Development Of A Spindle Motor Considering Of Maximum Torque And Efficiency

Risfendra, Habilbullah, Ali Basrah Pulungan, Hasan Maksum, Wawan Purwanto

Abstract: This paper presents a development of a spindle motor used in machine tool applications. The development process was started by developing of a performance improvement of the spindle motor including electromagnetic force, size evaluations, torque, and efficiency. Then, the optimal designs of the stator winding geometry to improve the maximum torque and efficiency of the spindle motor. The optimal design involves the following optimizations: Hooke-Jeeves optimization, the Taguchi method, genetic algorithms, response surface methodology, and finite element analysis. The purpose of present study is a design solution to reach performance in the manner of higher torque and efficiency of the high-speed spindle motor. The temperature rise of the motor was calculated based on power loss distribution model. Finally, a prototype spindle motor proposed model generated by response surface methodology was fabricated and tested to validate the finite element analysis.

Index Terms: Efficiency, spindle motor, torque, machine tools, rotor, stator winding, temperature.

1. INTRODUCTION

THE manufacturing of high-speed spindle motors has become a topic of interest in recent years, because of their wide use in various industries, from traditional machining to modern precision manufacturing [1], [2], [3], [6]. Recently, besides of high-performance considerations, a spindle motor was also applicable for various applications. The stator winding geometry such as stator length, stator slot geometry, the number of winding turns per slots, and wire diameter are a critical component in establishing the electromagnetic force (EMF). Thus, it was also affected to transfer the EMF and convert the electrical energy to the mechanical energy from the stator winding to the rotor bring in a high performance of the spindle motor [4], [5]. High performance for various applications of the spindle motor can be developed through the refinement of the stator winding geometry such as: winding connections, pole numbers, and wire diameter using finite element method [7], [8], [9], [12], stator teeth width, yoke width, air-gap length, bore diameter, bridge distance, and slot opening using, response surface methodology [2], [13], Taguchi method [3], for electromagnetic design using Hooke-Jeeves optimization [11] and genetic algorithm [10], [12], [13]. By using several designs and making comparison results of all designs, this present study was focused on the development of a high-speed spindle motor in the interest of machines tool applications at the speed of 21.000 rpm. In the applications, the spindle motor was designed to prove a high performance in maximum torque for load stability and efficiency for electrical energy saving. Hooke-Jeeves optimization, Taguchi method, genetic algorithm (GA), and response surface methodology (RSM) coupled by the finite element analysis (FEA) was employed to gain the optimal stator winding geometry values, including stator length, stator slot parameters, wire diameter, and the number of winding turns per slot with a fixed inner and outer diameter of the stator. In high-speed operation, aside from electromechanical design considerations, thermal design is also crucial. In most cases, the temperature rise of a spindle motor predicted using thermal difference model, equivalent resistance thermal model, thermal difference and finite element method, and power loss distribution model [12], [13]. In this paper, temperature rise of the spindle motor calculated using power loss distribution model [12], [14]. Finally, the proposed model of the stator winding geometry gained by RSM was fabricated [2] and tested to validate the simulation results.

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2 PERFORMANCE IMORICEMENT OF HIGH-SPINDLE MOTORS

2.1 Improve Electromagnetic Characteristics

The magnetic flux density on the cross section of a stator core on which electromagnetic forces act was calculated using the 2D transient magnetic field complex eddy-current model [13].

2.2 Size Evaluation

Selecting stator winding parameters facilitate increasing EMF in the stator winding with less coil length and maintaining the same flux density distribution in proportion to the coil area. Generally, in a high-speed operation of the spindle motor, the stator winding loss is a predominant problem, and it need appropriate recommended stator current density Jc. A higher stator current density in consequence of a smaller wire diameter and high stator resistance, and it leads to increases in the copper loss stator winding, the stator winding operating temperature, and reduce motor efficiency [11], [12], [13].

2.3 Improve Efficiency based on Stator Winding

Efficiency and power factor are increases with power and decreases with the number of poles with a value slightly smaller than the corresponding efficiency for existing motors [12]. When determine the machine performance characteristics, the power factor of the machine should be determined for each load point using power factor concept. Generally, larger stator length allows for smaller stator bore diameter (for given torque) leads to the shorter stator winding end connections, lower winding losses, lower inertia, and higher efficiency, but the temperature rise along the stator length must be lower. An optimal value of aspect ratio (λ) is highly dependent on the spindle motor design specifications

TABLE 1
PERFORMANCE COMPARISON

Parameters	ID	HJ	TM	GA	RSM [2]	Experiment	Error (%)
Stator leakage reactance (Ohm)	2.967	2.746	2.061	2.244	2.351	2.353	7.61
Magnetic flux linkage (Wb)	0.082	0.086	0.087	0.087	0.085	0.084	1.18
Maximum torque (Nm)	3.12	7.56	7.89	7.82	7.65	8.12	6.14
Efficiency (%)	86.45	92.38	92.97	92.91	92.23	92.23	0.07

and the objective function is taken into consideration.

2.4 Temperature Rise Calculation

Heat transfer in a spindle motor depends on the level of losses, machine geometry, and the method of cooling. In terms of the total dissipating area from the stator core (C_m), cooling constant (q), and total loss (power loss distribution) model of the motor, the temperature rise in the spindle motor can be calculated as [12].

3 OBJECTIVE FUNCTION AND CONSTRAINS

For achieving the performance requirement of high-speed spindle motors, the breakdown torque and efficiency are to be objective functions. Equivalent circuit analysis is used in computing the breakdown torque as [12]. In this study, power losses calculation is as shown in Fig 1. Thus, efficiency can be obtained by using power balance monitoring as [11]. To obtain a desirable spindle motor performance, constraints in the optimizations are starting torque, stator leakage reactance, and magnetic flux leakage.

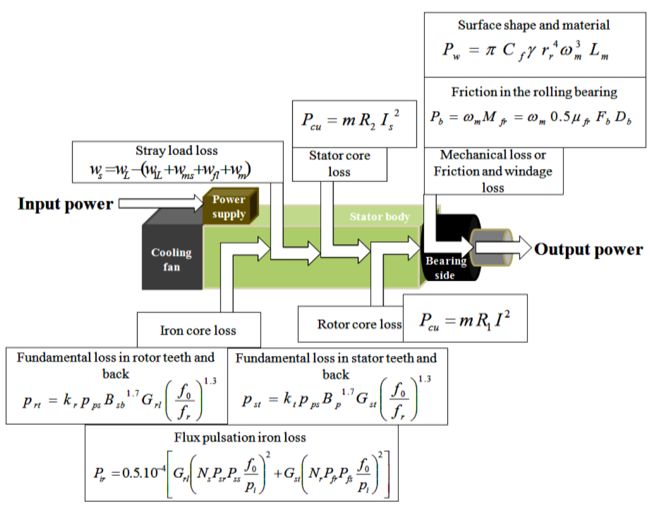

Fig. 1. Power loss calculations.

In this study, Spindle motor specifications were obtained from an industrial spindle motor design, which had a rated output of 14 kW, four poles, a Δ connection, and 380 V, with general specifications listed in [2]. By using calculation model in Finire element analysis, this spindle motor can be predicted the efficiency of 86.45% and maximum torque of 3.12 Nm. Thus, this efficiency and torque must be raised to load stability and electric energy saving by adjusting of stator winding geometry. A stator winding geometry was optimized on the basis of the rotor geometry produced by an industrial spindle motor design. By considering the obtained results in the statistical analysis, the optimization procedure has been defined as shown in Fig. 2.

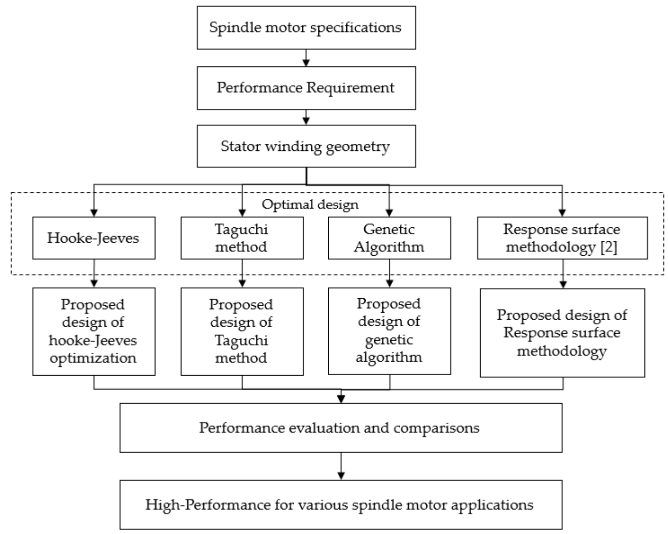

Fig. 2. Optimization procedurs.

In this study, experimental measurements conducted based on the IEEE standard 112-Method F_1 test [14]. Table I represent a comparison of the calculation results from the initial design, the proposed optimization design, and experimental results. It is can be seen that short length of the stator required requires shorter hs, bs_2, and the small wire diameter (such as the results of the Taguchi method). The effect is to reduce the stator resistance with lessening of coil length and to prevent an increase in stator current, stator current density, stator thermal load, as well as maintaining the flux density distribution equitable to the coil area. Furthermore, the slot cross-sectional area available for the number of windings turns per slots decreases, and consequently the stator current density and copper losses stator winding increases, so appropriate the wire diameter can be a solution. Decreases of the stator current density and increases MMF lead to decreases stator leakage reactance and increase magnetic flux density. Proposed optimal design (Hooke-Jeeves, Taguchi method, GA, RSM, and experiment results) produces lower leakage reactance (Fig. 3) and higher stator teeth flux density, stator yoke flux density, and air-gap flux density than does the industrial design. High magnetic flux density in the proposed optimization model give rise to increasing magnetic flux linkage from the stator to the rotor, torque, and efficiency of the spindle motors in all speed up to 21.000 rpm as shown in Fig. 4 - 6.

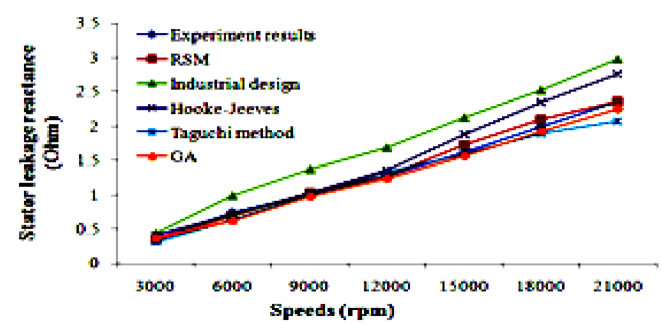

Fig. 3. Stator leakage reactance characteristics.

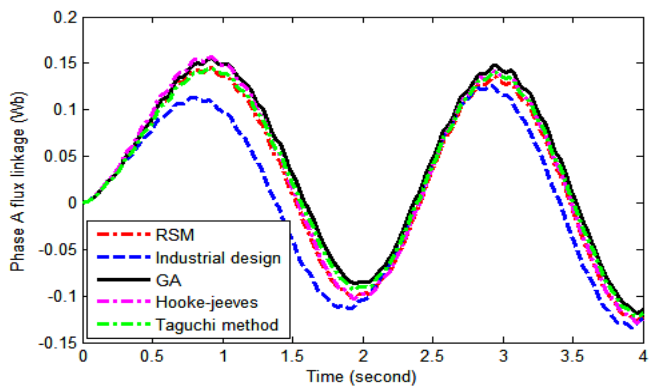

***Fig. 4**. Phase A flux linkage characteristics at 21.000 rpm*

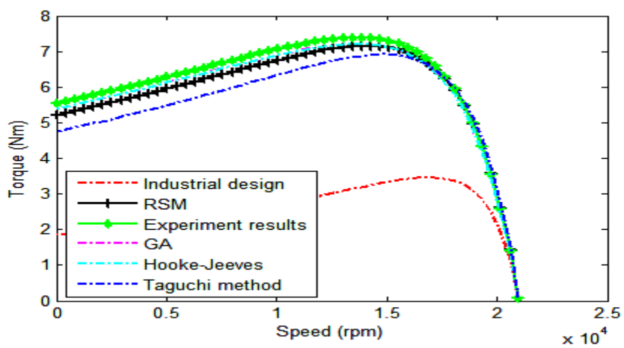

***Fig. 5**. Torque-speed characteristics*

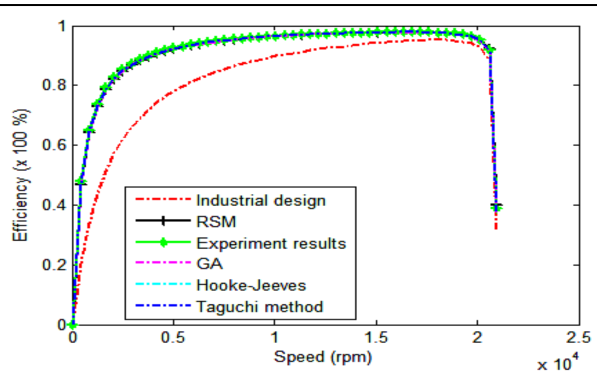

***Fig. 6**. Efficiency-speed characteristics*

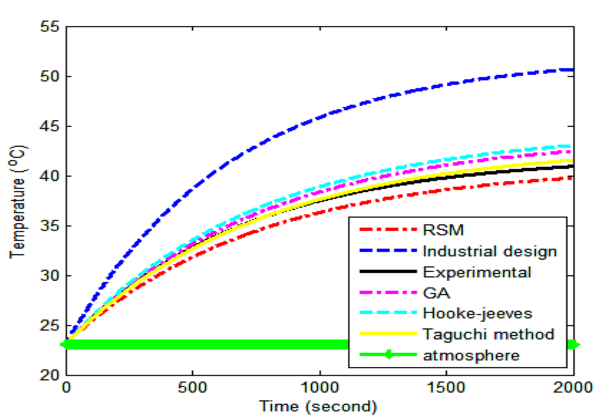

***Fig. 7**. Temperature rise characteristics*

Thermal measurement in this experiment conducted using an infrared laser thermometer with measuring a range of -50-380 ^{0}C, at an accuracy of 1.5+ 1.5 ^{0}C, resolution of 0.1 ^{0}C, and emissivity of 0.95. Infrared laser measurement is a non-contact method. Motor coolant controlled in room temperature at 23 ^{0}C with flow rate 0.0288 m3/s, and for the simulation, the temperature rise calculated using additional power loss model. The temperature rise characteristics for this spindle motor are shown in Fig 7. The proposed optimization model generates lower temperature rise than the industrial design. The temperature rise is approximately of 43 ^{0}C in proposed model and in industrial design of 51 ^{0}C. As shown in Table I, the percentage errors in the stator leakage reactance and breakdown torque are 7.11% and 6.14%, respectively. A possible cause of the measured experimental value being higher than the simulation value is a slight change in the value of the stator slot geometry caused by the manufacturing process. Therefore, the high speed caused a high stator slot difference coefficient, leading to a high stator leakage reactance and reduces breakdown torque. Overall, the measured experimental results are in favorable agreement with the simulation results.

6 CONCLUSIONS

In this paper, a high-speeds spindle motor with high torque and efficiency for machine tool applications was developed using Hooke-Jeeves optimization, the Taguchi method, GA, RSM, and the FEM. The proposed model based on RSM results was fabricated to verify the simulation results according to experiment measurements. The simulation and experimental results showed the proposed optimization model (Hooke-jeeves, Taguchi method, GA, and RSM) has increased torque and efficiency compared with the industrial design. Comparing the experimental and simulation results validated the accuracy of the proposed model, with a percentage error at or less than approximately 7%. Rotating speeds of 3000, 12.000, and 21.000 rpm were investigated. Furthermore, the model used is considered applicable for high-speed spindle motors in machine tool applications at speeds of 3000 to 21.000 rpm with higher breakdown torque for load stability and efficiency for electrical energy saving.

ACKNOWLEDGMENT

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