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Optimizing Linear Stepping Actuator Using Evolutionary Strategy Method

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Abstract: Throughout this paper, we are going to optimize a linear tubular stepping actuator. Our aim is to maximize the trust force taking into account the actuator's weight which is considering as the most important constraint. The contribution of the machine weight minimization is principally a cost decrease that permits its integration in small systems. The optimization method approach is evolutionary strategy method. Finite-element analysis is then employed to calculate a series of designs and determine the optimum one.

Key words: Linear stepping actuator · Finite element analysis · Optimization · Maximizing force · Minimizing weight · Evolutionary strategy method · Optinet infolytica

INTRODUCTION

The actuator used in this paper is a linear stepping actuator with a tubular form and a variable reluctance switched structure. The mechanical model is composed essentially of a mover, four stators module, four coils and three spacers as it shown in the Figure 1.

The mover is made by cold rolled steel material. The length measure 127mm, the width 29.8mm. The thirteen mechanical teeth spaced apart a distance of 5.08mm. Each tooth height is 4mm.

The coil material is Copper (5.77e7 Siemens/meter) and has 200 turns. Each one of the four coils is excited with a nominal DC current of 2A. The inner radius is equal to 16mm and the outer radius is 40.9mm. The coil thickness considered here is 5.08mm.

A fix stator has the same material as the mover, the inner radius is equal to 15mm and the outer radius is 45.9mm. The stator's thickness considered here is 15.24mm. The coil is inserted in one stator module as it shown in the Figure 4.

A non-magnetic separation is placed between two successive stators called spacer. The inner radius is equal to 15mm and the outer radius is 45.9mm. The stator's thickness considered here is 2.54mm.

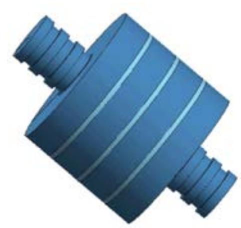

Fig. 1: Linear Tubular Stepping Actuator.

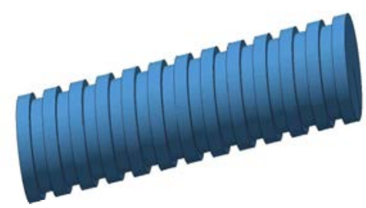

Fig. 2: The mover.

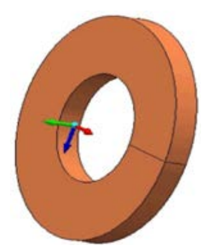

Fig. 3: The coil.

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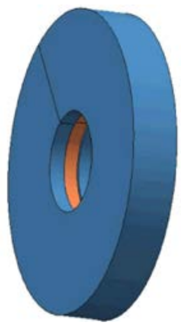

Fig. 4: The stator module.

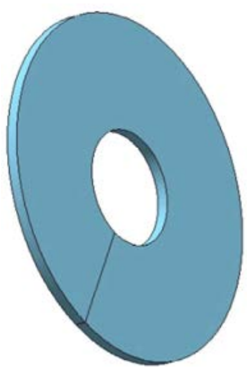

Fig. 5: The spacer.

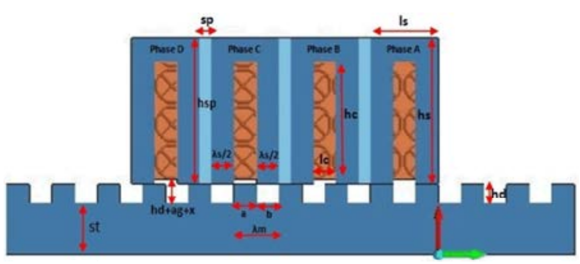

Fig. 6: A longitudinal section of the actuator

The linear tubular stepping actuator is controlled in open loop by 4 phases (A, B, C and D). Each phase represents one module which composed of stator module and a coil. The mover is distant than the four stators modules with an air gap of 0.1 mm. As the displacement is linear, the rotor here is called a mover. For a good interpretation of the linear actuator parameters, a longitudinal section is given in the Figure 6 [1].

In order to ensure smooth functioning, we choose the tooth pitch of the stator 'λs' and the tooth pitch of the mover 'λm' to be equal. The tooth width 'a' and the slot width 'b' are equal too according to equations (1) and (2) [2].

$$\lambda s = \lambda m = \lambda = a + b \tag{1}$$

Table 1: Parameters Values of the model

Parameters	Designations	Values (mm)
a	coil	5.08
b	slot width	5.08
hd	tooth high	4
λs	stator tooth pitch	10.16
λm	mover tooth pitch	10.16
ag	air gap	0.1
st	mover inner radius	10.9
x	distance between stator and coil	1
ls	stator width	15.24
hs	stator height	30.9
hc	coil height	24.9
lc	coil width	5.08
sp	separation width	2.54
hsp	separation height	30.9

Table 2: Control Mode

	Step1 (2.54 mm)	Step2 (5.08 mm)	Step3 (7.62 mm)	Step4 (10.16 mm)
Phase A	1	0	0	0
Phase B	0	1	0	0
Phase C	0	0	0	1
Phase D	0	0	0	1

$$a=b \tag{2}$$

According to equation (1) and (2), the single step when only one phase is excited is given by equation (3).

$$step = \frac{\lambda}{N} \tag{3}$$

With N: Number of phases

According to figure 6, a non magnetic separation 'sp' is placed between two successive phases so that only one statoric phase can be aligned with the mover teeth when it is supplied. The non magnetic space is fixed by equation (4) [3].

$$sp = \frac{\lambda}{N} = \frac{a}{2} \tag{4}$$

The actuator model is defined by the single step chosen equal to 2.54 mm. The single step is obtained by equation (3) provided that equation (1) and (2) must be satisfied. The different parameters used to design the linear actuator are listed in Table1.

Concerning the control of the linear tubular stepping motor in open loop control and in order to have a fixed step of 2.54 mm, we excite one phase per time so the first coil related to the phase A will get a current of 2 A followed by Phase B then C and finally D. The control mode is represented in Table2 when numbers 1 and 0 denote respectively the energized and the de-energized phase [4].

Optimization: The main objective of this paper is to optimize the structure of the linear tubular stepping actuator. The initial model represented by Figure 1 and table 1 should be minimized. The optimization criteria imposed to the actuator's mover is to obtain a maximum thrust force with a minimum global mass.

There are two kinds of optimization algorithms to optimize the actuator, the deterministic and the stochastic optimization. Among the deterministic optimizations, there is the gradient-based method. The other method is the stochastic one, there exist many stochastic optimization methods but in this paper the only one that is studied and used is the evolutionary strategy method because it is the most convenient and intuitive [5].

The Evolutionary Strategy is considered as a robust, good general purpose optimization method, which guaranties that there is a non-zero probability to find the global minimum. It is based on a stochastic approach, in which each design variable is represented as a random value rather than a deterministic one. In the present case, this random character is mathematically expressed as a Gauss probability density function. Evolutionary Strategy has proven to be a cost-effective algorithm able to identify the optimum of objective functions dependent on several design variables, even in the case they are non convex, non-smooth and numerically ill-conditioned [6].

The flow chart of the evolutionary strategy method is presented in the Figure 7.

The optimization is based on the software OPTINET from INFOLYTICA Cooperation, the flow chart is divided in three essential parts:

Generation Stage: Starts with a search region of extend 'd_0' (internally determined) centered at the initial configuration 'm_0' provided by the user. The generation of first stochastic sample is:

$$x_0 = m_0 + u.d_0 \tag{5}$$

Then proceeds, using a random sample:

$$0 \langle u \langle 1 \tag{6}$$

Mutation Stage: A new design vector 'x' replaces 'm_0' when 'x' is located in the feasible region and O.F.(x) < O.F.(m_0)

Annealing Stage: Concerned with the size 'd' of the search region when a better point is found. The trend is first established: said to be positive when success rate of the past iterations > p, negative otherwise. If trend > 0, 'd_0' is increased to:

$$d = \frac{d_0}{q} \tag{7}$$

Where q < 1. Otherwise 'd_0' is decreased to:

$$d = q.d_0 \tag{8}$$

This stochastic algorithm therefore becomes braver and covers a larger space in order to see if there would be another good candidate in the neighborhood, then does the opposite when this is not deemed possible. This is different from a deterministic approach, in which the search region would be narrowed down around an improved point to quickly converge towards the nearest minimum [6].

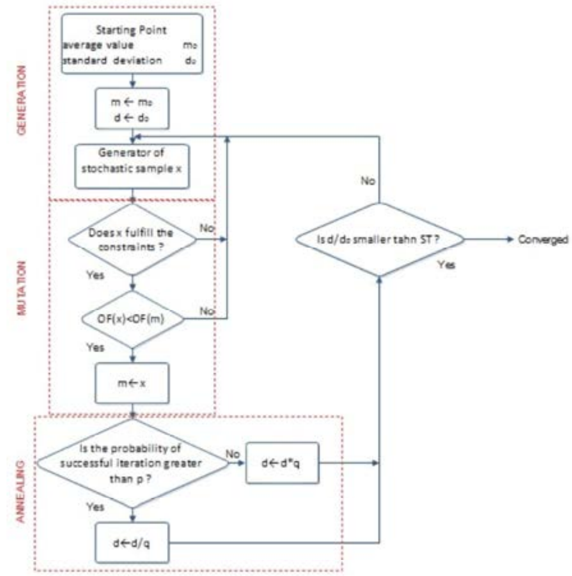

Fig. 7: Flow chart of the evolutionary strategy method

The optimization problem is mathematically defined as follows: the global optimum of the objective function "f" is to be determined, respecting: the free parameters limit (LU) and the equality constraints (CE) and the inequality constraints (CN). The limits LU and constraints CE and CN define a domain 'D' in the space. The objective is to determine the global optimum of the function "f" on the domain D.

The optimization presented in this paper is based on the evolutionary strategy method, the software Optinet from Infolytica Cooperation presents a best tool for optimization. The main goal of the optimization is to maximize the thrust force along ‘y’ axis which is given by equation (5) [7].

$$F_y = \frac{\pi.\mu_0.(st + hd + 0.5.\text{ag}).(N.i)^2}{2.\text{ag}} \tag{9}$$

Where ‘μ_0’ is the air magnetic permeability, ‘N’ is the number of coil turns and ‘i’ the supply current in the coil.

The global mass ‘m’ of the actuator is equal to the sum of the different components constituting the actuator:

$$m = m_{mover} + m_{coils} + m_{stators} + m_{spacers} \tag{10}$$

Where m_{mover}, m_{coils}, $m_{stators}$ and $m_{spacers}$ are respectively the mass of the mover, the mass of the four coils, the mass of the four stators and the mass of the three spacers.

Each one of the different mass is proportional to the volume and density ‘ρ’ of the material. The material used to construct the mover and the stators is “Cold rolled 1010 steel” (CR10), the mass density is 7600 Kg/m3 [8]. The mover volume and mass equations are respectively (11) and (12):

$$V_{mover} = 13.\pi.(st + hd)^2.\text{a} + 12.\pi.\text{st}^2.\text{a} \tag{11}$$

$$m_{mover} = \rho_{mover}.V_{mover} \tag{12}$$

The coil material is Copper (5.77e7 Siemens/meter), the mass density is 8954Kg/m^3.The coils volume and mass equations are respectively (13) and (14):

$$V_{coils} = 4.\pi.(hc)^2.lc \tag{13}$$

$$m_{coils} = \rho_{coils}.V_{coils} \tag{14}$$

The material for the spacers is a non magnetic material, the mass density is 1000 Kg/m^3. The spacers’ volume and mass equations are respectively (15) and (16):

$$V_{spacers} = 3.\pi.(hsp)^2.\text{sp} \tag{15}$$

$$m_{spacers} = \rho_{spacers}.V_{spacers} \tag{16}$$

The four stators modules material are “Cold rolled 1010 steel” (CR10), the mass density is 7600 Kg/m3. The volume and mass equations are respectively (17) and (18):

$$V_{stators} = 4.\pi.(hs)^2.\text{ls} \tag{17}$$

$$m_{stators} = \rho_{stators}.V_{stators} \tag{18}$$

The parameter limits (LU) are:

$$15 \le hc \le 30 \tag{19}$$
$$1 \le hd \le 5 \tag{20}$$
$$20 \le hs \le 40 \tag{21}$$
$$20 \le hsp \le 40 \tag{22}$$
$$5 \le st \le 15 \tag{23}$$
$$0.1 \le x \le 2 \tag{24}$$
$$0.1 \le ag \le 1 \tag{25}$$

The parameters a, b, λm, λs, lc, ls and sp must remain constant, according to table1, in order to get a single step of 2.54 mm when one phase per time is energized.

The inequality constraint (CN) is:

$$m \prec 3Kg \tag{26}$$

The initial values for the input parameters are chosen as:

$$hc = 24.9mm \tag{27}$$
$$hd = 4mm \tag{28}$$
$$hs = hsp = 30.9mm \tag{29}$$
$$st = 10.9mm \tag{30}$$
$$x = 1mm \tag{31}$$
$$ag = 0.1mm \tag{32}$$

The objective function is the mover’s thrust force F which has to be maximized.

RESULTS

To optimize the thrust force, both of the software OPTINET and MAGNET from INFOLYTICA Cooperation were used and functioned on the machine INTEL CELERON Processor CPU (1.6 GHz x 1.6 GHz), 4096 Mb RAM.

The Table 3 shows the optimization results and rate between the old model and the optimized one. Through analyzing the Table 3, the thrust force increase with an optimization rate of 45.41% while the mass decrease with a rate of 22.3%.The tooth height 'hd' and the coil height 'hc' are the principal parameters which present a large decrease, we note an optimization rate of 58.84% for 'hd' and 38.15% for 'hc’.

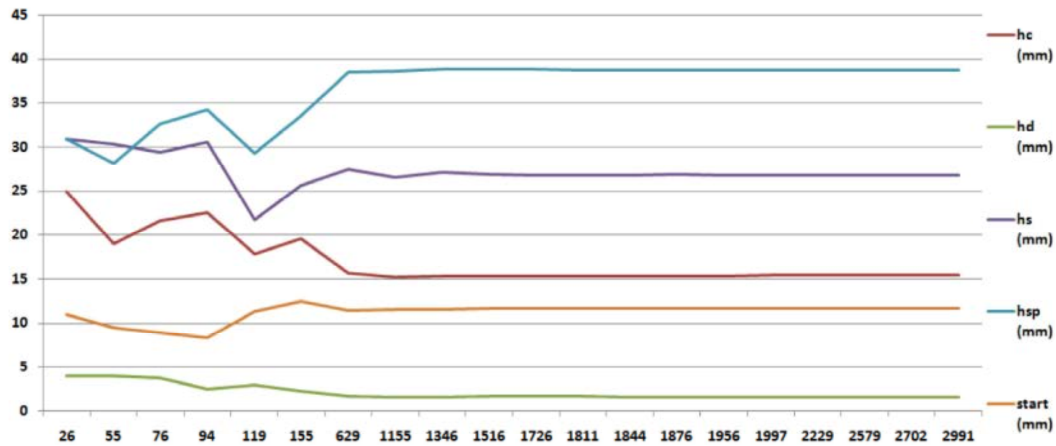

Fig. 8: Parameters variation 1

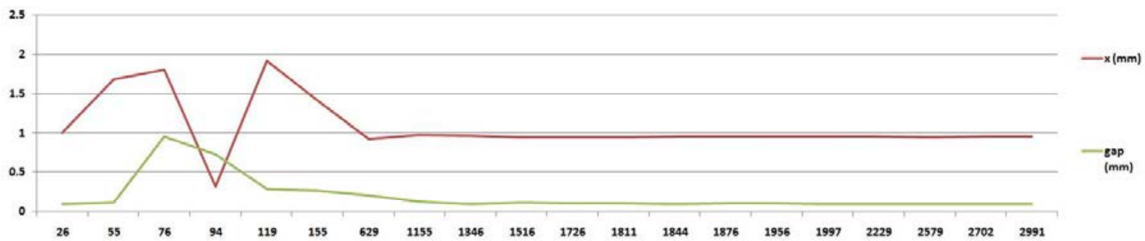

Fig. 9: Parameters variation 2

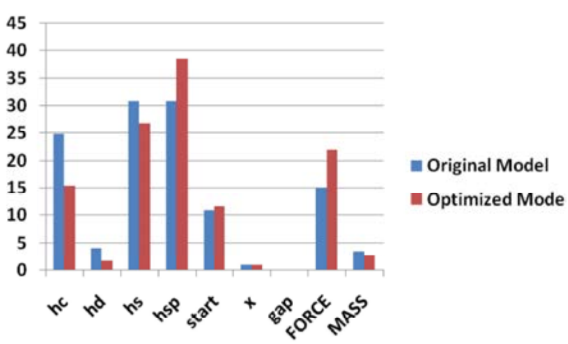

Fig. 10: Comparison

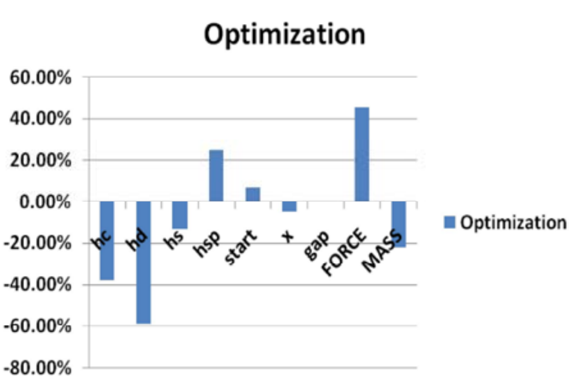

Fig. 11: Optimization rate

Table 3: Optimization rate

Parameters	Original Model (mm)	Optimized Model (mm)	Optimization Rate
hc	24.9	15.40	-38.15%
hd	4	1.65	-58.84%
hs	30.9	26.80	-13.28%
hsp	30.9	38.62	+24.97%
start	10.9	11.64	+6.75%
x	1	0.95	-4.95%
gap	0.1	0.10	+0.21%
FORCE	15.13472415	22.01	+45.41%
MASS	3.450796197	2.68	-22.30%

The variation of the parameters hc, hd, hs, start and hsp are represented in Figure 8 while the parameters x and gap are represented in Figure 9. The initial parameters change stochastically respecting the parameters limits 'LU'. Once the optimization is done, the new parameters values for hc, hd, hs, hsp, start, x and gap are respectively 15.4, 1.65, 26.8, 38.62, 11.64, 0.95 and 0.1.

Figure 10 and 11 summarize the optimization rate of different parameters and present a comparison between the old model and the optimized one. The objective and the constraint evolution were given in Figure 12, the force reached with the optimized model is 22 N with a mass of 2.68 Kg.

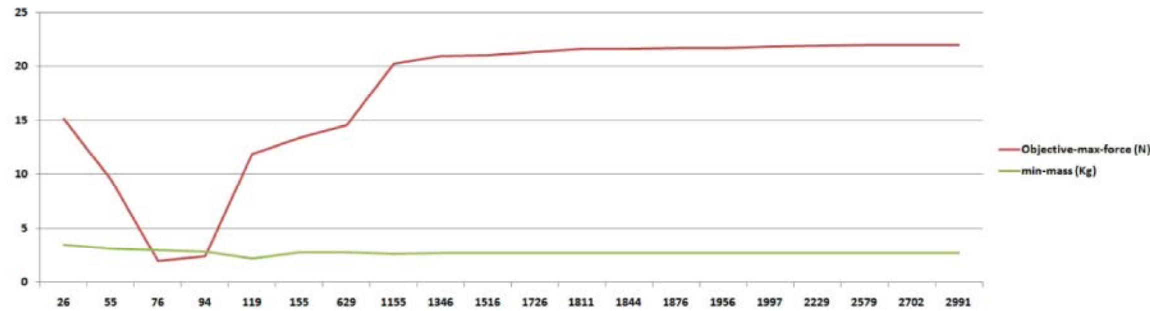

Fig. 12: Objective and constraint

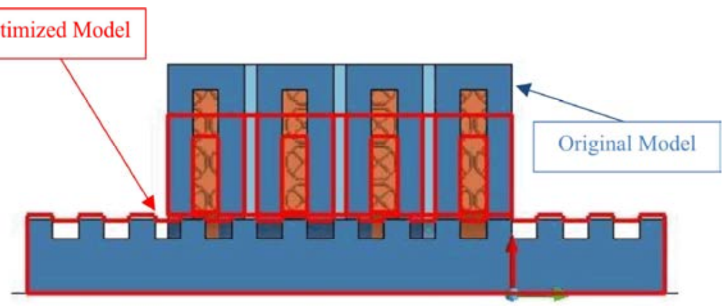

Fig. 13: Optimized Model

The comparison is needed when the optimization problem is imposed. In Figure 13, we note that some parameters are maintained constants like the tooth width 'a' and 'b', the stator and the mover tooth pitch λs and λm, the stator width 'ls', the coil width 'lc' and the separation width 'sp'. All the previous parameters are maintained fixed in order to get a single step of 2.54mm, while other parameters were modified like the coil height 'hc', the tooth height 'hd', the stator height 'hs', the spacer height 'hsp', the parameter 'start' and 'x' and the air gap 'gap'.

CONCLUSION

In this paper, a first model of a linear tubular stepping actuator is studied, the different components that constitute the model were parameterized. In order to get a single step of 2.54mm when one phase per time is energized, some parameters maintained fixed while others are variables.

As optimization method is designed to improve the mechanical and the magnetic performances in electrical machines, our aim is to maximize the thrust force of the mover satisfying the minimization of the actuator weight. The evolutionary strategy method is introduced and used in this paper based on the software OptiNet from INFOLYTICA which present a good tool for optimization.

The thrust force increase with an optimization rate of 45.41% while the mass decrease with a rate of 22.3%. The tooth height 'hd' and the coil height 'hc' are the principal parameters which present a large decrease.

We note an optimization rate of 58.84% for 'hd' and 38.15% for 'hc'.

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