Analysis and Design of Slotted Tubular Linear Actuator for the Eco-Pedal System of a Vehicle

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Abstract —This paper presents the design and analysis of a linear actuator for vehicle Eco-Pedal system. To prevent the excessive gas consumption for fuel-efficient vehicle the electric actuator produces a counter force to the vehicle's pedal to be pressed stiffly. Major performances of the actuator are required such as a high force density and a low detent force. In this paper, the design of the actuator is optimized to satisfying the requirement of the actuator, and the finite element method is used to analyze the actuator. The advisability of the design result is verified with the experimental result.

I. INTRODUCTION

Recently, the needs of motorization in vehicle system have increased as a wide range of reasons, such as a vehicle safety, convenience and energy consumption. An Eco-Pedal System (EcoPS) is one of them. The EcoPS is installed in the accelerator pedal in the vehicle. Unlike conventional mechanical pedal, it is generally run by an electric actuator generating resistance force against drivers' foot press force as the need arises for high efficient driving or emergency situation [1]. Previous EcoPS utilized rotary motor with mechanical gear system which brings unexpected breakdown and failure. To overcome the troubles by mechanical parts, linear actuator is utilized. Since the pedal press is linear motion, the active pedal system with linear motor does not need the gear system. This paper proposes a new slotted tubular linear actuator for the EcoPS. Its design is optimized to satisfying the requirement of the actuator such as a high force density and a low detent force, the simple analysis model and the finite element method are used to the design and analysis of the suggested actuator. The experimental result and the design result are compared in this paper.

II. BASIC STRUCTURE OF ACTUATOR

A tubular linear actuator is generally composed of a slot-less stator and a ring type magnet. This type actuator has some drawbacks such as a low force density. To overcome the inherent drawback, a new slotted tubular linear actuator is proposed for simplicity in construction and high force density, and three phase inverter is utilized to drive the designed linear actuator. This drive scheme is used with six step drive based on 60^{o} commutation, and three hall sensors are installed in the stator core sheet to measure the mover's position at any time [2].

Fig. 1 illustrates the configuration of the new slotted tubular linear actuator.

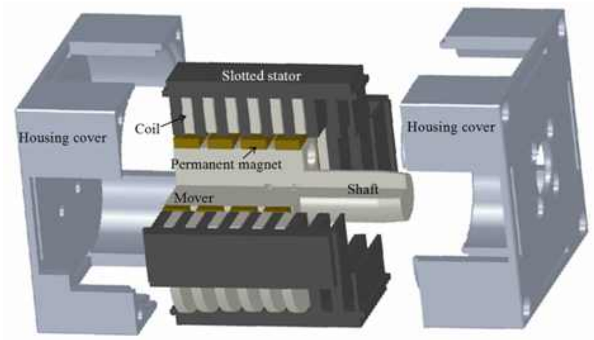

Fig. 1. Configuration of the slotted tubular linear actuator

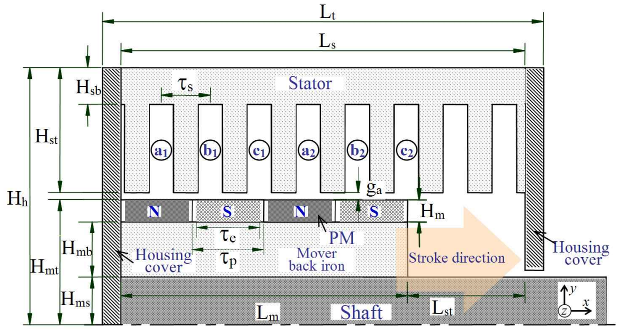

Fig. 2. Cross section of a quarter part of the slotted tubular linear actuator

The tubular actuator consists of a slotted tubular stator wounded coils and a mover mounted permanent magnets. The slotted tubular stator is made up of four and its surfaces are faced with four equal sectors of the mover surface respectively. Therefore, the actuator is divided into four equal parts and a quarter part of the actuator is shown in Fig. 2. A quarter part of the actuator is made up of 6 slots and 4 poles. Thus, it is considered as the linear motor with 6 slots and 4 poles, the length of which is L_s and the axial length of which is D_m. So, the performance of the actuator can be analyzed by using 2D finite element method to solve 2D static magnetic field [2]-[4].

III. ANALYSIS AND DESIGN OF ACTUATOR

In order to design the actuator, Table I lists the power conditions required to operate the EcoPS and the dimension condition of the actuator size. For the required force of the actuator is 100 N, from Fig. 3, the thrust force per pole of a quarter model is expressed as

$$F_{pole} = 100(N) \times \frac{1}{4}(model) \times \frac{1}{4}(pole) = 6.25(N) \qquad (1)$$

TABLE I
DESIGN REQUIREMENTS and SIZE LIMITATION

Title	Value	Unit
Voltage	12	V
Current density	20	A/mm^2
Moving Stroke	15	mm
Active Average force	100	N
Actuator Width	70	mm
Actuator Height	70	mm
Actuator Length	60	mm
Coil Fill Factor	50	%

The air-gap flux density B_g per pole is computed as

$$B_g = \frac{H_m}{g_a + H_m} \times B_r \times \delta \ (T) \qquad (2)$$

Where, B_r is the residual magnetic flux density of the permanent magnet, g_a is the length of the air-gap, H_m is the thickness of the permanent magnet, δ is the leakage coefficient for considering a leakage flux of the air-gap, a magnetic saturation of the core, and the dead zone of the permanent magnet. By using Lorentz force law, the magnetic motive force (MMF) to produce the thrust force per pole is required as

$$M_{mf} = \frac{F_{pole}}{B_g \times D_m} = I \times S_n (AT) \qquad (3)$$

Where, F_{pole} is the thrust force per pole, which is obtained by (1), B_g is the air-gap flux density per pole, which is computed by (2), H_d is the axial length of a quarter model, I is a phase current and S_n is the number of turn of one coil.

Beside that elementary dimensions of the initial design of the actuator are illustrated in Table II. From the given voltage and the size limit, the first step is an assumption of the phase resistance, and the phase current is obtained by Ohm's law. The second step, the coil diameter calculates for satisfying the condition of the current density. Thus, the number of the coil turn can be computed from required the MMF. Next step, the phase-resistance must be renewed from the obtained coil specification. This process is repeated until approximating between the old value and renewed value of the phase resistance. When it reaches, the condition the fill factor of the stator winding should be confirmed. If the fill factor exceeds the limit, this process has to return to the first step, and the modification of the initial assumed resistance need.

TABLE II
INITIAL DIMENSIONS OF THE ACTUATOR

Title	Variable	Value	Unit
Axial length of a quarter part	D_m	28	mm
Stator back-iron thickness	S_b	5	mm
Permanent-magnet thickness	H_m	2	mm
Air-gap length	g_a	1	mm

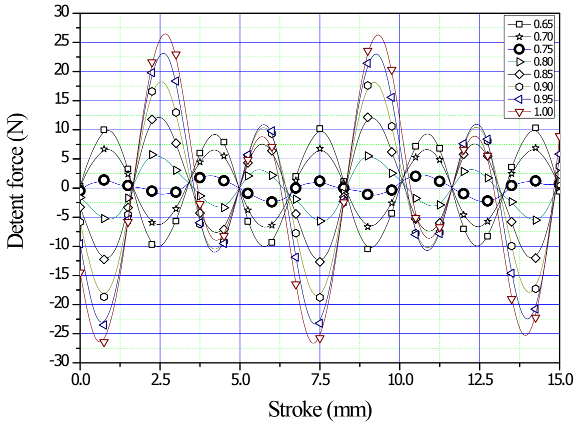

Fig. 3 Detent force according to the effective pole ratio

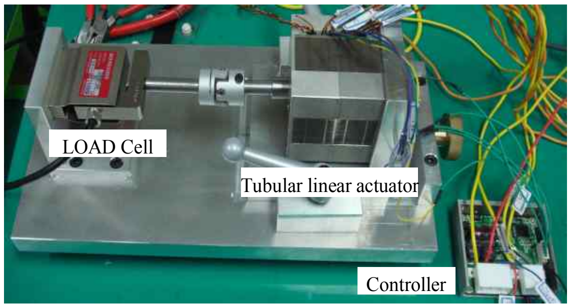

Fig. 4. Test bench for proto type linear actuator

From the overall design process, the design of the actuator is accomplished with satisfying its requirements. Then, in order to reduce its detent force, it is optimized according to the effective pole ratio of the pole pitch τ_p to the effective pole pitch τ_e.

IV. Results and Conclusion

Fig. 3 shows the detent force according to the effective pole ratio. When the ratio is 0.75, the detent force is smallest as shown in this figure. Fig. 4 shows the test bench for the proto type proposed linear.

In this paper, the structure of the slotted tubular linear actuator is suggested for the EcoPS. In order to have the high force density and the low detent force, the actuator is designed by using the simple equivalent model and the 2D finite element method. In full paper, the more detail of this study included experimental results will be presented.

V. References

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