Design, Analysis and Experimental Validation of Permanent Magnet Synchronous Motor for Articulated Robot Applications

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Smart Actuator consists of Permanent Magnet Synchronous Motor (PMSM), controller, incremental and absolute encoders, harmonic drive and electric brake and so on. KERI (Korea Electrotechnology Research Institute) is developing and focusing on a surface permanent magnet (SPM) type of synchronous motor and a PWM-driven inverter. This technology virtually improves average torque considering several pole-slot combinations. The simulation result is well accorded with experimental result, with a maximum error of 2% considering mechanical loss. The design, analysis and experiment of the PMSM for articulated robot applications have been developed successfully.

***Index Terms*—Smart Actuator, pole-slot combination, surface permanent magnet type synchronous motor (PMSM), response surface methodology (RSM), back-to-back testing**

I. Introduction

SMART ACTUATOR consists of Permanent Magnet Synchronous Motor (PMSM), controller, incremental and absolute encoders, harmonic drive and electric brake and so on. KERI (Korea Electrotechnology Research Institute) is developing and focusing on a surface permanent magnet (SPM) type of synchronous motor and a PWM-driven inverter. This technology virtually improves average torque considering several pole-slot combinations. This paper deals with the design, analysis and experiment of the PMSM for articulated robot applications.

II. Smart Actuator

This paper deals with smart actuators which are composed of hollow type PMSM (permanent magnet synchronous motor), reducer (single-stage 100 : 1 reduction, zero backlash gear), absolute and incremental type encoders and controller aim to establish the flexibility of articulated robot applications. The developing prototype is able to embed the motors directly into the articulation axes without need for additional housings. The smart actuator is well developed as medium-sized products in particular. Fig. 1 shows smart actuator for articulated robot applications.

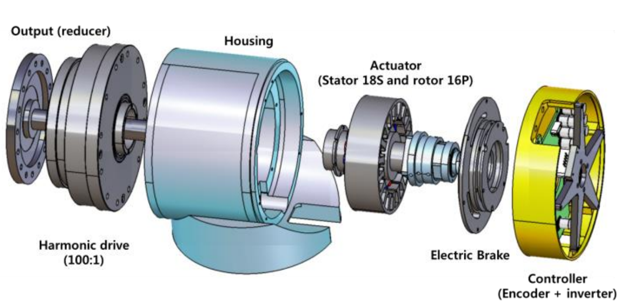


Fig. 1. Smart actuator for articulated robot applications.

TABLE I
THE SPECIFICATION OF ACTUATOR

Item	Value	Appearance
Pole/stack length	16/31	NdFeB42SH/mm
Slot/stack length	18/31	mm
Stator core	-	35PN440
Rotor core	-	35PN440
Power	350	W
Speed	2,000	rpm
Torque	1.6	Nm
Motor efficiency	87	%
Control	-	PWM, incremental encoder
Bearing	-	Deep groove ball
Input voltage of inverter	48	DC voltage

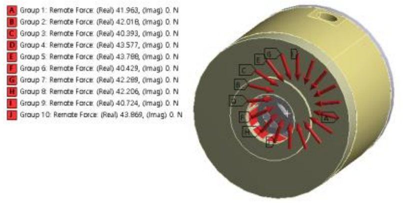
III. Performance Analysis Result

A. *Electric performance analysis*

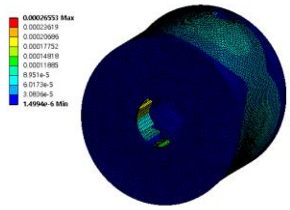
The winding factor and forced vibration mode are considered and compared according pole slot combination [1]. The developed motor for performance improvement is thoroughly examined and selected to maximize output power density and torque density within 1% torque ripple ratio among the several pole slot combinations. All cases(14P12S, 14P18S, 16P18S, 20P18S, 20P24S, 22P18S, 22P24S, 22P30S, 24P27S) that have higher winding factor and higher forced vibration mode are preferentially analyzed and compared with that of the commercial product with 10 pole 12 slot combination applied to universal robot(UR 10). 16P18S model is selected among all cases. All results will be dealt with in full paper.

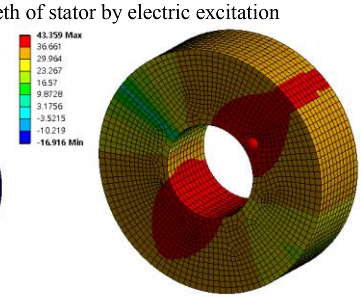
B. *Forced vibration and noise analysis*

In this paper, forced vibration and noise analysis were performed by electric excitation that pole passing frequency is dominant as shown in Fig. 2.



(a) Normal force on teeth of stator by electric excitation



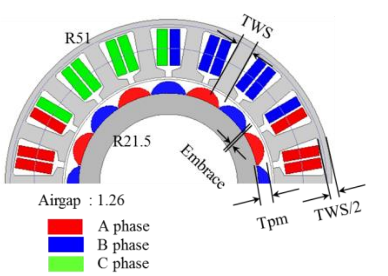


(b) Forced vibration mode (c) Noise distribution

Fig. 2. Multi-physics analysis (2,000rpm, pole passing frequency, 534Hz)

C. Optimum design

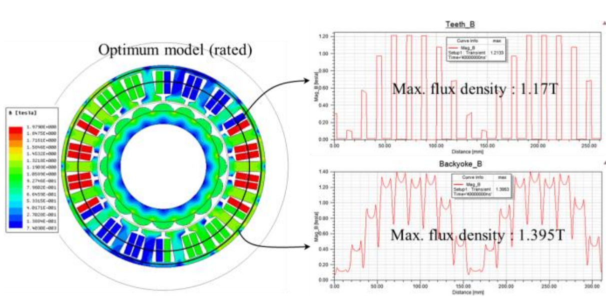
For reasonable comparison, stator outer diameter, hollow shaft inner diameter of rotor, PM volume and slot area made it the same conditions. When taking into consideration all the conditions, the highest torque density and output power density are chosen as a good model, 16P18S maintaining torque ripple ratio within 1%.



(a) Normal force on teeth of stator by electric excitation

NO.	TWS	Embrace	Tpm	Torque_avg (Nm)	Tripple ratio (%)	Output power(W)	Max. B(T) Backyoke teeth	Weight (kg)	Output density(W/g)	Torque density(Nm/kg)
1	4.8	0.85	3.1	1.6375	0.73	342.96	1.4332	1.15064	0.298	1.423
2	5.6	0.85	3.1	1.6363	0.2	342.7	1.228	1.18973	0.288	1.375
3	4.8	0.95	3.1	1.6415	0.78	343.81	1.4376	1.15203	0.298	1.425
4	5.6	0.95	3.1	1.6428	0.2	344.07	1.1811	1.21468	0.283	1.352
5	4.8	0.85	3.7	1.7232	1.02	360.9	1.4863	1.1475	0.315	1.502
6	5.6	0.85	3.7	1.7275	0.18	361.8	1.2624	1.21016	0.299	1.427
7	4.8	0.95	3.7	1.7313	1.03	362.6	1.4907	1.15082	0.315	1.504
8	5.6	0.95	3.7	1.7359	0.17	363.57	1.2653	1.21347	0.3	1.431
9	4.8	0.9	3.4	1.6908	0.93	354.11	1.4665	1.15052	0.308	1.47
10	5.6	0.9	3.4	1.6931	0.18	354.6	1.2494	1.21318	0.292	1.396
11	5.2	0.85	3.4	1.684	0.25	352.7	1.3101	1.1807	0.299	1.426
12	5.2	0.95	3.4	1.6865	0.25	353.21	1.3113	1.18306	0.299	1.426
13	5.2	0.9	3.1	1.631	0.27	341.59	1.2829	1.18336	0.289	1.378
14	5.2	0.9	3.7	1.7248	0.32	361.24	1.3313	1.18122	0.306	1.46
15	5.2	0.9	3.4	1.6828	0.29	352.44	1.3093	1.18222	0.298	1.423

(b) Central Composite Design



(c) Flux density of optimum model

Fig. 3. Optimum design using response surface methodology.

For optimization, this paper utilized RSM(response surface design) and 2-D magnetic FEA since this approach has been used in various optimization studies with proven effectiveness and reliability[2] as shown in Fig. 3. All results will be dealt with in full paper.

D. Back-to-back testing

Fig. 4 shows HMI and back-to-back testing of optimum model. The experimental results are shown in Fig. 5. The maximum efficiency is 89.63% at 2.5Nm@2,700rpm. The simulation result is well accorded with experimental result, with a maximum error of 2% considering mechanical loss.

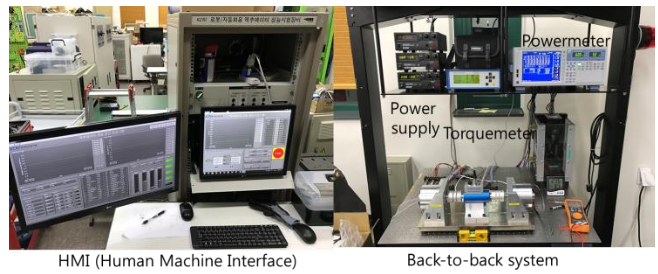
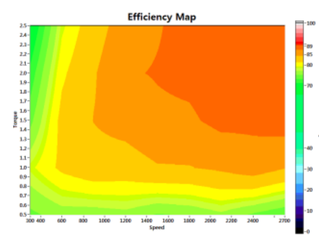
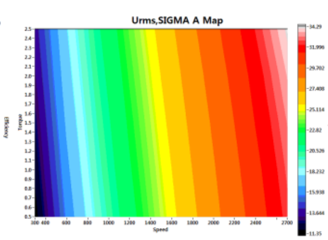
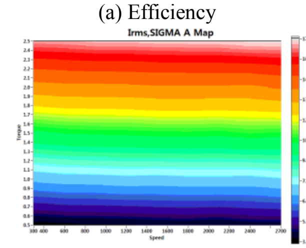


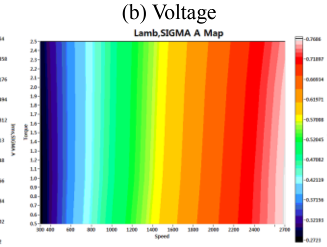
Fig. 4. HMI and back-to-back testing of optimum model (16P18S)
; torque sensor (kistler, 4503B5WP1B1KA2), powermeter(wt1800)





(a) Efficiency (b) Voltage





(c) Current (d) Power factor

Fig. 5. Experimental results (16P18S)

E. Conclusion

This paper deals with smart actuator for articulated robot applications to improve average torque considering pole-slot combinations. Analysis and experimental results show promising results that the proposed prototype displays high torque density and output power density.

References

[1] S. U. Chung, J. M. Kim, D. H. Koo, B. C. Woo, D. K. Hong, and J. Y. Lee, "Fractional Slot Concentrated Winding Permanent Magnet Synchronous Machine with Consequent Pole Rotor for Low Speed Direct Drive," *IEEE Trans. Magn.,* Vol. 48, No. 11, pp. 2965-2968, Nov. 2012.

[2] D. K. Hong, M. H. Ahn, D. S. Joo, B. C. Woo, and D. H. Koo, "Development of a Super High Speed Motor-generator and Controller," *IEEE Trans. Journal of Applied Physics,* Vol. 115, 17E705, 2014.