Design and Finite Element Analysis of Hybrid Stepper Motor for Spacecraft Applications

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Abstract— **This paper presents the design and analysis of a 400-step hybrid stepper motor for spacecraft applications. The design of the hybrid stepper motor for achieving a specific performance requires the choice of appropriate tooth geometry. In this paper, a detailed account of the results of two-dimensional finite-element (FE) analysis conducted with different tooth width/tooth pitch ratios (t/λ) and also with different tooth/slot shapes such as square and trapezoidal, is presented. The use of equal t/λ ratio on stator and rotor provides nearly 10% more torque than the case with unequal t/λ ratio ,but with corresponding increase in detent torque and distorted static torque profile. For the requirements of maximum torque density, less-detent torque, and better positional accuracy and smooth static torque profile, different pitch slotting with equal tooth width has to be provided. From the various FE models subjected to analysis trapezoidal teeth configuration with unequal tooth pitch on the stator and rotor is found to be the best configuration and is selected for fabrication. The designed motor is fabricated and the experimental results is compared with the FE results.**

Index Terms—**Hybrid stepper motor, Finite-element (FE) analysis, torque, space application.**

I. INTRODUCTION

The motor having the permanent magnet rotor and multiple teeth both on the stator and rotor poles, with excitation in stator poles is called the hybrid stepper motor. Stepper Motors are divided in to two major groups, one without permanent magnet and the other with permanent magnet. The term hybrid is derived from the fact that the motor is operated under the combined principles of permanent magnet and variable reluctance motors. Hybrid stepper motors are widely used in space applications, office and factory automation applications. Hybrid stepper motors are highly preferred in space applications as they can provide accurate positioning in open loop system. The positional accuracy of the stepper motors will be high only when its step angle is very small. Hence for space applications hybrid stepper motor is the best choice as it can offer small step angles in the ranges of 0.5^0 to 1.8^0.The other classes of stepper motors such as variable reluctance stepper motor and permanent magnet stepper motor will be suitable only for applications which require large step angles. The design of a hybrid stepper unlike that of conventional ac motors such as induction motor and synchronous motors using equivalent magnetic circuit analysis is not easy because of the complex air gap geometry, which results in complex air gap permeance variation. Because of this, analysis using Computational Electromagnetics, a complex task and this results in the dependency of Finite Element Technique for design and Analysis Purpose. Since Hybrid stepper motor has a large number of teeth on the stator and rotor surface and a very small air gap, the magnetic saturation in the teeth becomes severe while increasing the flux density in the airgap. In addition both radial and axial flux is produced because of axially magnetized permanent magnet and geometric characteristics [1]. This makes the analysis of hybrid stepper motor more difficult using 2D FE modeling. Three dimensional finite element analysis is one of the solution for nonlinear analysis of axially unsymmetrical hybrid stepper motor under this situation [2]. But in order to reduce the computational time involved in the analysis a 2-D equivalent of the 3-D model of the motor was developed and used.

II. FINITE ELEMENT ANALYSIS

Most electromagnetic problems involve either partial differential equations or integral equations. While partial differential equations are usually solved using the finite difference method or finite element method, integral equations are solved conveniently using moment method. In contrast to other methods, the finite element method accounts for nonhomogeneity of the solution region [3]. The systematic generality of the method makes it a versatile tool for a wide range of problems. Finite Element Analysis is used extensively for the design and performance prediction of all types and topologies of permanent magnet machines and for calculating field distributions, torque and force. Commercial Finite Element package has been used to carry out the analysis.

III. DESIGN METHODOLOGY

The volume and mass of the motor should be minimal for any optimal design and development of Hybrid Stepper Motor. The volumetric efficiency as well as the torque to inertia ratio

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of the motor has also to be considered while designing. The aim of the work is to design and develop a power optimal hybrid stepper motor having dimensional and space constraints. The outer diameter and the axial length of the machine are fixed as 94 mm and 45 mm respectively. According to the standard design guidelines for stepper motors [4] based on magnetic circuit analysis, the following dimensions has been arrived at:

Yoke Thickness = 4 mm
Stem Length = 8 mm
Stem Thickness = 4 mm
Pole Height = 3 mm
Rotor stack thickness = 6 mm

Air gap radius of the machine is found as 32mm

A. *Number of poles, teeth and configuration*

Using a bipolar drive system is a universal practice in hybrid stepper motor as it gives maximum torque output for the given volume of copper [5]. Two coils can be provided on each pole with one as Prime and the other as Redundant. The coils can be interconnected to form a four phase bipolar redundant winding configuration. For the operation of any stepper motor, at least four poles are required on the stator. It is better to have the minimum number of poles for the ease of fabrication and winding. However this has been worked out depending upon the required step angle in full step mode as 16 numbers of poles. Half step mode of operation is normally not envisaged in stepper motors used in spacecraft, due to the fact that the torque available for acceleration in succeeding steps will be different and hence will cause different disturbance levels on the spacecraft. Out of 32 coils, 16 have been earmarked for redundancy requirement. With the unifilar windings, 4 poles/phase, 4-phase bipolar drive configuration is used separately for Prime and Redundant modes.

The use of equal tooth pitch (λ) on stator and rotor structure provides nearly 10% more torque output from the motor than with unequal tooth pitch [6],[7]. However there is corresponding increase in the detent torque. Being maximum torque density, better positional accuracy and moderate detent torque are the requirement; equal tooth width slotting with equal tooth pitch on stator and rotor is adopted (i.e., t/ λ = 0.5 for both stator and rotor)

For a stepper motor,

$$\theta = \frac{360}{mN_r} \tag{1}$$

Where, θ is the step angle, *m* is the number of stator phases and *Nr* is the number of rotor teeth.

Since the hybrid stepper motor to be designed is for space application, the positional accuracy of the motor should be very high. So a step angle of 0.9^0 is selected based on the requirement. Hence the number of rotor teeth required for the 4 phase hybrid stepper motor is computed from *(1)* as *Nr = 100.*

Step angle θ of a hybrid stepper motor is also given by a formula,

$$\theta = 360\,\frac{N_s \sim N_r}{N_s N_r} \tag{2}$$

Thus number of stator teeth (2) is calculated as Ns = 80. Thus the total number of steps required by the motor to complete one complete revolution (3) is 400.

$$n = \frac{360}{\theta} \tag{3}$$

Where, n is the number of steps required by the motor to complete one full revolution. The tooth pitch of the machine is (4) is 2.

$$n = \frac{Airgap\ Circumference}{No\ of\ Rotor\,Teeth} \tag{4}$$

The tooth width t of the motor is taken as 1 mm and 0.8mm for t/λ = 0.5 and 0.4 respectively. Since the motor has 16 poles, number of stator teeth/pole is 5 and the inter-polar gap is calculated to be 3.5 mm.

B. *Permanent Magnet Details*

Permanent magnet type : Sm_2CO_{17}
Diameter of the magnet : 5 mm
Length of the magnet : 7.5 mm
Number of magnets : 60
Shape of the magnet : Pellet

C. *Stator Winding*

Stator winding is chosen in such a way that the alternate 8 poles connected in series provide optimum stator excitation under these 4 poles and also by ensuring that the phase current does not exceed the rating of the copper wire used for the entire range of the supply voltage from 30V. Two coils per pole are provided to make the configuration suitable for redundant 4-phase bipolar drive circuit.

D. *Module-geometry*

For fixed outer and inner diameters of the motor, calculation of axial length plays a key role in designing an optimized hybrid stepper motor. The entire volume and mass consumed by the motor geometry shall be fully utilized. The permanent magnet and the stator and rotor stacks should be optimally utilised for their full capability, without causing magnetic saturation. The rotor of the hybrid stepper motor is divided in to two identical modules of axial length 15mm stacked back to back.

Even though the hybrid stepper motor to be designed has a

3-D geometry, it is necessary to develop its equivalent 2-D model as this will significantly reduce the computation time involved in the analysis. The 2D FE software will calculate the working flux for the depth of 1m of the permanent magnet which is been made use of in developing the equivalent 2-D model. Four stator poles has been modeled taking symmetry of the machine in consideration. 2 D model for the designed motor with square and trapezoidal teeth having t/λ = 0.5 and 0.4 is modeled in the 2-D modeler of the Maxwell-2D software separately and analysed.

E. Designed data

A brief design data of the developed hybrid stepper motor is given below:

Number of phases = 4
Number of coils/Ph = 8
Number of poles = 16
Number of Stacks = 2
Number of steps/revolution = 400
Step angle = 0.9^0
Number of Stator teeth/pole = 5
Number of Rotor Teeth = 100
Number of coils /pole = 2
Permanent Magnet = Sm_2Co_{17}
Air gap = 0.1mm
Dimension = ϕ94 mm x 45mm
Supply voltage = 30 VDC
Drive circuit = Bipolar, 4 phase

IV. ANALYSIS

The analysis of the designed hybrid stepper motor is done in four steps such as Holding torque analysis, Detent torque analysis, Holding Torque variation with change in excitation and air gap variation at peak torque position

A. Holding Torque Analysis

Holding Torque is defined as the maximum load that can be connected across the output shaft of the motor under excited condition with the motor not losing its equilibrium position. The Holding torque (developed torque) analysis of the machine is carried out with an excitation of 200 AT for both the square and the trapezoidal models with t/λ = 0.5 and t/λ=0.4. From the above analysis, the position of the rotor, which gives maximum torque, is found out. For further analysis purpose both the motor excitation and the air gap is varied at this position and the characteristics is studied. Fig.2 shows the finite element mesh generated by the FE software for motor having square teeth with t/λ = 0.5 and 200 AT excitation. Flux Density distribution and its variation in stator poles, Stator and rotor teeth and yoke portion is shown in Fig.1. Material saturation can be identified with this. Fig.3 shows the holding torque variation with stroke length. A comparison of the holding torque characteristics for motor configuration with square and trapezoidal teeth having t/λ ratios of 0.5 and 0.4 is obtained as shown in Fig.3.

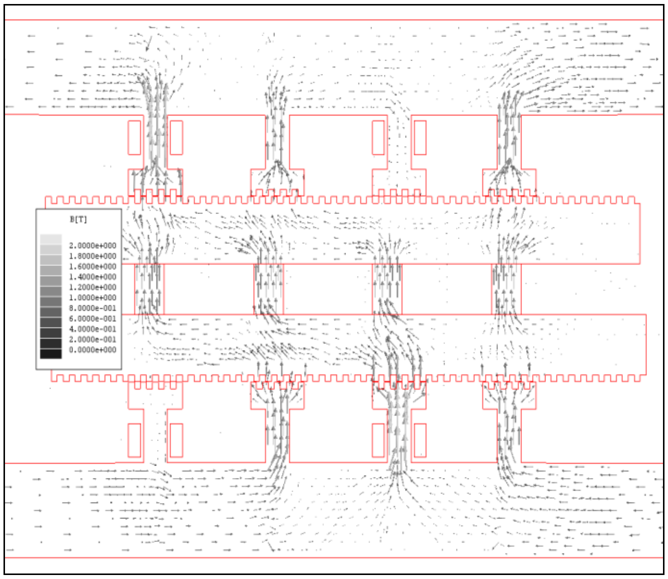


Fig. 1. Flux Plot of Hybrid Stepper Motor - 2D FE Model

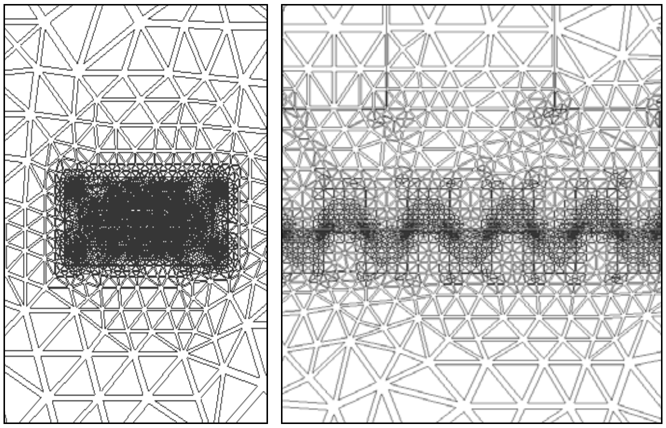


Fig. 2. Hybrid Stepper Motor - 2D FE Mesh

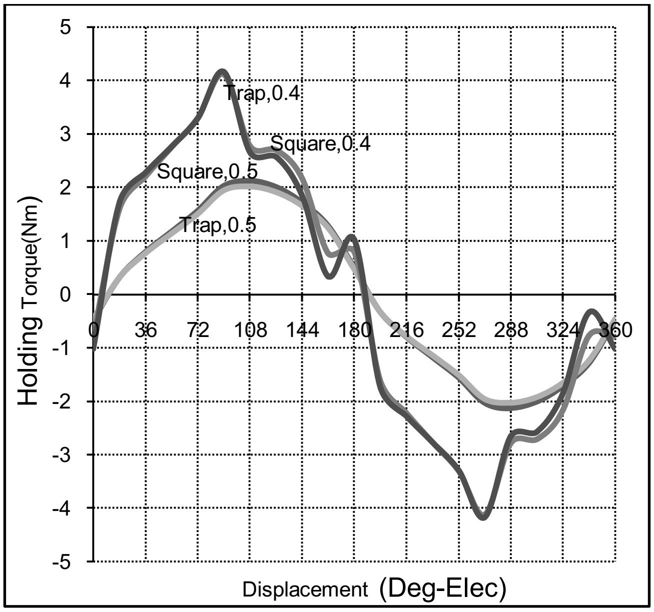


Fig 3. Holding Torque Characteristics – Different Configuration (FE Result)

From Fig.3, it is clear that the peak torque as well as the average holding torque developed by the machine is high for lower values of t/λ.The peak torque is obtained for the motor configuration with square teeth and t/λ =0.4.But the profile of the developed torque pattern obtained with t/λ =0.4 is not as smooth as that is obtained with t/λ=0.5. The difference between the developed torque of square and trapezoidal configuration is less. Because of the better stiffness offered by the trapezoidal teeth configuration, it is preferred over square configuration.

B. *Detent Torque Analysis*

Detent Torque is defined as the maximum load that can be connected across the output shaft of the motor under un-excited condition with the motor not losing its equilibrium position. For the detent torque analysis of the motor the coil is in un-excited condition since this torque is produced solely due to the presence of permanent magnets. The presence of detent torque in the designed hybrid stepper motor is very small as compared to the developed torque of the motor. This Detent torque presence will suit the performance of the motor, as it will help the motor to maintain its positional accuracy after the removal of the excitation. The variation of Detent Torque for various configurations is shown in Fig 4. From the Fig.4 it is clear that there is a sharp increase in the detent torque produced when t/λ is reduced from 0.5 to 0.4 for both square and trapezoidal configurations. Also the detent torque pattern for t/λ =0.4 is not as smooth as compared with t/λ = 0.5.

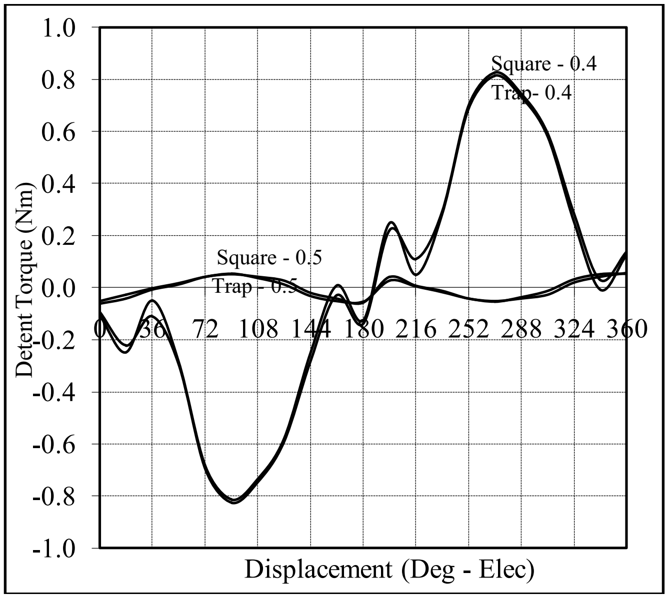


Fig 4. Detent Torque Characteristics – Different Configuration (FE Result)

C. *Analysis with varying excitation and air gap*

Fig. 5 and Fig. 6 show the effect of variation of excitation and air-gap on the developed torque of the motor at its peak torque position. From the variation of the air-gap and motor excitation it is found that the developed torque is maximum when the air-gap is minimum. The importance of the selection of smaller air-gaps in stepper motors is evident from Fig.5. Based on fabrication feasibility, air gap of 0.1mm is chosen.

From the Fig. 5 it is clear that the developed torque is increasing linearly up to 160 AT excitation and after that the effect of saturation evident in 160-220 AT excitation range.

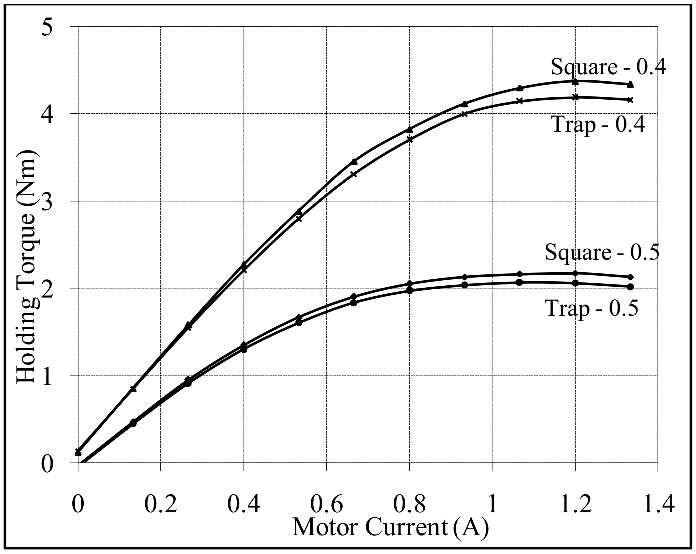


Fig 5. Variation of Peak Torque with Excitation – Different Configuration (FE Result)

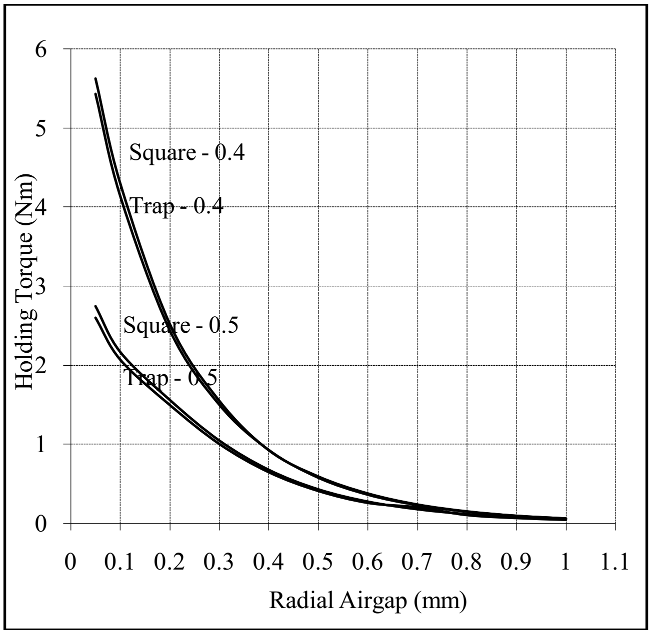


Fig 6. Variation of Peak Torque with Air gap – Different Configuration (FE Result)

D. *Improved Design employing unequal t/λ ratio on stator and rotor*

Even though the trapezoidal teeth motor with t/λ ratio of 0.4 on stator and rotor is the best configuration among the four models which are subjected to analysis it has certain disadvantages. The model is having high detent torque and distorted static torque profile which is not desirable for spacecraft applications. Hence the design was modified by employing unequal t/λ ratio on stator and rotor. Fig.7 and Fig.8 shows the comparison between the holding torque profile and detent torque profile of a trapezoidal teeth motor when equal and unequal t/λ ratios are employed on stator and rotor. From Fig.7. it is clear that the holding torque profile of the trapezoidal teeth motor with t/λ=0.383 on stator and t/λ=0.4 on rotor is much smoother as compared to the model with t/λ=0.4 on the stator and rotor. Also from Fig.8.it is clear that the model with unequal t/λ ratio on stator and rotor produce less detent torque as compared to the high detent torque produced by the equal t/λ ratio model .Because of its numerous advantages the motor configuration with trapezoidal teeth and unequal t/λ ratios of 0.383 and 0.4 on the stator and rotor respectively is preferred over the other model even though it produces 10% less torque.

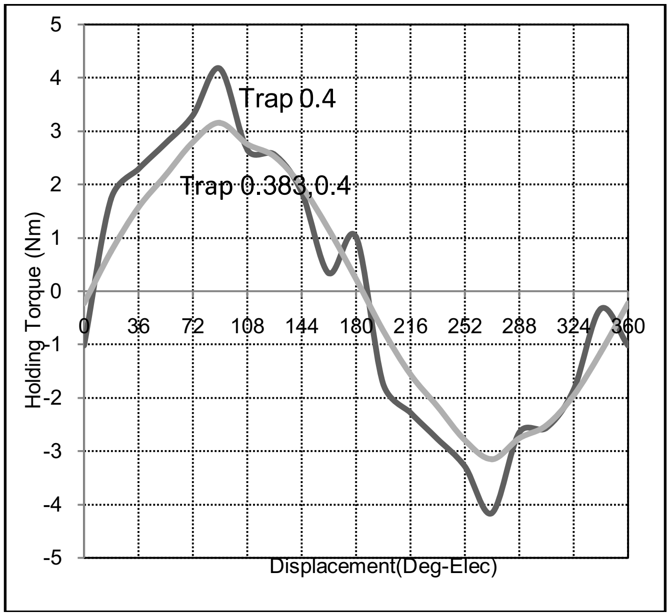


Fig 7. Comparison of Holding Torque Characteristics of trapezoidal model with equal and unequal tooth pitch on stator and rotor. (FE Result)

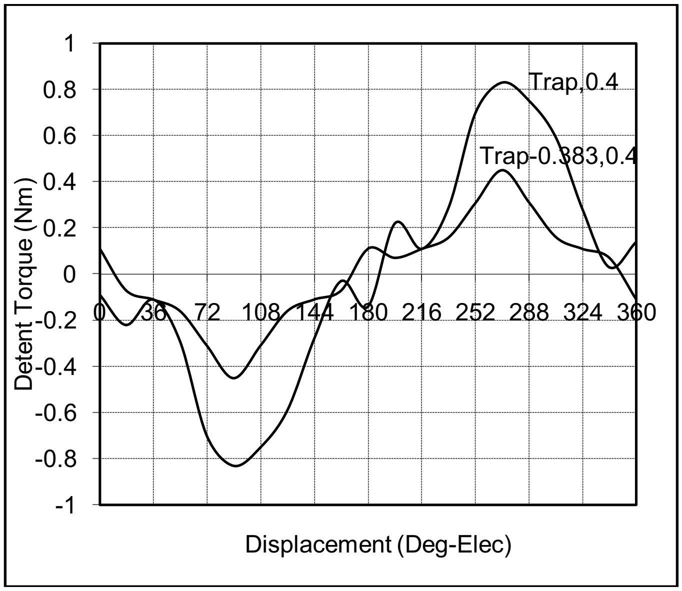
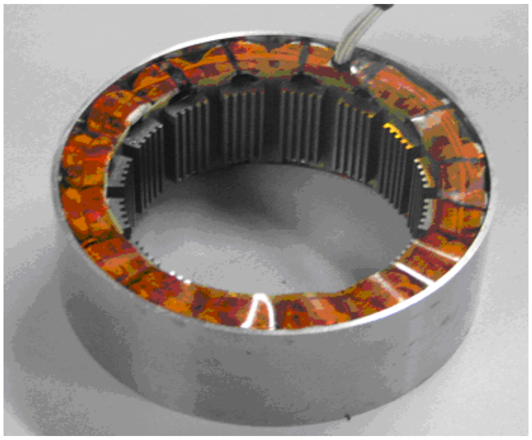


Fig 8. Comparison of Detent Torque Characteristics of trapezoidal model with equal and unequal tooth pitch on stator and rotor. (FE Result)

V. DEVELOPMENT AND TESTING

Based on the above design parameters, the machine is realized with trapezoidal teeth and unequal tooth pitch in stator and rotor. The hardware of the machine i.e. the stator and rotor assembly is shown in Fig.9.



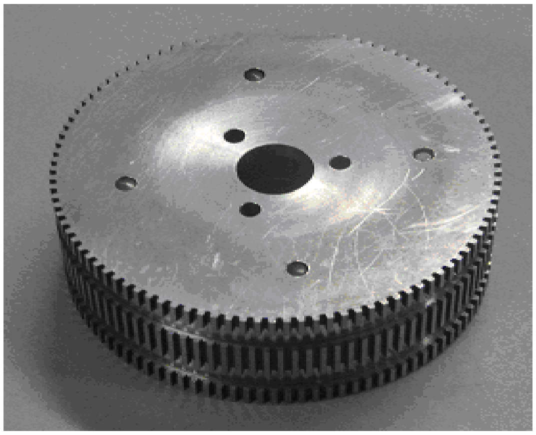


Fig 9. Stator and Rotor Assembly of the fabricated Hybrid Stepper Motor.

The designed hybrid stepper motor is tested for the validation of its static torque characteristics with the 2D FE analysis carried out and the test rig for validation is shown in Fig. 10. Piezoelectric dynamometer is being used as the torque sensor and torque profile is measured by holding the rotor and rotating the stator using the microcontroller based rotary table. Table 1 gives the comparison of the FE and the test results. Because of the 2D approximation, there is discrepancy between FE and test results. This can be overcome with3D analysis of the machine.

TABLE I
COMPARISON OF FE AND TEST VALUES

Excitation (AT)	Torque (Nm)	
	FE	Hardware
100	1.7	1.9
150	2.5	2.9
200	3.1	3.5

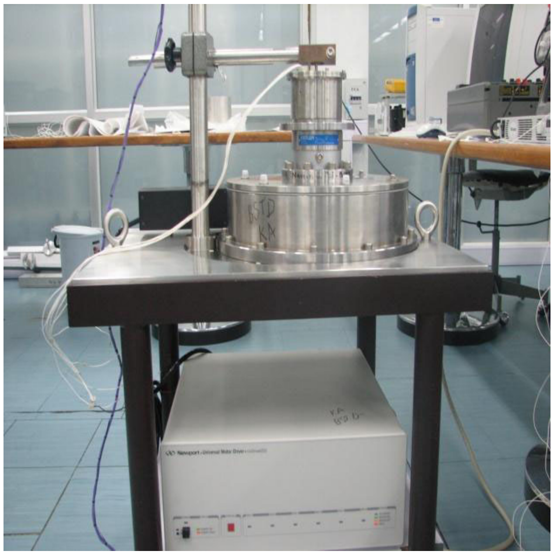


Fig 10. Experimental setup of the designed Motor

VI. CONCLUSION

A power optimal hybrid stepper motor with dimensional constraints was designed taking care of the volumetric efficiency. Holding torque characteristics and Detent Torque characteristics of each model were obtained using FE software. The effect of the variation of air-gap and Stator excitation on Holding Torque was also found out. Four models with equal t/λ ratio on stator and rotor have been subjected to analysis and of these the best possible configuration is found to be the motor having trapezoidal teeth and t/λ ratio of 0.4 on the stator and rotor. Trapezoidal tooth shape is preferred over square tooth shape because of the stiffness. This model was further modified since it has a distorted static torque profile and high detent torque which does not suit space applications. The design was modified by employing equal tooth width/unequal tooth pitch on stator and rotor thereby smoothening the static torque profile and reducing the detent torque. When unequal tooth pitch is provided in stator and rotor, the torque pattern became smoother with the minimal decrease in holding torque. The machine is realized, tested and the results were compared with the FE results.

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