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DESIGN OF OPTIMUM SIZED ROTOR OF A BLDC MOTOR FOR A HIGH PERFORMANCE ACTUATOR

KEYWORDS
BLDC motor, Rotor, Compact, Actuator

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ABSTRACT *High performance actuation systems are used in flight duties with demands of high bandwidth and high power in restricted size, weight and shape. This paper presents the concerns in Rotor design for a brushless permanent magnet (BLDC) motor for a short duty high performance actuator. Important criteria in shaping the rotor are investigated and optimum sized rotor is designed for a new BLDC motor. Design is verified by simulations, making a prototype and testing it. It is found that the most important design criterion for rotor is the determination of its dimensions, high quality materials and applying high electrical loading without rotor magnet demagnetisation.*

INTRODUCTION

Now a days, the use of BLDC motor are increasing in the control systems due to their advantages of rugged construction like induction motors and controllability like brushed DC motors. The actuators used in control systems use motor as a prime mover, a gear system to amplify the motor torque, a sensor on the output position and an electronics for servo controlling. Electric motor for control systems has to meet up several constraints like- compact size, modular shape, high demands of load and speed, low inertia etc. There were many papers explaining the approaches to design a compact BLDC motor for various specific applications. But approaches for designing motor for high power, high bandwidth applications are not many. In this paper an analytical study for a design approach on rotor of a compact BLDC motor to be used for short duty actuation application is presented. To prove the concept, a new motor is designed; a model motor is fabricated and tested. In compact drives, motors coupled with gears have more space advantage than ungeared motors. Depending on the requirements of a typical flight control actuator, the specifications of the motor to be designed are derived a shown in table-I. The complicate demands that are coming on the motor are: high torque, high speed, maximum power output, high acceleration, low inertia, compact winding with low overhang, reliable operation etc.

TABLE I
Specifications of BLDC motor

Parameter	Specifications
Working Voltage	28 V
Maximum Torque	> 0.25Nm
Maximum Speed	13000 Rpm
Limit on Current	< 20 A
Limit on Weight	250 Gms
Limit on length of Motor	< 25mm
Limit on Motor outer diameter	< 54mm
Duration of one operation	< 180 s
Maximum Acceleration	223600 rad /sec2

ROTOR DESIGN CONCERNS

Rotor of a motor is an important element because it is it that converts the electromagnetic energy into mechanical energy and gives the required motion. It consists of permanent magnets attached on a soft magnetic core and the whole assembly is inserted over the shaft. This shaft is supported by bearings at the ends and it becomes the first part of the transmission system for torque amplification. Rotor design directly influences the design of stator and thus influences the motor performance. Proper understanding of the demands on the rotor is essential for building a compact high performance motor.

Duty cycle

The characteristic duty cycle of speed and torque of the position servo system of a self-governing flight vehicle is as shown in following Figure-1.

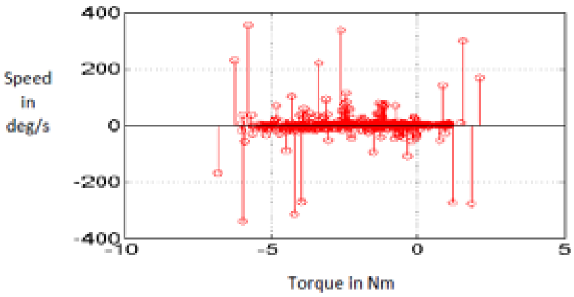

Figure-1: Speed vs Torque of a typical flight actuator with gears

Understanding the duty cycle is very essential to come to a decision about the machine's rating and efficiency. It can be inferred from figure-1 that the rotor continuously experiences rapid accelerations and decelerations in both directions for meeting the demands of actuator.

Equivalent rated torque (*M*) of the load cycle of above nature can be expressed as

$$M = \frac{\sqrt{(M_1^2 t_1 + M_2^2 t_2 + M_3^2 t_3 + \ldots\ldots M_n^2 t_n)}}{(t_1 + t_2 + t_3 + \ldots\ldots t_n)} \quad \ldots(1)$$

Where M_1,M_2,M_3 and Mn are different periodic load torques with respective time periods t_1, t_2, t_3 and tn.

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It can be observed from the above duty curve that the ratio of peak torque to rated torque is very high and therefore the rotor design should aim for maximum power output from the machine. The gross mechanical power developed by a motor can be highest when back e.m.f. is equal to half the applied voltage and this result in the motor efficiency to be nearby of 50%.

Dimensions of rotor for high power

Torque generated from the motor increases as the volume of the rotor increases with relation as below

$M = (P\ Ø)(ZI)/3\pi$..(2)

$= (\pi D^2 L\ Bav\ Ac) / 3$....................................(3)

Where P is no. of poles, Ø is flux per pole, Z is no. of conductors, I is current, D is diameter of rotor, L is effective length of rotor, Bav is flux density of air gap and Ac is specific electric loading. To meet high power the dimensions of the rotor should be increased. But as the outer dimensions of motor are limited, any increase in rotor dimensions reduces the volume of stator and thus increasing the resistance of winding in the stator which is undesirable.

Dimensions of rotor for high bandwidth

The high bandwidth of a servo system demands high acceleration from the motor and this happens at starting of the motor. The high acceleration in turn demands high starting torque to overcome inertia of the rotor. For a constant value of motor torque constant (K_T) the mechanical torque can be written as

$M_{motor} = K_{T\,*}.I$..(4)

M (at starting) = Macceleration = J * Acceleration ... (5)

$KT^*I = (WD^2/8)\ {}^*Acceleration$.................................(6)

$Acceleration = 8K_T{}^*I / WD^2$.................(7)

Where J is Moment of inertia, W is mass of rotor.

If a rotor is designed with smallest feasible volume to meet the demand for high acceleration, then the rated torque generated may not be sufficient to meet the load torque. But increase in volume decreases the acceleration ability due to limits for current and size

The relation between rotor diameter, acceleration and torque (as per equations-3 and 7) is shown in the figure-2. It can be inferred from these equations that to meet rated torque, the rotor diameter should be more; but to meet the acceleration demand, it should be less. This is a very delicate situation.

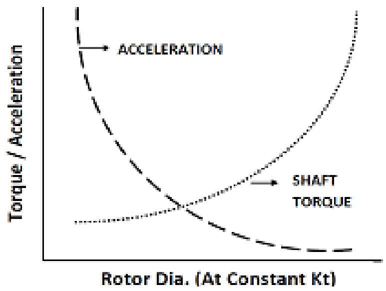

Figure 2: Shaft torque vs. rotor diameter and Acceleration vs. rotor diameter.

A trade-off is to be made and an optimum length and diameter of the rotor is to be selected to meet the both ends. Therefore, computation of rotor dimensions is an iterative process involving the rotor inertia, gear ratio, as well as the suitability of the motor for meeting the dynamic requirements of the servo system. The final dimensions can be finalised only after satisfying the analysis of the motor simulation and the load model.

Motor Load model and analysis

To come to conclusion of optimal rotor dimensions for meeting the load torque as well as acceleration demands, it is crucial to analyse the analytical parameters in the load model for the motor performance analysis. For achieving optimum size of rotor, the torque equation of an electric drive is followed.

$Mm = \sum(Macceleration + Mfriction + Mload)$ **...................... (8)**

The torque equation can be modelled as shown in figure-3 for the load analysis. As it contains inertia, load, acceleration and friction components, the output gives the torque-speed characteristic of the motor with the assumed motor constants.

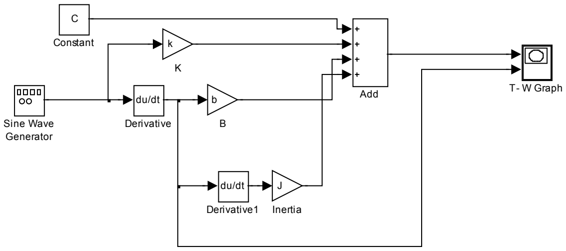

Figure 3: Load model for finding motor performance

Magnetic and Electric loading

To design a compact machine, the values of specific magnetic and electric loadings should be pushed up for higher potential values. The maximum value of electric loading is determined by the type of duty of the motor and magnetic saturation of the materials. The customary values of short duty rated motors are 20000 Ac/m but this will not meet the present demand as it makes the motor dimensions oversized. As the duty is intermittent with high acceleration and deceleration, very high value of electric loading has to be selected for compactness. But the upper limits are to be cross checked by the demagnetisation effects that reduce the effective magnetic loading and in turn reduce the torque generated. This can be analysed in the torque-speed curve of the motor model.

The higher values of specific loadings can be achieved by selecting the finest magnetic materials. For the permanent magnets of rotor, rare earth materials can be selected for their advantage of higher remnant magnetism. For the rotor back iron, soft magnetic material-Permandur alloy is best suited for their highest value of saturation flux density and very high magnetic permeability. The concern in using these special materials is their availability and affordability.

TABLE-II

Typical properties of magnetic materials

'soft material'	Permeability	Max. flux density

Ferroxcube	650	0.4 T
CRNGO-A	15000	1.5 T
CRNGO-B	2000	1.7 T
Permalloy	75000	1 T
Permandur	13000	2.3 T
'hard material'	BH_{max}(KJ/m3)	Max. flux density
Ferrite	15	0.5 T
ALNICO	35	0.76 T
Sm2Co17	200-250	1 T
NdFeB	250-350	1.2 T

Dimensions of rotor for low threshold

The threshold is the smallest signal for which actuator starts responding. A lower value of threshold is desired for the actuator sensitivity for high bandwidth systems but achieving it involves physical limitations of motor and tuning of controller. Equations-5 and 6 shows that lower threshold value for motor current demands lower inertia of the rotor in turn requiring smaller rotor dimensions.

Air gap over Rotor

A lower value of air gap for a motor is desirable but difficult to achieve in practice with machinability tolerance. Whereas the higher value of gap increases the required mmf and thus demands increase in magnet thickness resulting increased rotor dimensions. A typical value of 0.5mm over rotor diameter can be selected from the point of precision engineering tolerance in fabrication.

Rotor Position Sensor

Commutation of BLDC motor is to be done with the help of rotor position sensors. Sensor less system can be considered but it is yet to be proven for a fast response closed loop systems. Using Hall Effect sensors is the simplest rotor position sensor for implementation of commutation with minimum space occupying when compared to other sensors like resolvers, encoder etc. When the rotor magnetic poles pass over the hall sensors, they give high or low signal indicating North or South Pole to commutation electronics. The figure 4 shows the proper location of hall sensors for good commutation in both forward and reverse directions of rotation of a 8-pole rotor.

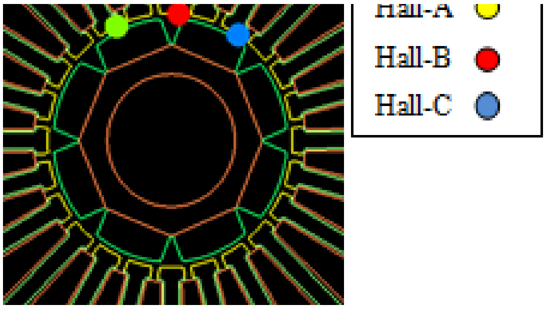

Figure 4 Hall sensors placement over the rotor

SIMULATIONS

The design output parameters of the motor derived from above said procedure are to be analysed by Electric motor software for fine tuning of parameters. This software was used as a tool for finding the performance of the machine in a repetitive iterative optimization until the desired objectives are achieved. The parameters calculated analytically by above mentioned equations are given as input for the analysis and fine tuning of other parameters are done.

Finite element analysis is now a part of machine analysis for parametric characterisation. Figure-5 shows the flux density variation across a rotor and the values of air gap flux density shows the validity of values of electrical and magnetic loadings. As the analysis is carried out with some assumptions and limits on values, the model results are pessimistic over the hardware test results with slight variation.

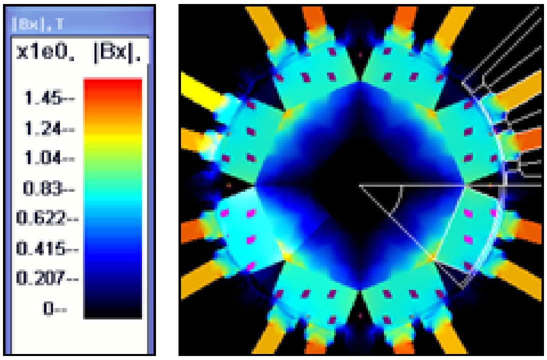

Figure 5: Flux density distribution across the rotor

PROTOTYPE

A prototype motor for short duty intermittent applications based on the design procedures described above has been built as shown in figure-6. Rare earth Sm2Co17 magnets are glued on the Permandur made rotor body and an Aluminium sleeve cover is fitted around the magnets to counter the centrifugal forces generated due to high speeds. Stator is skewed by half slot pitch to minimize the cogging torque. The dimensions and test results of the prototype are presented in table-III.

MEASUREMENTS AND TEST RESULTS

The machine physical parameters and functional parameters are tested and measured values are compared with the specified values.

TABLE III

Test results of main parameters of the motor

Parameter	Specification	Achieved
Torque constant	0.02 Nm/A	0.02 Nm/A
Rated Torque	0.15 Nm	> 0.15 Nm
No-load Speed	13000 rpm	>13000 rpm
Rated speed	4000 rpm	>4000 rpm
Acceleration	223600 Rad/s^2	>223600 Rad/s2
Maximum Current	< 20 A	< 20 A
Maximum Weight	< 250 gm	< 250 gm
Space envelope mm	25(L)x 54 (dia)	25(L)x54 (dia)

The Torque –speed characteristic or the load test is carried out on the dynamometer test set-up. The acceleration parameter is tested with motor fixed with gears and made into closed loop system with position sensor and then finding the frequency response of the system.

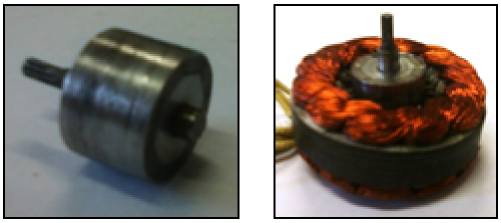

Figure 6: (a) Rotor (b) Stator and rotor

The figure-6 shows the realised hardware of the motor whose weight and dimensions are shown the table-III. This motor is integrated in the actuator housing along with gears and servo controller and the system met the specifications of the intended position servo system. The main dimensions of the motor and its major parameters are shown in table-IV.

TABLE IV
Dimensions and properties of the proto motor.

Parameter	Value
Phases number	3 phases
Pole number	8poles
Air gap	0.5 mm
Rated torque	0.15 Nm
Air gap flux density	~ 0.8 Tesla
No-load speed	13000 rpm
Motor constant	0.02 V/Rad/S
Rotor diameter	20 mm
Stator inner dia.	21mm
Rotor back height	2 mm
Magnet thickness	3 mm
Active motor length	10 mm
End turns length	14 mm
Mass of motor	~ 250 gm

CONCLUSIONS

The design of a compact BLDC motor for actuation systems for short duty depends a lot on the design of the rotor. It is found that the Rotor dimension is the most critical parameters for achieving high accelerations along with meeting the load torque. The BLDC motor prototype built for short time operations as a design example shows satisfactory results. The measured machine constant agrees with the calculated values and the tested parameters meet the input specifications. Similar procedure can be implemented in other position servo systems where the size is very acute and the demands on the motor are high. A brushless permanent magnet motor is one of the desired solutions from a compactness and design effort perspective, when a new motor design is necessary for a control system.

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