Multiphysics design optimization of a high precision Flexural-based Electromagnetic Actuator (FELA) for improved precision and efficiency

Jonathan Hey[1,2], Choon Meng Kiew[2], Tat Joo Teo[2], Wei Lin[2], Guilin Yang[2]
[1]*Department of Mechanical Engineering, Imperial College, London, UK*
[2]*SIMTech, Singapore*
hhh09@imperial.ac.uk

Abstract

A 3D Finite Element (FE) model incorporating multiphysics interaction was developed to optimize the performance of a nanopositioning actuator, termed FELA, in terms of precision, power output and efficiency. Its operation involves the interaction of electromagnetic force generation and thermal elastic deformation. By running independent parametric study of the three design variables; packing arrangement of the windings, coil radius and wire diameter, an optimum design is obtained by aiming at the reduction of heat generation and thermal expansion. The end result is a device that uses 55% less power to produce the same output force leading to higher efficiency and a 54% reduction of shaft thermal expansion.

1 Introduction

FELA is a nanopositioning actuator, which has successfully broken through the millimeter-range barrier encountered by state-of-the-art nanopositioning actuators, through the marriage of an electromagnetic driving scheme with flexure-based supporting bearings[1]. Hence, it delivers key performances on a single platform that are crucial for next-generation high-precision systems. However, some form of input energy is converted to heat during its operation and this causes thermal expansion of the actuator which is undesirable[2]. This paper presents the design improvements of FELA using a Finite Element (FE) model to conduct a parametric sweep of the design variables to obtain an optimum design. The design variables considered are (i) winding aspect ratio, (ii) wire diameter and (iii) coil radius as illustrated in Fig 1. The objective of the optimization process is to improve its performance in terms of its precision, power output, efficiency and cost.

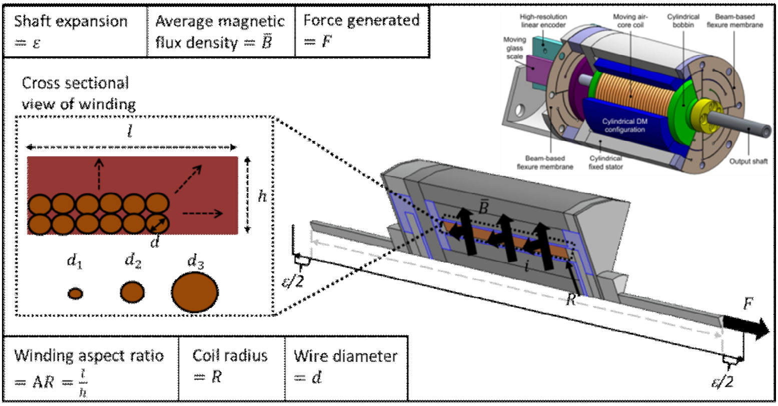

Fig 1 Illustration of FELA and FE model

2 Finite Element (FE) multiphysics model

FELA generates force by the interaction of current carrying coils and a magnetic field. The coils are suspended between two Permanent Magnets (PMs) by a flexure mechanism as shown in Fig 1. The magnetic flux density within an air gap between two PMs is dependent on the magnet and gap geometry[3]. The force produced depends on the strength of the magnetic flux density, current and length of wire while the current flowing through the coils causes resistive heating. The internal temperature gradient depends on the heat generated, thermal resistance of the heat transfer path and heat loss at the device boundary. The expansion of the shaft is derived from the temperature and material thermal expansion coefficient.

The steady state multiphysic interaction is simulated using COMSOL. Only a sector of the machine is modelled because of the axis symmetry. The output parameters, as illustrated in Fig 1, such as maximum winding temperature (T), total shaft expansion (ε), average magnetic flux density ($\bar{B}$), volume of wire used (V), heat generation (Q_{gen}) and output force generated (F) are obtained from the simulation. Some of the simulation parameters are compared against the experimental measurement of the current design and shown in Table 1. There are some discrepancies due to idealization of the model such as perfect packing of the windings and measurement error with the maximum error being less than 13%.

Table 1 Simulated and measured output parameters

Physical parameters	Simulation	Experimental	Error (%)
Shaft expansion (μm)	42.0	45.0	-6.6
Average magnetic flux density (T)	0.14	0.16	-12.5
Maximum winding temperature (°C)	42.7	46.2	-7.6

3 Optimization process

Other design configurations were simulated using the validated model. Discrete design points were used to ensure the solver stability numerically and limit the search space to only feasible designs. The individual designs were evaluated by defining an objective function (F_{obj}) as a function of simulation output parameters as defined in (1). Parameters indicated by a '^' in (1) are inverted so that all parameters are to be minimized in the optimization process. All output parameters are normalized such their values fall within 0 to 1. Weights (w) are introduced into the objective function to shift the design point towards one which maximizes the magnetic flux density so as to maximize the force generation while limiting the heat generation. Three sequential direct minimization processes were performed to determine the best design configuration for each design variables and the cycle is iterated thereafter. Only design variables are varied during the optimization process.

$$F_{obj} = w_1 V + w_2 \hat{F} + w_3 Q_{gen} + w_4 \hat{\bar{B}} + w_5 \varepsilon$$

Where $w_1 = 0.1, w_2 = 0.1, w_3 = 0.1, w_4 = 0.6, w_5 = 0.1$ (1)

4 Result and discussion

The current configuration is: aspect ratio = 13.3, coil radius = 9.6mm, wire diameter = 0.5mm. After the optimization process, the design is improved to a new configuration of: aspect ratio = 7.5, coil radius = 12.6mm, wire diameter = 0.5mm as indicated by the minimum point in Fig 2. The output force is increased due to the design improvements so the applied current is adjusted such that the force remains constant in order to make fair quantitative comparison. The output parameters from the simulation of the new design are shown in Table 2. Although thermal expansion is a linear function of temperature, it is also affected by the geometry. The larger reduction in thermal expansion is due to geometric optimization from the analysis.

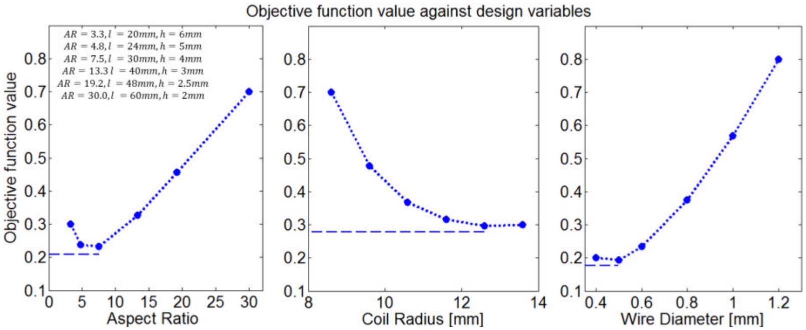

Fig 2 Objective function value against design variables

Table 2 Comparison of output parameters for current (A) and optimized (B) design

Design Variable	Design A	Design B	Change (%)
Volume of wires (mm^3)	8824	11008	+24.8
Heat generation rate (W)	1.92	0.86	-55.2
Thermal expansion (µm)	42.0	19.4	-53.8
Magnetic flux density (T)	0.14	0.19	+35.7
Temperature (°C)	42.7	29.98	-29.8

5 Conclusion

A design optimization of the FELA device is presented in this work. Improvements in the key areas of precision, force generation and efficiency were obtained. By maximizing the magnetic flux density, the device is able to generate more force while limiting the increase in heat generation. Heat generation was reduced by 55% and the shaft expansion decreased by about 54%. However, the new design resulted in a device that used more materials which would increase cost.

References:

[1] T. J. Teo, G. L. Yang, I. Chen, and W. Lin, "A Novel Actuator with Nanometres Resolution and High Force-Current Ratio throughout Millimetres of Stroke," *7th Euspen International Conference*, 2007.

[2] R. Ramesh, "Error compensation in machine tools — a review Part II: thermal errors," *International Journal of Machine Tools and Manufacture*, vol. 40, no. 9, pp. 1257-1284, Jul. 2000.

[3] T. J. Teo, I.-M. Chen, G. Yang, and W. Lin, "Magnetic field modeling of a dual-magnet configuration," *Journal of Applied Physics*, vol. 102, no. 7, pp. 074924.1-12, 2007.