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TOPOLOGY OPTIMIZATION OF SCROLL COMPRESSOR CONSIDERING MAGNETICS AND HEAT TRANSFER

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ABSTRACT

This paper presents a new approach regarding both magnetic and thermal characteristics associated with design of a scroll compressor that is the low-pressure type. In the scroll compressor, the single-phase induction motor (SPIM) does not only play a role of source for dynamic force, but also generates high heat exerting negative influence on both lifetime and performance. Thus, it is necessary to design the scroll compressor considering two physical disciplines in order to improve the performance and to be protected against overheating. In this paper, firstly, numerical analysis of electromagnetic field is carried out by the nonlinear transient finite element method (FEM). Secondly, the linear static FEA of magneto-thermal field is implemented by applying source current computed by the nonlinear transient analysis. FE results are validated in terms of electromagnetics and heat transfer by experiments. And then, the pseudo-transient topology optimization using a multi-objective function is performed.

1. INTRODUCTION

A lot of engineers have been focused on the electromagnetic energy to increase torque and efficiency of the electrical machines in compressor systems. But practical techniques for improvement of the efficiency considering purely electromagnetics are nearly saturated in design of the electrical machines.

When current flows on conductive materials embedded in the core, generated high heat, Joule's loss, transfers from the stator and the rotor to outside air. This heat has negative influences on the electromagnetic quantities such as the torque and the efficiency. In addition, gas is heated by high temperature of the electrical machines when it comes into the compressor through suction tube. Then the compressor is operated unreliably by dynamic force of the electrical machine.

In order to avoid those phenomena, generated heat in the compressor should be radiated toward outside air as much as possible. In those aspects, the design of the electrical machines regarding thermal properties is necessary for improving performances. Thus, this paper aims for maximizing heat transfer of the scroll compressor to reduce thermal influences. In the meanwhile, magnetic energy of the single-phase induction motor (SPIM) is maintained for stable dynamic force.

For topology optimization considering electromagnetics and heat transfer, design sensitivity equations are derived using the density method. And the optimization program is developed in terms of electromagnetic and thermal field.

The nonlinear transient characteristic of the SPIM for the scroll compressor is analyzed using FLUX2D. Temperature distribution of the scroll compressor is analyzed using ANSYS. In order to validate the FE results,

several experiments are performed in terms of electromagnetics and heat transfer. And then, the pseudo-transient topology optimization based on a multi-objective function is performed using ANSYS. To obtain the meaningful topology optimization, the linear static FEA of magneto-thermal field is implemented by applying source current computed by the nonlinear transient analysis.

2. DESIGN SENSITIVITY EQUATION

2.1 Electromagnetic System

Consider a measure of electromagnetic performance that may be written in integral form as

$$\psi_{EM} = \iiint_{\Omega} g(A, \nabla A, u) d\Omega \quad (1)$$

where A is the vector potential, $u = [J_s, \mu]^T$ is the design vector of current density and permeability.

Using the variational form of objective function of (1) and direct differentiation result [1], the sizing design sensitivity equation is [2]

$$\begin{aligned} \psi'_{EM} &= \iiint_{\Omega} [g_A A' + g_{\nabla A} \nabla A' + g_u \delta u] d\Omega \\ &= \iiint_{\Omega} g_u \delta u d\Omega + l'_{\delta u}(\lambda) - a'_{\delta u}(A, \lambda) \end{aligned} \quad (2)$$

The magnetostatic field can be described using the set of Maxwell's equations. By introducing a vector potential, A , such that $B = \nabla \times A$ and eliminating H , a single governing equation can be expressed as

$$\nabla \times \left(\frac{1}{\mu} \nabla \times A \right) = J_s \quad (3)$$

To obtain the variational equation, multiplying the both sides of (3) with the virtual vector potential \bar{A} and integrating over the domain and applying boundary condition [1-2], then the variational equation becomes

$$a_{\Omega}(A, \bar{A}) = l_{\Omega}(\bar{A}) \quad \text{for all } \bar{A} \in \tilde{A} \quad (4)$$

$$\begin{aligned} \text{where } a_{\Omega}(A, \bar{A}) &= \iiint_{\Omega} \left[(\nabla \times A) \cdot \left(\frac{1}{\mu} \nabla \times \bar{A} \right) \right] d\Omega \\ l_{\Omega}(\bar{A}) &= \iiint_{\Omega} [J_s \cdot \bar{A}] d\Omega \end{aligned} \quad (5)$$

$a_{\Omega}(A, \bar{A})$ is the energy bilinear form and $l_{\Omega}(\bar{A})$ is the load linear form. Those are functions of permeability μ and system output A .

Using design sensitivity formula of (2) and variations of the energy bilinear form and load linear form from (4), the sensitivity about permeability is [2]

$$\frac{\partial \psi_{EM}}{\partial \mu} = \iiint_{\Omega} \left[g_{\mu} + \frac{1}{\mu^2} (\nabla \times A) \cdot (\nabla \times \lambda) \right] d\Omega \quad (6)$$

2.2 Thermal System

As electromagnetic system, thermal performance may be written in integral form as

$$\psi_{TH} = \iiint_{\Omega} g(T, \nabla T, v) d\Omega \quad (7)$$

where T is the nodal temperature, $v = [k, h_c]^T$ is the design vector thermal conductivity and convection coefficient.

Then, design sensitivity equation for thermal system can be expressed as

$$\psi'_{TH} = \iiint_{\Omega} g_v \delta v d\Omega + l'_{\delta v}(\lambda) - a'_{\delta v}(A, \lambda) \quad (8)$$

A general equilibrium equation in the steady state can be derived from energy balance and Fourier' law [3]

$$\nabla \cdot (k \cdot \nabla T) = -q^b \quad (9)$$

The variational equation can be derived taking integral by parts of (9) using Galerkin method and applying boundary conditions on the domain in Figure 1.

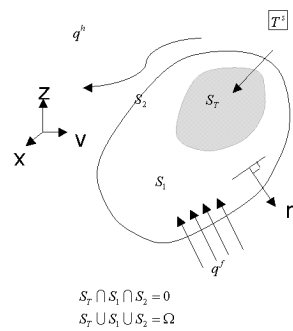


Figure. 1 Body Subject to Heat Transfer

$$a_{\Omega}(T, \lambda) = \iiint_{\Omega} (k \cdot \nabla \lambda \cdot \nabla T) d\Omega + \iint_{S_2} \lambda \cdot h_c \cdot T d\Gamma \quad (10)$$

$$l_{\Omega}(\lambda) = \iint_{S_1} \lambda \cdot g^f d\Gamma + \iint_{S_2} \lambda \cdot h_c \cdot T_b d\Gamma + \iiint_{\Omega} \lambda \cdot g^b d\Omega$$

In order to represent the porous material, fictitious material properties are the thermal conductivity and the convection coefficients. If material of design domain is changed to air in the process of optimization, convection occurs. Then, convection coefficients should be taken consideration. Therefore, the sensitivities with respect to thermal conductivity and convection coefficients are

$$\frac{\partial \psi_{TH}}{\partial k} = \iiint_{\Omega} (g_k - \nabla \lambda \cdot \nabla T) d\Omega \quad (11)$$

$$\frac{\partial \psi_{TH}}{\partial h_c} = \iiint_{\Omega} (g_{h_c} + \lambda \cdot T_b - \lambda \cdot T) d\Omega \quad (12)$$

3. EXPERIMENT

The single-phase induction motor (SPIM) for the scroll compressor yields mechanical output 4.5[Hp] at rated speed 3470 [rpm], when input voltage 220[V] having frequency 60[Hz] is applied. The combination ratio between the stator slots and the rotor slots is 0.8. As shown in Figure 2, a dynamometer and an encoder are utilized for measurement of electromagnetic characteristics such as the voltage, current, power factor, torque and speed. The K type thermocouples are attached on the surface of the stator and the shell for temperature distribution. To understand heat source, the thermocouples are inserted in the winding of the stator and the end-turn part.

The experiment is advanced in two steps. Firstly, both electromagnetic characteristics and temperature of the SPIM are simultaneously measured for itself. Secondly, the scroll compressor is measured under practical conditions

using the calorimeter.

As the experimental result of the SPIM, the efficiency is peak at speed 3470 [rpm] in Figure 3. The efficiency is can be calculated as ratio between electric input and mechanical output.

$$\eta = \frac{T \cdot W}{VI \cdot \cos\theta} \times 100\% \tag{13}$$

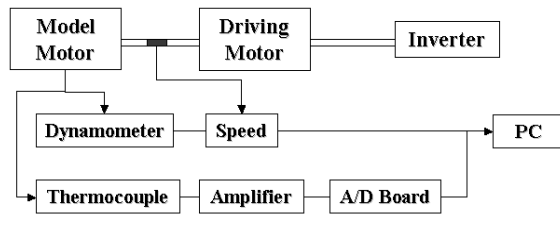


Figure. 2 Schematic of Experimental Setup

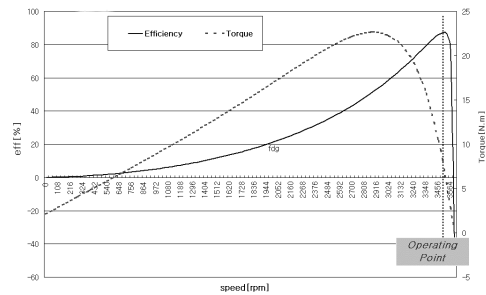


Figure. 3 Experimental Result of Electromagnetics

In the SPIM test, maximum temperature is measured up to 110 ° C in order to avoid destroying the winding insulation. So temperature saturation of the SPIM cannot be identified. The highest heat is generated at the end-turn part of stator. Because most coils passed through the stator slots are not only concentrated in end-turn part, but there isn't also any medium around end-turn part to transfer heat toward outside. It is figured out that temperature in the stator slots is depending on the number of coil from experimental result.

In the scroll compressor test, it takes an hour to arrive at steady state. Temperature of the suction tube side is the lowest due to cold gas relatively. The gas coming into the suction tube is heated by depriving of the heat generated in the SPIM. The partial heat is radiated to outside and the rest lifts up compressor temperature.

4. FINITE ELEMETN ANALYSIS

In this paper, firstly, numerical analysis of electromagnetic field is carried out by the nonlinear transient finite element method (FEM). Secondly, the linear static FEA of magneto-thermal field is implemented by applying source current computed by the nonlinear transient analysis.

The SPIM of the scroll compressor is analyzed by using the 2D FEA in FLUX 2D. The FE model and the external circuit for driving the SPIM are constructed. For the non-linearity of the stator and the rotor, the saturation point of magnetic density is defined as 1.79 [T] as shown in Figure 4. From the nonlinear transient FEA, the torque property and current profile of the SPIM are focused at rated speed 3470 [rpm]. The plot of torque vs. time is shown in Figure 5. These results are validated with the experimental data as shown in Table 1. The error is below 5 %.

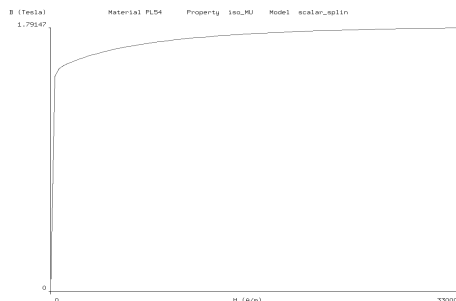


Figure. 4 B-H Curve of Stator and Rotor

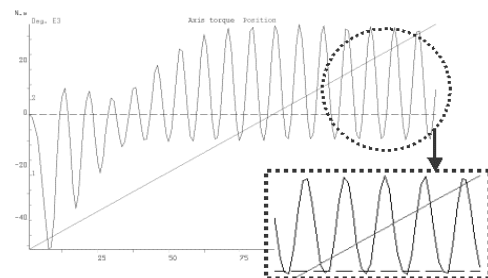


Figure. 5 Torque in Transient FEA [3470 rpm]

Table. 1 Comparison between Experiments and FEA

	Voltage [V]	Current[A]		Torque [N.m]
		Main	Auxiliary	
Experiment At 3470rpm	220	12.2	7.3	9.0
FEA At 3470rpm	219.6	13.3	7.6	9.4
Error	-	4.7%	4.4%	4.7%

In magneto-thermal analysis, the target domain is the cross-section in axis middle of the SPIM mounted on the compressor. 2D model of the compressor is shown in Figure 6. As material properties and boundary condition, thermal conductivity and convection coefficient are given as Table 2 and 3, respectively [3]. The bulk temperature is temperature inside the calorimeter during experiment. The comparison between experiment and FE result is shown Table 4. The error is below 2 %.

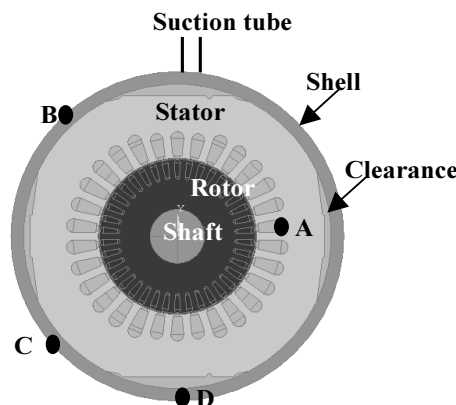


Figure. 6 2D Model of Scroll Compressor

Table. 2 Material Properties

Thermal Conductivity [W/m ° C]				
Stator Core (Radial/Axial)	Shaft	Rotor Bar	Coil	Air gap
23/2	63	237	390	0.0784

Table. 3 Boundary Condition

Bulk Temperature [° C]	Convection Coefficient [W/m ² ° C]	
	Stator	Shell
35	58	38

Table. 4 Comparison between Experiments and FEA

	Temperature [° C]			
	A	B	C	D
Experimental Result	68.4	50.7	65.1	68.2
FEA Result	68	51	65.5	69

5. MULTI-PHYSICS TOPOLOGY OPTIMIZATION

In multi-physics topology optimization, the problem is defined as (14) using multi-objective function. The multi-objective function is composed of magnetic energy and nodal temperature. Optimization program is developed using weighting factor α_1, α_2 to be suitable for designer's purpose. In this paper, both weighing factors are 0.5 to maximize heat transfer maintaining initial magnetic energy. Since torque is calculated by the derivative of energy, magnetic energy is used. Design domain is the stator core except the stator coil, and constraint is volume of the stator to be remained as less as 80% of initial volume.

$$\text{Maximize } \psi = \alpha_1 \frac{\psi_{EM}}{\psi_{EM,initial}} + \alpha_2 \frac{\psi_{TH}}{\psi_{TH,initial}} \tag{14}$$

$$(\psi_{EM} = \frac{1}{2} \iint_{\Omega} B \cdot Hd\Omega, \psi_{TH} = \text{Nodal temperature})$$

$$\text{Subject to } g = \frac{\iint_{\Omega_1} \rho Atd \Omega_1}{0.8V_0} - 1 \leq 0 \tag{15}$$

Bounded to $0 \leq \rho \leq 1$ for all $\rho \in \Omega_1$

where A is the area, t is the thickness, and V_0 is the initial volume.

In order to reduce whole temperature of the compressor, opposite direction to suction tube is defined as target node. Except for a clearance near to suction tube, the rest is filled up with core material, as a preceding step for pseudo-transient topology optimization. Because it is possible that unexpected holes and cuts improve performance of the scroll compressor.

Figure 7 shows sinusoidal current profile computed by nonlinear transient analysis. There are many possible optimal topologies depending on time. Among continuous points of sinusoidal current, 6 points are so critical for rotational magnetic field that optimal topologies are obtained only at those points. In optimization problem, it is needed to find an optimal topology that could be global optimum in whole time. Thus, the final optimized topology can be obtained by summing up topology results at each time. On the basis of final result from topology results as shown in Figure 8 (a) and (b), a number of different designs are possible. In this paper, optimal shape is designed as shown in Figure 9, because of the intention for maintaining the initial torque. Effectiveness of the optimal design is confirmed by comparison between initial and optimal design in Table 5.

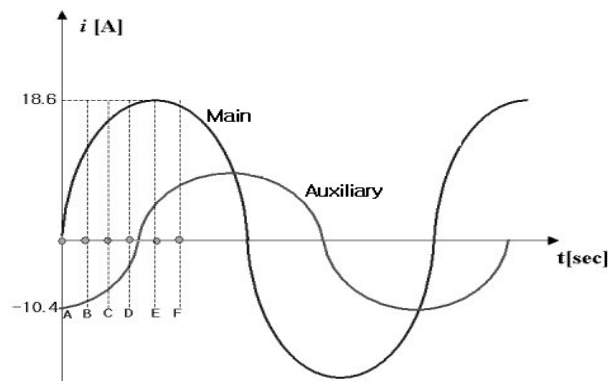
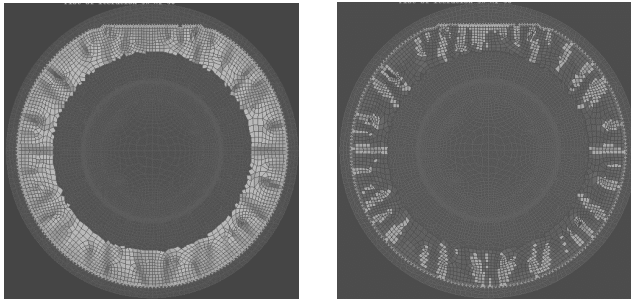


Figure. 7 Current Profile



(a) Gray View of Final Result (b) Color View of Final Result
Figure. 8 Final Result

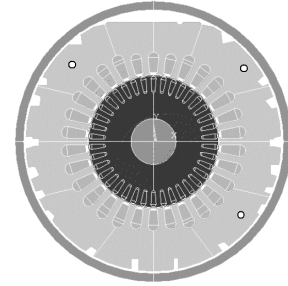


Figure. 9 Optimal Design

Table. 5 Comparison between Initial and Optimal Design

	Initial Design	Optimal Design
Torque [%]	100	102.1
Min Temperature of Motor [° C]	57.7	56.3
Max Temperature of Motor [° C]	232.6	228.5
Area of Stator [%]	100	100.1

6. CONCLUSIONS

In this paper, the multi-physics topology optimization of the scroll compressor is carried out for maximizing heat transfer while maintaining magnetic energy. The experiment is implemented to validate FE results in terms of electromagnetics and heat transfer. Commercial codes such as FLUX 2D and ANSYS are used for the nonlinear transient electromagnetic analysis and topology optimization of magneto-thermal field, respectively. Optimal topology suggests several holes and cuts in the stator.

NOMENCLATURE

$a_{\Omega}(\cdot, \cdot)$ Energy bilinear form	$l_{\Omega}(\cdot)$ Load linear form
Ω Design space	A Magnetic vector potential
λ Adjoint variable	\bar{A} Virtual vector potential
μ Permeability	u Design vector for electromagnetics
v Design vector for heat transfer	ψ_{EM} Object function of electromagnetics
ψ_{TH} Object function of thermal field	B Magnetic flux density
H Magnetic field intensity	J_s Source current density
k Thermal conductivity	q^b The rate of heat generated per unit volume
q^f Input heat flow	T^S Known temperature
T_b Known environmental temperature	h_c Heat convection film coefficient
η Efficiency	V Voltage
I Current	θ Phase Difference between voltage and current
T Torque	W Speed of Revolution

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