ANALYSIS AND DESIGN OF HYBRID STEPPER MOTOR AND TORQUER USED IN SPACE APPLICATION

By

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CERTIFICATE

Certified that the thesis entitled **"Analysis and design of hybrid stepper motor and torquer used in space application"** being submitted by **Mr. K. R. Rajagopal** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy,** is a record of the original bonafide research work carried out by him under our joint supervision and guidance and that the results contained in it have not been submitted in part or full to any other university or institute for the award of any degree or diploma.

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Dedicated

to

my mother ***Mrs. M. Sunanda Bai***

and my father late ***M. D. Ramanadha Sarma***

ABSTRACT

Hybrid stepper motors used in space application, owing to their operational requirements, necessitate improvements in its design to make it suitable for operation with nearly constant torque performance, in the face of varying dc supply voltage and varying operating temperature conditions. Study is also needed to arrive at optimum switching strategies for the hybrid stepper motor, used as the drive motor of slow-speed mechanism of satellite, to reduce the power input as well as disturbance to the satellite subsystems. Arriving at an optimum switching pulse, for such a motor, requires the knowledge of exact static torque and detent torque patterns. Various parameters, influencing the torque profiles, need detailed investigations. Similarly, improved design methodology of the hybrid stepper motor, has to be developed with a view for improving its performance, in terms of figures of merits, such as torque-to-mass, torque-to-volume, and torque-to-power ratios. For this purpose, the new design tools, like, Finite Element (FE) analysis package, etc., can be employed.

In this research work, a novel procedure for the design and development of compact high resolution hybrid stepper motor having pole/coil redundancy, suited for varying supply voltages and varying operating temperatures, has been formulated. Various design parameters of the hybrid stepper motor have been examined. 2-D FE analysis conducted for selection of optimum tooth geometry, confirms that the best tooth-width/tooth-pitch ratio (t/λ) for doubly slotted structures working in the moderate range of saturation, lies between 0.38 and 0.42. The analysis has also shown that the slot depth of half the tooth-pitch is the optimum one and the rectangular shape for the slot gives better performance than the trapezoidal, triangular and circular slots. 3-D FE analysis conducted for the tooth-geometry of the hybrid

stepper motor has given the optimum t/λ ratio between 0.38 and 0.4. Equal tooth-width and t/λ for the stator and rotor, result in better torque density than different t/λ ratios for stator and rotor, with a corresponding increase in detent torque. This causes presence of small dips in the static torque profile. But, equal tooth-width and different tooth-pitch for stator and rotor, make the static torque profile smooth, as the detent torque is comparatively lesser in this case. Therefore, for meeting the requirements of maximum torque density, high detent torque and better positional accuracy, equal pitch slotting with equal tooth-widths have to be adopted. Instead, for maximum torque density, less detent torque, and moderate positional accuracy and smooth static torque profile, different pitch slotting with equal tooth-width are required. The concept of "optimum-module" using 3-D FE analysis for the hybrid stepper motor for reduction of the mass and volume, has been introduced. For fixed outer and inner diameters of the motor, the optimum module length, which comprises of the lengths of rotor stacks and permanent magnet ring can be minimised by fine tuning the motor module-geometry using 3-D FE model.

In this work, a new phenomenon has been identified namely, the "torque saturation", achievable only in hybrid stepper motor. This phenomenon can be made use of in controlling the developed torque to a nearly constant value, in the face of varying supply voltages. In the torque saturation range, the incremental increase in the positive and negative torques at the respective rotor stacks, is made equal such that they neutralise each other, and the motor delivers a nearly constant torque. The torque saturation phenomenon, unique to the hybrid stepper motor, is obviously different from the magnetic saturation observed in the conventional electrical machines.

Two high resolution hybrid stepper motors, viz. (i) 1.8^0, 0.55 Nm, 2-phase, bipolar drive motor, and (ii) 0.5^0, 1 Nm, 4-phase unipolar drive motor, have been designed, developed and tested. Both the motors have winding redundancy, and they are suited for varying supply voltages of 28 V to 42 V, and also for varying operating temperature range form -55^0C to $+75^0$C. The test results have confirmed the validity of the predictions arrived at on the basis of 2-D and 3-D FE analyses. The developed motors provide nearly constant torque for varying supply voltages and varying operating temperatures. Measured static torque curves reveal that the developed motors are capable of providing better positional accuracy. The step response of the motors in different onboard operating modes are also quite satisfactory. The figures of merit, like torque-to-mass, torque-to-volume, and torque-to-power ratios, for the 1.8^0 motor are found to be better than those of the leading manufactures of such high performance hybrid stepper motors.

Usage of solid stator and rotor stacks has increased the accuracy of fabrication without affecting the performance of the motors, since the maximum speed at which these motors run are very low. Similarly, usage of a number of small cylindrical samarium cobalt permanent magnets put in a ring form in the rotor, which is mandatory in pancake type design, is noted to have no adverse effect on the performance of the motor, to a noticeable level.

Airgap non-uniformity has to be controlled to obtain a repeatable and accurate performance from a hybrid stepper motor. The non-uniform airgap introduces a position dependent fundamental detent torque alongwith the conventional fourth harmonic detent torque. This changes the detent torque and static torque profiles of the motor, making it position dependent. The static torque curves for different phases of the same motor, are different, thereby changing the stable equilibrium positions of the motor. The soft magnetic material used for the stator stack has some residual magnetism, which develops a fundamental detent torque after the withdrawal of the excitation of a phase. The magnitude of this fundamental detent torque is different for different excitation levels, and hence will cause undesirable stepping behavior which reduces stepping accuracy. As both the airgap non-uniformity and the hysteresis property of the soft magnetic material, cause the presence of a fundamental detent torque, analysis of the measured detent torque pattern, requires the history of the magnetic condition of the motor, at the time of testing as pre or post-excitation, to identify the respective torque components.

The repetitive pulse switching scheme has been found to be better than the continuous single pulse switching scheme for high resolution hybrid stepper motor used as the drive motor of very slow speed mechanism of satellite. It reduces the power intake as well as the disturbance due to stepping, which is otherwise severe in the satellite. Varying pulse width voltage switching, which provides a ramp type current increase and decrease, is found to be better than the repetitive pulse switching scheme with regard to the overshoot and disturbance, but requires more power intake.

Stepper motors are being very widely used in aerospace, military, and industrial applications. It is hoped that the work reported here, on the design and development of high performance hybrid stepper motors, would benefit the designers of such motors in reducing the size and power intake. Motors, which are made insensitive to supply voltage and operating temperature variations, would also attract significant applications in industry. The results of the 2-D FE analysis of tooth-geometries of doubly slotted machines, and the concept of module-optimization using

3-D FE analysis, would be helpful to those who are engaged in the design and development of various types of stepper and switched reluctance motors.

For a high performance Inertial Navigation System (INS), the gyroscopic sensor, having a permanent magnet (PM) torquer as the torque-to-null actuator, the temperature sensitivity of -450 ppm/^{0}C is of great concern. It causes unacceptable errors in the gyro output, which is the angular rate of the satellite or the launch vehicle. The cumulative error over a period of time can cause a mission failure. There are traditional methods to reduce this error, but they put heavy penalty on the satellite or launch vehicle, as they need additional subsystems to monitor the temperature, electronic correction circuits, software correction, etc. This increases the launch mass, and also makes the entire satellite control system sluggish. Therefore, a passive temperature compensation by design, as an inherent characteristic for the PM torquer, is very much desirable.

In this research work, extensive FE analysis has been carried out to model the PM torquer and to analyse the magnetic circuit, for providing inherent temperature compensation. The analysis conducted for arriving at an optimum temperature compensated PM torquer configuration, has revealed the limitations of the conventional shunt compensation method. The conventional method is suited only to permanent magnet having very small thickness in a direction orthogonal to its magnetic axis and also for magnetic circuit having smaller physical airgaps. This method is of no use in the torquer used in gyroscope, owing to its larger physical airgap (5mm) and higher magnet thickness (6mm).

A novel method of temperature compensation is arrived at, in which the direct flux path between two permanent magnets, alongwith the conventional shunt path, has been used. In a PM torquer developed with this novel method, the temperature sensitivity of the scalefactor has been measured as -12 ppm/^{0}C against the designed value of -5 ppm/^{0}C over the entire operating temperature range of 0^0C to 70^0C, usually encountered by the gyroscope, used in space application. Sensors and actuators used in aerospace inertial and industrial applications utilise special devices having permanent magnets for high performance requirements. It is hoped that, the work reported here, on temperature compensation for permanent magnet devices, would be useful to the designers of high performance sensors and actuators, which utilise permanent magnets.

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