltages, but operate quite efficiently with square wave voltages generated from a conventional DSE stepper motor controller. Torque performance at a specific velocity is proportional to power, unlike Permanent Magnet Motors where the torque is proportional to the square root of power. The torque per watt and peak torque capacity of an IMM is significantly lower than a similar frame size BPMM. This characteristic, however, is the key for operation at high velocity.

Analysis of an IMM at velocity is a bit more difficult to ascertain because of their isotropic characteristics. We look to empirical testing to determine capability and compliance with the requirements.

2.3.1 Empirical Testing of Isotropic Material Candidates

There are many isotropic materials to choose from, but experience has narrowed the selection down to two potential candidates. Previous applications have shown that a low Coercive Force is desired for high-speed application. We did not, however, select the potential candidate solely on the lowest Coercive Force. Table 2 delineates the isotropic materials conducted in our trade study.

Table 2 – Isotropic Material Candidates

Material Candidate	Residual Induction (Br) [Tesla]	Coercive Force (Hc) [A/m]
A	0.7	40,000
B	0.58	90,000

Without going into all of the test methods Table 3 delineates the observations and benefits of each of the material candidates:

Table 3 – Material Observations

Parameter	Preferred Material	Comment
Low Speed Torque Capacity	Material B	Advantage
Power Consumption at 34,000 RPM	Material A	Slight advantage
MoS at 34,000 RPM	Material B	Torque during acceleration better for Material B, although torque at desired velocity largely the same
Highest obtainable stable velocity	Material A	70,000 RPM plus versus 40,000

The highest obtainable stable velocity was the deciding factor in the selection of Material A. A comparison of the dynamic velocity versus torque performance of the two candidate materials in Avior's 32mm diameter motor is shown in Fig. 1. It is important to note that this performance represents the torque capacity at dynamic frequency operation (not at fixed frequency).

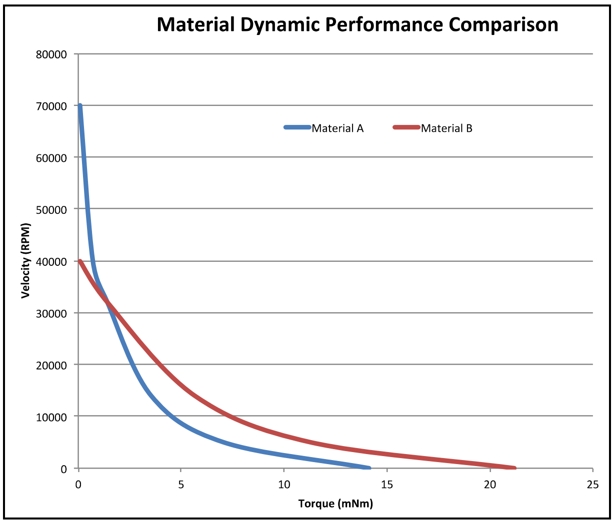

Figure 1. Dynamic Performance of Material Candidates

Figure 2. Avior's High Speed Motor and Controller

3. VERIFICATION OF MARGIN OF SAFETY

To verify the MoS of IMM using the requirements of [1] we derive Eq. (3) through (5):

$$MoS = \left[\frac{T_A - (T_{BR} \bullet K_V)}{T\alpha} \right] - 1 \quad (3)$$

$$T\alpha = J_T \bullet K_C \bullet \alpha \quad (4)$$

$$\alpha = \frac{\Delta\omega \div 9.55}{\Delta t} \quad (5)$$

Where:
MoS = Margin of Safety and must be > 0
T_A =Available Torque, in Nm
T_{BR} = Bearing Friction Torque at speed, in Nm
K_V = Variable Torque Factor of Safety
$T\alpha$ = Torque to accelerate load, in Nm
J_T = Total Load Inertia (Motor + Load) , in kgm^2
K_C = Known Torque Value Factor of Safety
α = Acceleration requirement in rad/sec^2
$\Delta\omega$ = Change in velocity, in RPM
Δt = Change in time, in seconds

Table 4 tabulates our variables and results:

Table 4 – MoS Variables and Results

Symbol	Value	Units
$\Delta\omega$	34,000	RPM
Δt	5	Seconds
α	712	Rad/sec
Jt	1.0E-06	Kg2
K_C	1.5	-
$T\alpha$	1.068E-3	Nm
T_A	4.0E-3	Nm
T_{BR}	1.4E-3	Nm
K_V	2	-
MoS	0.124	-

This analysis demonstrates the requirement of torque MoS is satisfied. It is important to note that we are assuming the Available Torque, T_A, is the minimum mean torque *over the ramped velocity profile*. In other words; as the velocity is increasing, the T_A at speed is decreasing, but we are looking for the torque over the range to achieve an acceleration rate profile. Further, when we have reached our desired velocity, there is no need for torque required to accelerate. To increase the MoS for this application, additional power input would be required.

With the final selected Material Candidate A, Avior measured a total power input to the motor controller of only seven watts at 34,000 RPM. Since the power loss at velocity for motor is so low, an increase in power to increase the MoS would be acceptable from a thermal perspective.

4. CLOSING A VELOCITY LOOP

For the subject application, the customer was willing to ramp up the step rate from 5,000 to 34,000 RPM through the controller in an open loop fashion. Avior wanted to test the concept of adding a rate sensor integral to the motor and automatically ramp the rate through a Voltage Controlled Oscillator (VCO). The concept is extremely simple; as the motor is enabled and the velocity is low, a set minimum frequency is sent to the controller “step” or Clock command. As the velocity increases, the frequency automatically increases to a maximum set frequency. By adding this function the robustness of the control motor increases significantly. For this test, we used a Dynic Labs custom control board along with a Dynic Labs 404 Stepper Motor Controller. The 404 controller was supplied with the deliverable high-speed motor and is an off-the-shelf configurable stepper motor driver [3]. The custom velocity controller is a simple tachometer demodulator with a VCO as described above. A simple schematic block diagram of this concept is shown in Fig. 4.

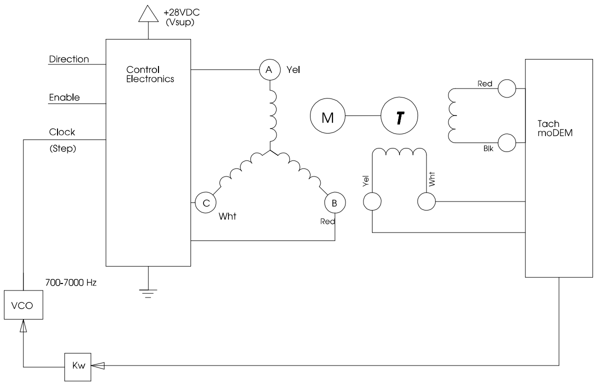

Figure 4. Auto-Ramping with Voltage Controlled Oscillator

The results of adding this simple control circuit were remarkable. In addition to the control motor automatically slewing up to the desired velocity, if the motor were to encounter a high torque that might pull the motor out of synchronism, the frequency slows down automatically, providing additional torque to resume desired operation. A conventional open look motor would simply pull out of synchronism and stall or run at a significantly lower rate. This feature significantly increases the MoS and robustness of the system.

5. IMPLICATIONS OF HIGH SPEED OPERATION

Mechanical considerations for the rotating members of the motor must carefully be considered when operating at extreme velocities. It may not be enough to try and design the rotor to be balanced, as uneven distribution of epoxy might be significant enough to cause imbalances which impact bearing performance.

High-speed ceramic hybrid bearings are best solution when operating at extreme velocities. Specifying the highest bearing quality, polished raceways and matched ball sizes can significantly increase performance and reliability. Solid machined crown cages are significantly more reliable and quiet when compared to stamped crown or ribbon retainers. Additionally, stamped retainers have much lower resonant frequencies when compared to machined crown retainers. The lower resonant frequencies of stamped retainers increase the likelihood of a resonant acceleration lock or resonant frequency fatigue failure, when compared to machined crown retainers.

6. CONCLUSIONS

Considering the various motor configurations and options of available and qualified motor configurations, Isotropic Magnet Motors can offer reliable and efficient performance at extreme high speeds of 34,000 RPM. These motors provided sufficient torque margin of safety while operating at a total power input of seven watts. Other technologies considered, such as Brushless Permanent Magnet and Stepper Motor technologies require significantly higher power consumption or cannot achieve these velocities at all.

Adding a simple rate sensor with a Voltage Controlled Oscillator significantly increased robustness and responsiveness.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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