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Robust Design of Air Compressor-Driving Quadratic Linear Actuator in Fuel Cell BOP System using Taguchi Method

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The linear actuator has the inherent drawback of air gap variation because its linear motion is usually guided by the springs, which destabilizes the dynamic performance. In order to design the linear actuator to be insensitive to air gap, this paper describes the robust design of the air compressor driving linear actuator using Taguchi method. The orthogonal arrays are constructed with selected control factors and noise factor for minimum experiment. The control factors are thickness of inner magnet, height of upper yoke, thickness of outer magnet and thickness of lower yoke while noise factor is airgap. The finite element analysis using commercial electromagnetic analysis program "MAXWELL" are performed instead of experiment. ANOVA are performed to investigate the effects of design factors. In result, the optimal robust linear actuator which is insensitive to air gap variation is designed.

Keywords : robust design, linear actuator, Taguchi method, air gap

1. Introduction

Air pollution, global warming, and the decrease in petroleum resources are stimulating interest in the development of safe, clean, and high-efficiency transportation. Hydrogen energy is receiving global attention as a new energy source because of the increasing concerns in the depletion of fossil fuels and emission of greenhouse gases. The major fuel supply modules in a hydrogen fuel battery are the pump, fan, compressor, and blower. Air is supplied to the cathode of the fuel cell to provide the oxygen that chemically reacts with the hydrogen in the cell to produce electricity. The supplied air is also important because the air blower has 20 to 30 percent effect on the fuel cell efficiency.

Linear motion requires less power consumption than rotary motion. Because all the driving forces in a linear compressor act along the line of motion, no sideway thrusts act on the piston. These types of compressors substantially reduce the sliding bearing loads; thus, a motion conversion mechanism is not needed. Therefore, a compressor driving linear actuator is more efficient than a reciprocating compressor [1, 2]. The motion of the linear actuators is guided usually a mechanical spring [3]. However, the spring guide has more difficulty in supporting the moving part at the center of the actuator during linear motion compared to the center axis used for rotary motion. Accordingly, the air gap in between the electromagnetic coil and permanent magnet in a linear actuator is varied during the operation and thus, the dynamic performance of the actuator becomes inconsistent.

Taguchi method is one of the best methods to eliminate variation during the design of a product and its manufacturing process. Thus, the robust design using Taguchi method is an efficient and systematic methodology that applies statistical experimental design for improving product and manufacturing process design. From the robust design, we obtain the constant and high magnetic force at insensitive air gap variance.

In this paper, the robust design of an air compressor-driving quadratic linear actuator based on the Taguchi method that is not influenced by the air gap variation is presented. Orthogonal arrays are constructed with the control factors such as the thicknesses of the permanent magnet and yoke and the noise factor of the air gap which critically influences the dynamic performance of the actuator. To simulate each model based on the orthogonal array, the finite element analysis using the commercial FEM software "MAXWELL" was performed. The optimal factors for the highest S/N ratio and performance were determined.

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2. Plan Factor Decision

Fig. 1 shows the schematic diagram of the cross-section of a quadratic electromagnetic linear actuator with a double (–) layer permanent magnet, which provides a high magnetic flux density [6]. The coil is energized by an oscillating current, and the compressor-driving actuator is driven by the Lorentz force, as shown in Fig. 2. The dynamic performance of this actuator is determined mainly by Lorentz force.

For the robust design of the quadratic actuator, the control factors affecting the Lorentz force were selected. Fig. 3 shows the control factors; inner magnet (A), height of the upper yoke (B), thickness of the outer magnet (C) and thickness of the lower yoke (D). The levels of the control factors and signal factors are shown, respectively, in Table 1. For the noise factor, an air gap is chosen. The initial actuator design values are A_2, B_2, C_2 and D_2. Which are the mid-values in the variation ranges of the factors. The full size of the linear actuator is fixed, and the constraint of each factor is given in Table 2.

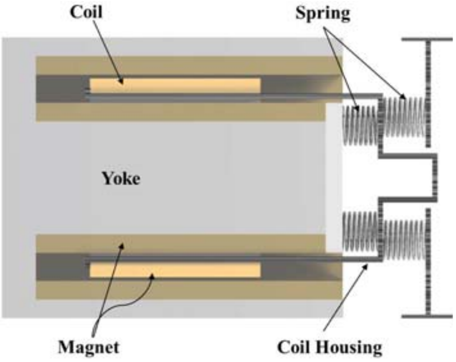


Fig. 1. (Color online) Schematic diagram of the cross-section of a quadratic electromagnetic linear compressor.

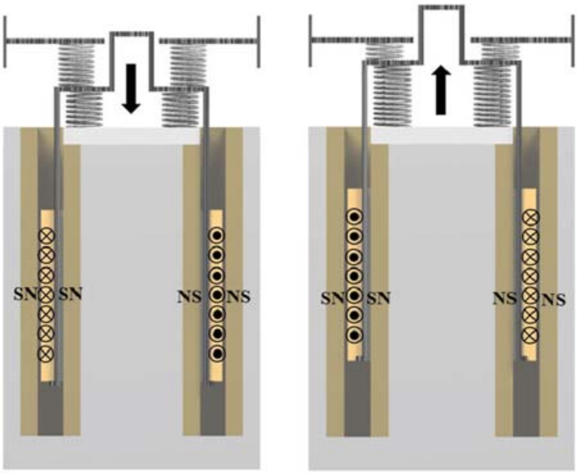


Fig. 2. (Color online) Principle of operation (a) at the upper position (b) at lower position.

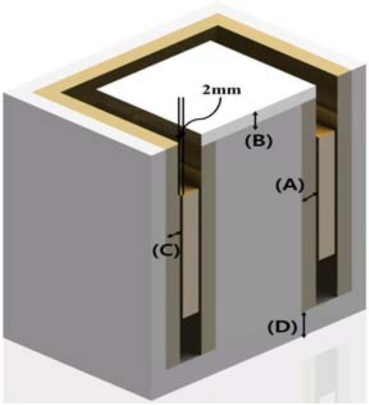


Fig. 3. (Color online) Control factors for Taguchi Method.

Table 1. Control Factors and Signal Factors.

	Indication	Name	1	2	3
Control Factor	A	Thickness of inner magnet	10 mm	15 mm	20 mm
	B	Height of upper yoke	5 mm	10 mm	15 mm
	C	Thickness of outer magnet	8 mm	11.5 mm	15 Mm
	D	Thickness of lower yoke	10 mm	21.5 mm	33 mm
Signal Factor	M	Current		30A	

Table 2. Constraint Factors.

	Indication	Constraints
Control Factor	A	10 mm ~ 20 mm
	B	5 mm ~ 15 mm
	C	8 mm ~ 15 mm
	D	10 mm ~ 33 mm

3. Optimal Design Using Taguchi Method

In engineering, orthogonal arrays are used to estimate the effects of several factors and to estimate the effect of their interactions by minimizing the number of experiments for the Taguchi method. In this paper, L27 (3, 4) orthogonal arrays that consist of 4 factors with 3 Levels was constructed to derive the optimal condition. Twenty-seven experiments were performed by FEM and their results are as shown in Table 3.

One of the key features of the Taguchi method is the use of the signal-to-noise (S/N) ratio, as defined by (1) to

Table 3. Configuration of orthogonal array matrix.

	Design parameters				Noise factor Air gap (mm)		S/N ratio	Mean of force
	A	B	C	D	1	2		
1	1	1	1	1	2417.4	2411.9	55.8601	2414.65N
2	1	1	2	2	3111.1	3100.5	52.3477	3105.80N
3	1	1	3	3	3248.6	3234.0	49.9376	3241.30N
4	1	2	1	2	3313.1	3291.2	46.5774	3302.15N
5	1	2	2	3	3483.7	3452.5	43.9290	3468.10N
6	1	2	3	1	2420.2	2399.1	44.1637	2409.65N
7	1	3	1	3	3654.1	3623.5	44.5150	3638.80N
8	1	3	2	1	2494.2	2475.6	45.5262	2484.90N
9	1	3	3	2	2977.9	2957.6	46.3089	2967.75N
10	2	1	3	1	2496.2	2488.3	52.9896	2492.25N
11	2	1	1	2	3338.3	3324.2	50.4781	3331.25N
12	2	1	2	3	3530.7	3508.3	46.9350	3519.50N
13	2	2	3	2	3166.9	3144.1	45.8330	3155.50N
14	2	2	1	3	3631.1	3597.3	43.5922	3614.20N
15	2	2	2	1	2654.9	2634.3	45.2223	2644.55N
16	2	3	3	3	3514.8	3478.0	42.5658	3496.40N
17	2	3	1	1	2678.1	2656.1	44.6826	2667.10N
18	2	3	2	2	3352.5	3326.6	45.2181	3339.55N
19	3	1	2	1	2622.8	2616.1	55.2514	2619.60N
20	3	1	3	2	3024.7	3008.9	48.6281	3016.80N
21	3	1	1	3	3212.3	3190.7	46.4283	3201.50N
22	3	2	2	2	3207.4	3185.3	46.2155	3196.35N
23	3	2	3	3	3378.4	3348.5	44.0326	3363.45N
24	3	2	1	1	2774.1	2755.2	46.3139	2764.65N
25	3	3	2	3	3409.8	3375.3	42.8644	3392.55N
26	3	3	3	1	2796.7	2774.2	44.8646	2785.45N
27	3	3	1	2	3273.0	3248.1	45.3521	3260.55N

transform the performance characteristic in the optimization process [7]. An S/N ratio optimum performance product is insensitive to noise factors.

$$\text{S/N ratio} = \frac{\text{Signal}}{\text{Noise}} \tag{1}$$

There are a few types of the S/N ratio such as nominal-is-better, smaller-is-better and larger-is-better. In this paper, the nominal-is-better S/N ratio is selected for S/N ratio calculation. S/N ratio of each factor in Table 3 using the S/N ratio Eq. (2) for nominal-is-better type is calculated and its result is plotted in Fig. 4. Using ANOVA, we can find the control factors which influence the S/N ratio and performance of the actuator. The results of the orthogonal experiments were verified as shown in Table 4.

$$\text{SN} = 10\log_{10}\frac{\bar{y}^2}{s^2} \tag{2}$$

Table 4. ANOVA of S/N ratio.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	8.435	8.435	4.217	1.11	0.368
B	2	224.840	224.840	112.420	29.51	0.000
C	2	1.382	1.382	0.691	0.18	0.837
D	2	53.887	53.887	26.943	7.07	0.012
A*B	4	8.782	8.782	2.195	0.58	0.686
A*D	4	4.380	4.380	1.095	0.29	0.880
Error	10	38.092	38.092	3.809		
Total	26	339.797				

$$S^2 = \sum_{i=1}^{n}(y_i - \bar{y})^2/(n-1)$$

S^2 : estimate of dispersion
$\bar{y}$: arithmetic mean average
y_i : ith experiment

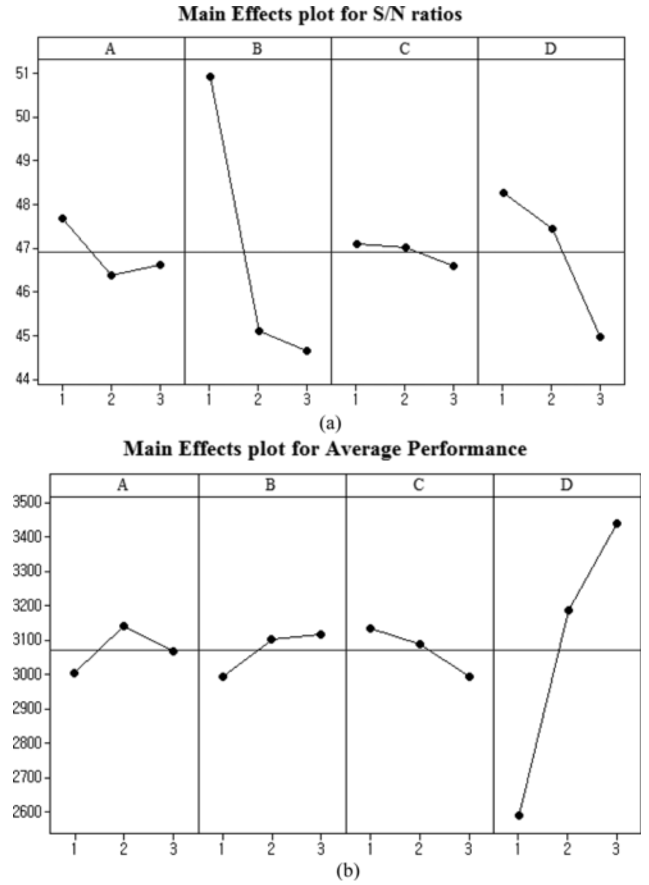
As shown in Table 4 DF means the degree of freedom, the Seq means sequential sums of squares, Adj SS means the adjusted sums of squares and Adj MS means the adjusted mean squares. The dispersion control factor influences the S/N ratio of the actuator. The P-value is in inverse proportion to S/N ration and average force, so the lower P-value is better. In this robust design, the P-value of each factor is constrained to be less than 0.05. Both factor B and factor D are the dispersion control factors of the actuators because they satisfy the constraint for P-value.

As shown in the Table 5, the P-values of factor A, factor B, factor C, factor D and factor A*D are less than 0.05. In result, these factors are mean adjustment factor. Moreover, the factor D is the most significant factor because its P-value is the lowest.

The Fig. 4(a) shows the S/N ratio value of each factors level. A Y-axis shows the S/N ratio value for each factors level. As shown in the Fig. 4(a) the factor B is the most effective factor for S/N ratio because the factor B has the

Table 5. ANOVA of average force.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
A	2	83831	83831	41916	7.03	0.012
B	2	79824	79824	39912	6.69	0.014
C	2	92323	92323	46161	7.74	0.009
D	2	3435646	3435646	1717823	287.92	0.000
A*B	4	24710	24710	6177	1.04	0.436
A*D	4	153960	153960	38490	6.45	0.008
Error	10	59663	59663	5966		
Total	26	3929957				



(a)

(b)

Fig. 4. (a) Main effect plot for S/N ratios (b) Main effect plot for Average Performance.

largest variation as input level is changed. The variance of each level is largest. The Fig. 4(b) shows the Average performance of each factors level and the Y-axis shows the magnetic force of each factors level. And the factor D is the most effective factor for average performance because factor B has the largest variation as input level is changed. The highest S/N ratio model in Fig. 4(a) is $A_1B_1C_1D_1$ and the highest performance model in Fig. 4(b) is $A_2B_3C_1D_3$. The goal is to find the model with both the highest S/N ratio and the highest average performance. As shown, the S/N ratios of A, B and D are inversely proportional to the average performance of them. The factor A and C are rarely influential on the average performance and S/N ratio. The factor B is critical effective factor of S/N ratio but, it is not considerably influential on the average performance. In contrast, the factor D is critical effective factor of average performance but, it is not considerably influential on the S/N ratio. Factor A_1 has the highest value of S/N ratio, but the lowest value of performance. In contrast, A_2 has the highest value of performance, but the lowest value of S/N ratio. Therefore, it is desirable to choose the factor A_3 which has less deviation of S/N ration and performance. For the factor B, B_1 which has the highest S/N ratio is chosen because the difference of performance according to level is very little. For the factor D, D_3 which has the highest performance is chosen because the difference of S/N ratio according to the level is very little. From the result, the height of upper yoke is the most effective factor for the S/N ratio and thickness of lower yoke is the most effective factor for the average performance. So, we can obtain the highest S/N ratio model with high average performance model through control the factor B and the factor D. Finally, the model $A_3B_1C_1D_3$ is chosen to be optimal. Table 6 compares the S/N ratio and force of initial model and optimal model. The S/N ratio and force are improved by 3.16 and 4%.

Table 6. S/N ratio and Average Force in case of Initial Condition and Optimal Condition.

	Initial model ($A_2B_2C_2D_2$)	Optimal model ($A_3B_1C_1D_3$)	Distinction
S/N ratio	45.77	48.93	3.16
Force	3288.98N	3419.97N	130.99N

4. Conclusion

This research suggested the Taguchi method based robust design of electromagnetic linear actuator that can be employed in the air blower of a fuel cell BOP system considering the air gap to be noise factor. Finite element analysis was performed for the experiment of the models in orthogonal arrays. The height of upper yoke is the most effective factor and the thickness of lower yoke is the most effective factor. In result, the performance is enhanced by 4% and the S/N ratio is enhanced by 3.16.

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References

[1] N. R. Van der Walt and R. Unger, Linear Compressors a Maturing Technology, Proc. Int. Appliance Technical Conference, May 9-11, University of Wisconsin, WI, USA, (1994) p. 239.

[2] H. K. Lee, G. Y. Song, J. S. Park, E. P. Hong, and W. H. Jung, Development of the Linear Compressor for a Household Refrigerator, Proc. Int. Compressor Engineering Conference, July 25-28, Purdue University, IN, USA (2000) p. 31.

[3] J. H. Kim, J. H. Kim, and C. H. Hwan, J. Magnetics **16**, 120 (2011).
[4] H. T. Wang, Z. J. Liu, and S. X. Chen, IEEE Trans. Magn. **35**, 3700 (1999).
[5] D. H. Wu and M. S. Chang, Material Science and Engineering A **379**, 366 (2004).
[6] J. H. Lee, J. H. Kim, and J. H. Kim, Journal of the Korean Society of Mechanical Engineers 2010, 1278 (2010).
[7] W. Y. Fowlkes and C. M. Creveling, Engineering Methods for Robust Product Design, Addison-Wesley, Cambridge (1995).