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Effect of Motor Parameter Variations on the Performance of Miniature Claw Pole Permanent Magnet Stepper Motor

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Abstract

This paper deals with a parametric study of Motor geometry and Material characteristics on the performance of a Small Claw-poled Permanent Magnet Stepper Motor. In this analysis effect of variation in individual factor on Motor performance is analyzed. Along with that combine effect of variation in different factors is also analyzed. Design of Experiment (DOE) using Taguchi Approach and Analysis of Variance (ANOVA) techniques are carried out to find out best suitable combination and relative contribution of selected factors on the Motor Performance.

Keywords: ANOVA, DOE, Motor Constant, Taguchi Method

I. Introduction

Small, claw-poled, PM, steppers are commonly used in many home appliances and the automotive industry ,optical disk drivers, printers, computer peripherals, digital cameras, and mobile communication devices due to their positioning abilities and their low cost [1],[2]. For small low cost brush less DC drive, claw pole geometry is the best option. This special type of machine is designed with a claw-pole stator and a permanent magnet excited rotor. The stator winding is a simple cylindrical coil situated in the stator [3]. This type of motor is driven by input pulse.

The general construction for claw PM stepper motor will be as shown in figure. Rotor assembly and stator assembly are separated by air gap. Air gap should be as minimum as possible because it creates reluctance to flux path. Rotor contains shaft and magnet assembly .Magnet is magnetized into number of poles as per step size requirement. Stator consists of claw pole cups in which coil is mounted. The current switching between phases and shifting between inner claw poles makes motor to run.

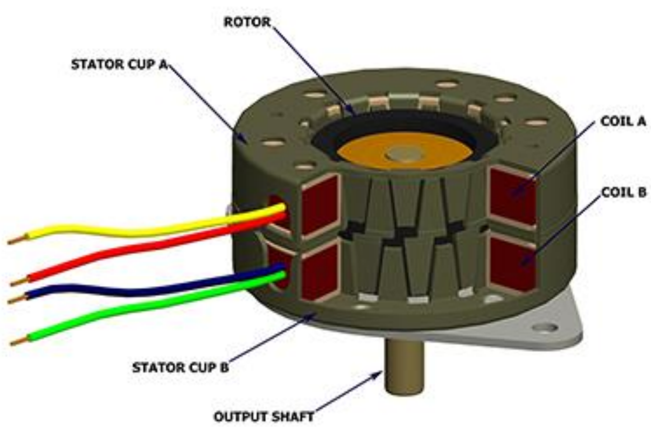

Fig. 1: Claw Pole Permanent Magnet Stepper Motor
(Source: www.portescap.com)

In this paper, firstly the effect of variation of one factor on motor Performance is analyzed by keeping other factors constant. Then effect of variation of different factor at a time on Motor Performance is analyzed by using Design of Experiments (DOE) and Analysis of Variance (ANOVA) technique. All this analysis is carried out by keeping size i.e. Outer Diameter of Motor constant.

Factor variation cause the Resistance of coil or Electromechanical Torque or may be the both to change. It ultimately changes the Motor constant. Based on the Coil space, Resistance and Number of turns of wire are calculated by keeping same coil wire size (AWG) for all models. Air gap is kept constant for all the models. Air gap flux density is calculated from the shape of the claw pole. Electromagnetic torque is calculated based on Claw Pole Geometry, Rotor Diameter, Electrical Loading and Air Gap Flux Density [3]. Motor Performance comparison is carried out by keeping size and power input constant for all motor models.

II. MOTOR PERFORMANCE CALCULATION

In this paper, Motor Performance is measured by the parameter called Motor Constant(K_m).Motor Constant is a tool for comparing relative efficiencies and power capabilities of different motor. Motor with low motor constant value will be the best one. The motor constant for a DC motor is defined as follows (1):

$$\text{Motor Constant } K_m = \frac{R}{{K_t}^2} \qquad (1)$$

Where,
R= Coil Resistance (Ohm), calculated based on the coil space coil wire size.
K_t= Torque Sensitivity K_t corresponds to Electromechanical Torque T (Nm) produced per unit supplied Current I (Amp).

Reference [3] has given detailed procedure to calculate the Electromechanical Torque (T). Equation (2) is used to calculate Electromechanical Torque (T).

$$T = \frac{\Pi * {d_r}^2 * h_{cp}}{2} * A * B_g \qquad (2)$$

Where,
d_r=Rotor Diameter.
h_{cp}=Height of claw pole.
A =Electric Loading.
B_g=Mean air gap flux density.

III. FACTORS WITH THEIR EFFECT

A. Rotor diameter

Rotor diameter represents the diameter of Magnet. Rotor diameter variation affects the Bend line distance from centre of claw pole plate. Bend line is the line where claw poles are bending. Air gap assumed to be constant in all models. This effect will cause to change in claw pole outer diameter, which is twice as that of bent line distance. So it changes the claw pole geometries like height, Root width and ultimately surface area. Coil width will be change in the same ratio as that of rotor diameter variation. Radial space of coil also changes. Due to which Resistance and Number of turns of coil will change. The above effects will cause to change Motor performance.

Rotor diameter variation is expressed with the help of Rotor Diameter Ratio. It is the ratio of Rotor diameter to the Maximum outer diameter of Coil. Refer to (3), Maximum coil Outer Diameter is calculated based on the allowable space between coil surfaces to Motor tube to avoid contact.

$$Rotor\ Diameter\ Ratio = \frac{Rotor\ Diameter}{Coil\ Outer\ Diameter} \qquad (3)$$

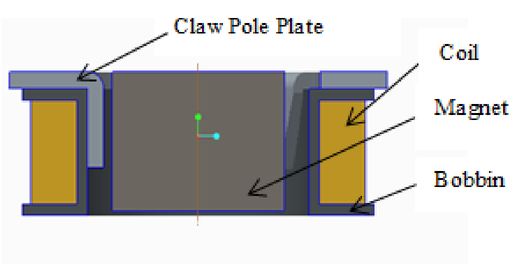

Fig. 2: General outline for motor

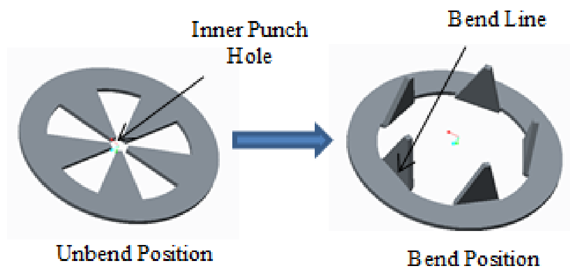

Fig. 3: clae pole plate

B. Inner Punch Hole of Claw Pole Plate

Claw pole plate bending operation is as shown in fig.3. For bending operation it is required to maintain a hole at the centre of claw pole plate. Change in inner punch diameter affects the claw pole geometries like surface area, height, and root width. This change tends to cause change in Airgap flux density which ultimately vary the Motor Performance.

C. Steel Sheet Thickness

It is the thickness of sheet used for Claw pole plates. Variation in steel sheet thickness for same size of motor will cause change in coil space while keeping constant air gap. Sheet thickness also affects the Air gap Flux Density due to change in flux at claw pole root [3].Above changes ultimately vary the Motor Performance.

D. Maximum Allowed flux density in Steel

It is the material property which describes the maximum amount of flux that the steel sheet allows to pass through it. It is different for different grades of steel. Variation in this parameter will change the amount of flux passing through claw pole root width. This factor doesn't affect the geometry of the motor.

IV. DESIGN OF EXPERIMENT (DOE) USING TAGUCHI APPROACH

The main aim of DOE is to arrange an efficient experiment with smaller number of experiments, shorter experiment cycle, and lower experiment cost, so as to obtain good experimental results and scientific analysis conclusions [4].

A Taguchi Approach is used for DOE. The DOE using Taguchi approach can economically satisfy the needs of problem solving and product/process design optimization projects. By learning and applying this technique, engineers, scientists, and researchers can significantly reduce the time required for experimental investigations.

Reference [5] gives the detailed procedure for DOE and ANOVA. Same procedure is followed here.

A. Objective

To find best combination of factors to get optimum Motor Performance. Here Optimum Motor Performance is represented by minimum Motor constant value.

B. Key Factors with their Levels

Following four factors are selected based on the brainstorming. Three levels are selected for each factor to get smooth results.

Table – 1
Factors value at respective Level

Control Factors ↓ / Levels→	*Unit*	*1*	*2*	*3*
Rotor Diameter Ratio A	*-*	*0.5*	*0.6*	*0.7*
Inner Punch Hole Diameter B	*mm*	*1*	*1.1*	*1.2*
Steel Sheet Thickness C	*mm*	*0.3*	*0.4*	*0.45*
Maximum Allowed Flux Density In Steel D	*Tesla*	*1.6*	*1.8*	*2*

C. Selection of Orthogonal Array

For Full Factorial Design of four factors with three level there will be total of 81 runs will be possible. But by using Taguchi fractional factorial design, orthogonal array L9 will be the best option with only 9 run.

'Y' is value for Motor constant in ($10^6/(Nm * s)$).L9 orthogonal array with calculated results is as follows, Refer Table-2,

Table – 2
L9 Orthogonal Array

Trials ↓/Factors→	*A*	*B*	*C*	*D*	*Motor Constant (Y)*
1	*1*	*1*	*1*	*1*	*6.62*
2	*1*	*2*	*2*	*2*	*3.67*
3	*1*	*3*	*3*	*3*	*2.83*
4	*2*	*1*	*2*	*3*	*3.06*
5	*2*	*2*	*3*	*1*	*4.86*
6	*2*	*3*	*1*	*2*	*4.83*
7	*3*	*1*	*3*	*2*	*11.04*
8	*3*	*2*	*1*	*3*	*6.23*
9	*3*	*3*	*2*	*1*	*9.35*

Here each trial is having different combination of levels for the factors. Based on the respective combination Motor Performance is calculated as explained in earlier section.

D. Computation of Average Performance

Average Performance is the average of total Performance at Respective Level. Total Performance is calculated by adding Result of same level for the respective factor.

Table – 3
Average Performance for factors at respective level

Factor with Level	*A1*	*A2*	*A3*	*B1*	*B2*	*B3*	*C1*	*C2*	*C3*	*D1*	*D2*	*D3*
Total Performance	*13.12*	*12.76*	*26.62*	*20.72*	*14.75*	*17.02*	*17.68*	*16.08*	*18.74*	*20.83*	*19.55*	*12.12*
Average Performance	*4.37*	*4.25*	*8.87*	*6.91*	*4.92*	*5.67*	*5.89*	*5.36*	*6.25*	*6.94*	*6.52*	*4.04*

E. Quality Characteristic

For Minimum Motor Constant, Quality characteristic will be "Smaller the Better". Average Performance is used to represents the optimum condition.

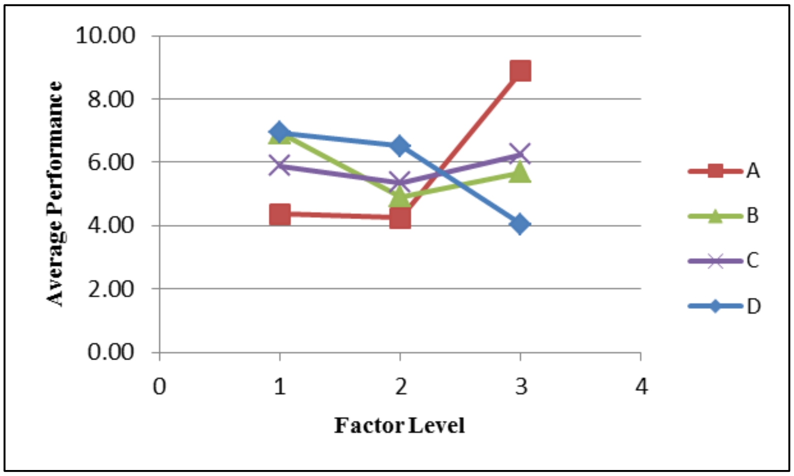

Fig.4. Average Performance with Respect to Factor Levels

V. Analysis of Variance (Anova)

ANOVA can be used to determine the significance of each parameter. ANOVA can be regarded as a statistical test that looks for significant differences between means [4].

Table-4 shows the ANNOVA Table based on L9 Orthogonal Array

Table – 4
ANNOVA Table 1

Factor	*Degree of freedom (f)*	*Sum of Squares (S)*	*Variance (V)*	*Variance Ratio (F)*	*Pure Sum of Squares (S')*	*Percentage Contribution*
A	*2*	*41.61*	*20.81*	*0*	*41.61*	*65.44*
B	*2*	*6.05*	*3.03*	*0*	*6.05*	*9.52*
C	*2*	*1.19*	*0.6*	*0*	*1.19*	*1.87*
D	*2*	*14.73*	*7.36*	*0*	*14.73*	*23.16*
Error	*0*	*0*	*0*	*0*	*0*	*0*
Totals	*8*	*63.59*	*31.79*	*0*	*63.59*	*100*

From Table-4 it is found that Factor C i.e. Steel Sheet Thickness has negligible Relative Contribution on Motor Performance. So factor C is pooled out from analysis. Percentage contribution is again calculated without factor C as follows, Refer Table-5.

Table - 5
ANNOVA Table 2 without factor C

Factor	*Degree of freedom (f)*	*Sum of Squares (S)*	*Variance (V)*	*Variance Ratio (F)*	*Pure Sum of Squares (S')*	*Percentage Contribution*
A	*2*	*41.61*	*20.81*	*34.92*	*40.42*	*63.57*
B	*2*	*6.05*	*3.03*	*5.08*	*4.86*	*7.65*
D	*2*	*14.73*	*7.36*	*12.36*	*13.53*	*21.29*
Error	*2*	*1.19*	*0.6*	*1*	*4.77*	*7.5*
Totals	*8*	*63.59*	*31.79*	*53.36*	*63.59*	*100*

VI. Results and Discussion

1) Figs.5 to 8 represents the Influence of various factors on the performance of Motor. It is cleared that, there is nonlinear variation of Motor constant with respect to the Rotor Diameter Ratio and Steel Sheet Thickness. As Rotor Diameter Ratio increases Motor constant will decreases slowly but after certain point there will be sudden rise in Motor constant. For Steel Sheet Thickness Motor Constant decrease up to certain point beyond that it will increase again. Motor constant is having direct linear proportion with Inner punch Hole Diameter and Inverse proportion with flux Density in Steel.

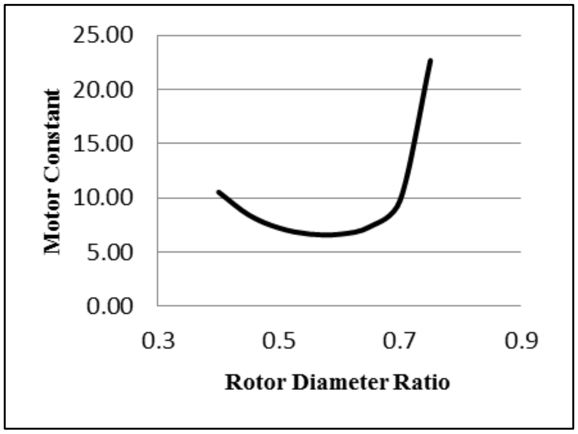

Fig. 5: Influence of Rotor Diameter Ratio on Motor Constant

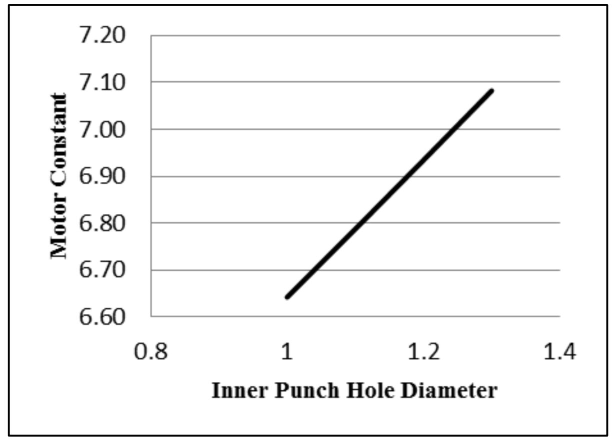

Fig. 6: Influence of Inner Punch Hole Diameter on Motor Constant

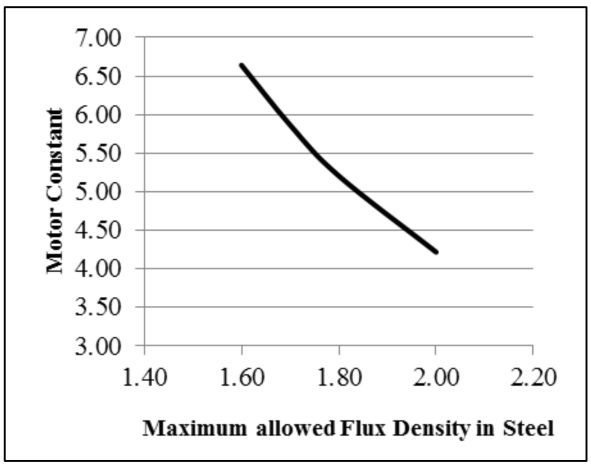

Fig. 7: Influence of Maximum allowed Flux Density in Steel on Motor Constant

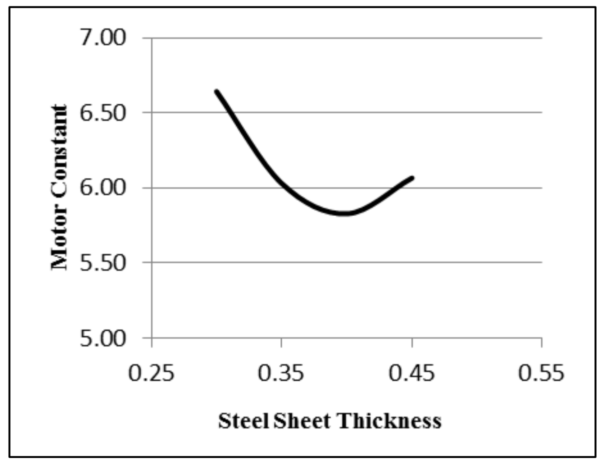

Fig. 8: Influence of Steel Sheet Thickness on Motor Constant

2) DOE gives the best combination of factors for Optimum Performance.Table-6 represents the Optimum value for factors for better Motor Performance.

Table – 6
Optimum Level value for Factors

Factor	*Unit*	*Optimum Level Value*
A-Rotor Diameter Ratio	*-*	*0.6*
B-Inner Punch Hole Diameter	*mm*	*1.1*
C-Steel Sheet Thickness	*mm*	*0.4*
D-Maximum Allowed Flux Density In Steel	*Tesla*	*2*

3) The result of ANOVA are visually place in Fig.1.For a given experiment from ANOVA it is cleared that, Rotor Diameter Ratio is the most influencing parameter and Steel sheet thickness is least influencing parameter on Motor Performance.

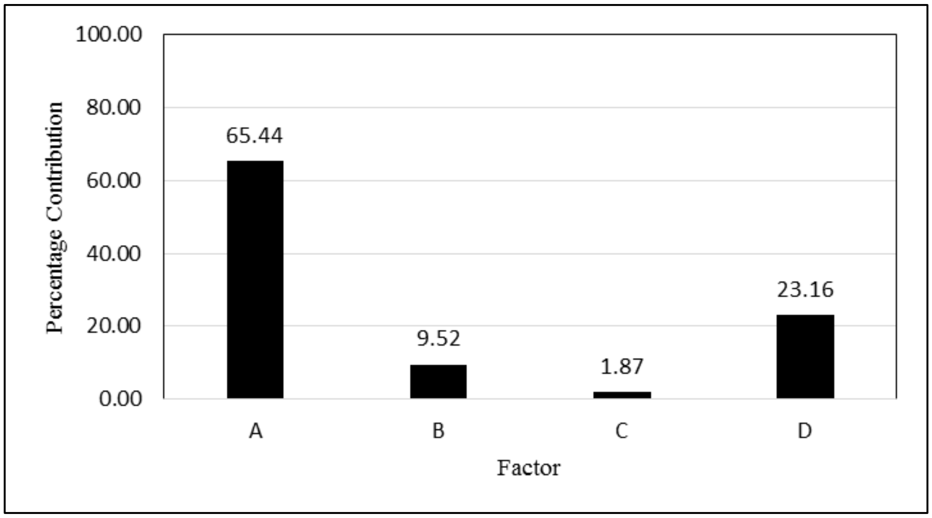

Fig. 9: Relative Contribution for Factors (Without Pooling of factor C)

The above results are validated by repeating same experiment for other size of Motor. The almost same results are obtained in that case also. Above analysis will help to improve Motor Performance while minimising design iterations.

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