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Variable Weight Coefficient Optimization of Gearshift Actuator With Direct-Driving Automated Transmission

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ABSTRACT Direct-Driving Automated Mechanical Transmission (DAMT) gearshift actuator is a kind of electromagnetic linear actuator. In practical application, the actual gearshift force in each steady states is significantly different from the electromagnetic force model. For the optimization of gear shifting actuator with undetermined volume constraint, this paper presents a variable weight coefficient optimization method of electromagnetic linear actuator which equates the output forces under different steady states in the fitness function. These are intended to adjust the relationships among the optimized objects by using the fitness function to improve the overall optimization effect. In order to obtain the fitness value of each combination parameter accurately, finite element analysis (FEA) is adopted in this paper, to improve the efficiency of the algorithm, and a more efficient simulated annealing –particle swarm optimization algorithm (SA-PSO) is used by the proposed optimization method. Finally, experiment is carried out based on prototype of gearshift actuator to verify the optimization results. The results show that the maximum electromagnetic force and terminal electromagnetic force are both increased by more than 20%, and the volatility of gearshift force is reduced 26.4%, which ensures the structure compactness and fast response. The proposed method decreases the volatility by 27.5% compared with the constant weight coefficients and improves the gearshift force in each stage.

INDEX TERMS DAMT, gearshift actuator, variable weight coefficient optimization, experiment.

I. INTRODUCTION

With the increase of environmental pollution, the electric vehicles have attracted extensive attention owe to their advantages of zero emissions. When developing the transmission system of electric vehicles, high efficiency and low cost are two key points that should be taken into consideration [1].

Compared with the pneumatic and hydraulic modes, the electric Automated Mechanical Transmission (AMT) has the advantage of compact structure and simple control, which is a more promising form of transmission. The clutchless AMT has received extensive attention as a hybrid and pure electric vehicle transmission system [2]. Gao *et al.* [3] designed a two-speed AMT for pure electric vehicles. Chen *et al.* [4] built gearshift model of AMT by hybrid automata, and pointed out that the gearshift time and impact degree in the AMT-Motor direct connection system were significantly reduced. Zhun *et al.* [5] proposed a speed control strategy with excellent robustness. Li *et al.* [6] trained neural network through Broyden Fltecher Goldfarb Shanno algorithm to achieve AMT stationary control. G. kong used displacement control method to optimize the gearshift process [7]. Fan *et al.* [8] designed a novel two-speed uninterrupted mechanical transmission. The above researches on AMT mainly focus on traditional mechanical transmission and the gearshift actuator driven by rotating motor. The DAMT studied in this paper is a new type of direct driving transmission using electromagnetic linear actuator in gearshift mode, which has the advantages of compact structure and faster response speed.

Electromagnetic linear actuator is a type of electromagnetic driving device. Unlike conventional rotary motors,

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it converts electrical energy directly into mechanical energy for linear motion without the participation of any intermediate conversion devices. In addition, the electromagnetic linear actuator has the advantages of simple structure, fast response speed and high motion precision. High-performance electromagnetic linear actuators are now in the process of development and have been widely used in aerospace, vehicle and other fields [9]–[11]. Applications in vehicle mainly include intake and exhaust valve, electronic injection device, suspension systems, gearshift hydraulic valve, etc. [12]–[14]. In this paper, DAMT as a new direct-drive transmission form is formed by integrating an electromagnetic linear actuator with AMT.

In recent years, various analytical, semi-analytical and numerical analysis methods have been proposed for the optimization of electromagnetic driving devices [15]–[22]. Takahashi carried out multi-objective optimization of permanent magnet size and magnetic circuit by 3DFEM-PSO [15] and performed linear vibration analysis performed, pointing out that the efficiency and cost of electromagnetic actuator was mainly affected by the design of structure and magnetic circuit. In order to improve the optimization efficiency of electromagnetic driving device, Mazhoud proposed a new optimization algorithm [16]. Tan *et al.* [17] presented a PSO-GA optimization method for bistable permanent magnet actuator. Li *et al.* [18] optimized the moving-coil actuator using a generalized topology method. Beniakar found a multi-objective group optimization method using differential evolution algorithm considering various parameters [19]. Park *et al.* [19] pointed out the magnetic saturation effect had a great influence on the design of magnetic actuator, and proposed an optimal structural topology optimization method for material saturation problems. Yatchev *et al.* [20] optimized the average output force of moving-iron linear driving device by using sequential linear programming and solving electromagnetic force with 3DFEM. Pham *et al.* [21] proposed a hybrid global optimization algorithm for optimizing augmented objective function by using PSO algorithm. Bortolozzi and Cheng optimized the structure of electromagnetic driving device [22].The above researches are mainly concentrated on the optimization of the structure and magnetic circuit of electromagnetic driving device, without improving the fitness function. For the optimization process, the selection of the weight coefficient in the fitness function will affect the optimization result. This paper proposes a variable weight coefficient optimization method based on the target parameters.

In conclusion, this paper innovatively applies electromagnetic linear actuator to gearshift actuator of AMT. The gearshift process of DMAT can be divided into five independent displacement steady stages. Aiming at the problem that electromagnetic force model is significantly different from the actual gearshift force in each steady state, a variable weight coefficient optimization algorithm for the gearshift process is proposed. The relationship between the optimization targets in the optimization process is balanced by the weight coefficient.

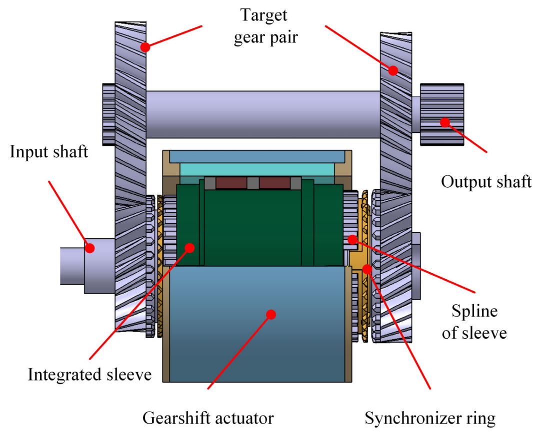

FIGURE 1. Structure of DAMT.

II. STRUCTURE AND MODEL

A. THE STRUVTURE OF DAMT

As a kind of two-speed direct-driving automated manual transmission, DAMT eliminates power transmission mechanisms such as forks and fork shafts. The gearshift actuator, which is sleeved on the input shaft, directly drives the integrated sleeve to complete the gearshift. Its working principle is that the gearshift actuator generates a gearshift force Fs when the constant current is applied. Since the mover of actuator is connected with the sleeve, the gearshift force directly acts on the integrated sleeve. Gearshift actuators work with the synchronizing ring and target gear to complete the shifting process. The structure of DAMT is shown in Fig.1. DAMT has the characteristics of high performance and high efficiency magnetic circuit, fast response speed, light mover mass, arbitrary change of motion trajectory and high control accuracy.

As a moving-coil type electromagnetic linear actuator, gearshift actuator is placed on input shaft of transmission. The schematic of gearshift actuator is shown in Fig.2. It mainly consists of permanent magnets, electromagnetic coil, inner and external yoke and integrated sleeve. The air gap magnetic field and the coil jointly determine the magnitude of the electromagnetic force, and the control of motion is achieved by adjusting the coil current size and direction.

In gearshift actuators, the magnetic circuit flux needs to pass through the inside and outside to form a closed loop so as to enhance the air gap magnetic field. Therefore, internal and external yoke should be made of material with higher magnetic permeability, less coercive force and saturation magnetization. After comparison, steel 08 was finally adopted. The permanent magnet is made of rubidium iron boron SH42 with high-performance, which has high residual magnetic flux density and coercive force. The permanent magnets are arranged in an array of eight tiles. This arrangement is conducive to enhancing the magnetic

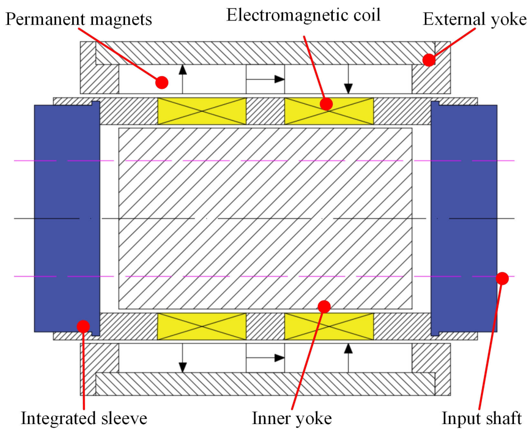

FIGURE 2. Schematic of gearshift actuator.

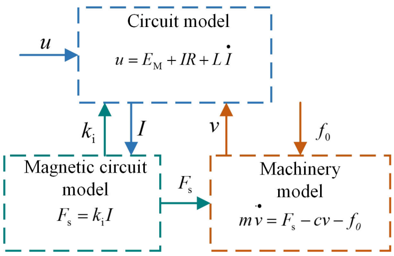

FIGURE 3. Subsystem coupling relationship in gearshift actuator.

flux density in the air gap and reducing the saturation of the yoke [23].

B. MATHEMATICAL MODEL

The gearshift actuator of DAMT is a complex system in which circuit and magnetic circuit couple with each other. As shown in Fig.3. Based on the circuit model, the real-time circuit is calculated by the given voltage and the output force of the actuator is obtained using the actuator force constant (k_i). The motion state of the mover is obtained from the mechanical model.

The different equations of each coupling relationship are:

$$\begin{cases} u = E_M + IR + L\dot{I} \\ F_s = k_i I \\ \dot{v} = \dfrac{F}{m} - \dfrac{cv}{m} - \dfrac{f_0}{m} \end{cases} \tag{1}$$

where m is the mass of the moving parts in the gearshift process of the DAMT, including the electromagnetic coil, the coil skeleton and the integral combination sleeve; v is gearshift speed; c is damping coefficient; u is voltage; I is the current of the coil; R is coil resistance; L is coil inductance; k_i is actuator force constant (the ratio of the maximum electromagnetic force to current); f_0 is external load.

III. PROBLEM FORMULATION

A. PROBLEM DESCRIPTION

The gearshift force of DAMT is provided by the gearshift actuator. Unlike the rotating motor as the power producer for AMT, the electromagnetic linear driving device exhibits electromagnetic force fluctuations, greatly affecting the gearshift process. For the gearshift process with high control accuracy requirements, the fluctuation quantity between the maximum electromagnetic force and the lowest value should be reduced under condition that the large average value of the electromagnetic force.

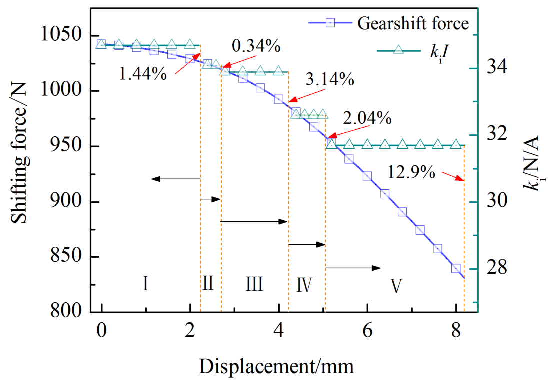

FIGURE 4. Gearshift force and error rate in each stage.

Unlike the bistable working state of the general electromagnetic linear actuator, the DAMT experiences five displacement stages during the gearshift process. Therefore, in the optimization process, the error between the actual gearshift force and the electromagnetic force model (actuator force constant k_i operates on current I) in each steady-state stroke should be reduced as far as possible. When the force-displacement characteristic curve is proportional, the control method can be used effectively to control the gearshift process. However, under non-ideal conditions, the force-displacement characteristic curve of general electromagnetic linear actuator presents a concave and convex shape, which will lead to insufficient gearshift force, directly affecting the response speed of the gearshift actuator and the overall gearshift performance.

As mentioned above, in the magnetic circuit model of the DAMT, the electromagnetic force F_s is equal to the actuator force constant k_i (the ratio of the maximum electromagnetic force to current in a certain displacement) and the current I, which differs from the actual gearshift force in the process, affecting the whole gearshift control accuracy, as shown in Fig.4 and Fig.5.

The five intervals in Fig.4 correspond to the five steady-state stages of displacement during the gearshift process, which is the sleeve approaches synchronizing ring, the sleeve rotates synchronizing ring, the sleeve approaches the target gear; the sleeve rotates the target gear, and the sleeve is fully integrated with the target gear. The corresponding error rate of gearshift force and magnetic circuit model in each stage ranged from 0.36% to 12.9%. As shown in Fig.4, the maximum error value was 120 N, the minimum error value was -4 N and the fluctuation rate was 21.2% in gearshift process.

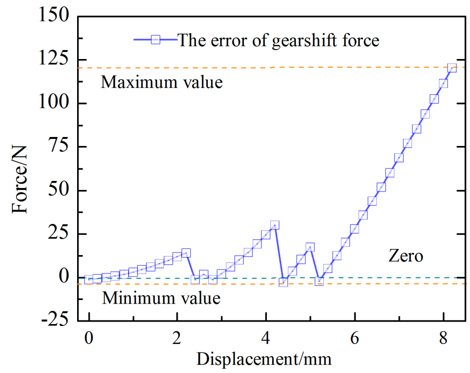

FIGURE 5. Gearshift force error during process.

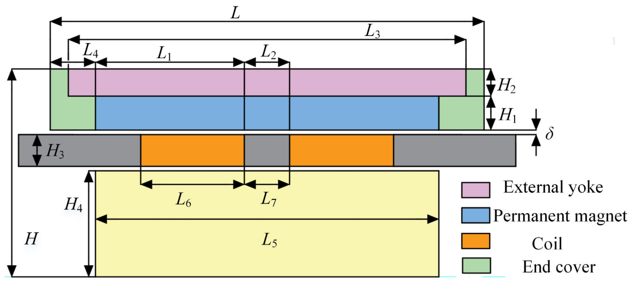

FIGURE 6. Schematic diagram of gearshift actuator parameterization.

B. FITNESS FUNCTION

Considering the fluctuation rate of the gear shifting force and the electromagnetic force density at different stages, the designed constraints and the optimization method were used to search for the optimal parameters in the multi-dimensional parameter space. The electromagnetic force of the gearshift actuator was larger on average, meanwhile reducing the steady state volatility and increasing the output force density. Constraint conditions were set for the overall structural parameters, as shown in Fig.6.

$L_1, L_2, L_3, L_4, L_5, L_6$, and L_7 represent permanent magnet ring length, magnetic ring length, external yoke length, cover length, inner yoke length, coil length, and spacing of coils, respectively. H_1, H_3, H_4, and H_5 represent permanent magnet ring thickness, external yoke thickness, and the thickness of the coil and the inner yoke, respectively. δ is the air gap width. Since the gearshift actuator adopts the moving-coil type, the air gap is left on both sides of the skeleton. As the synchronizer ring adopted is fixed in size, the sizes of the integrated sleeve and the spline hub are determined, and seven parameters are selected to be optimized for the gearshift actuator. The preliminary design parameters are listed in Table 1. Moreover, the structural parameters meet the formulas as follow:

$$\begin{aligned} &2L_1 + L_2 + 2L_4 = L \\ &H_1 + H_3 + H_4 + H_5 + 2\delta = H \\ &L_{\rm i} > 0, \quad H_{\rm i} > 0, \ i = 1, 2 \ldots \end{aligned} \tag{2}$$

Since the type of the synchronizer ring is determined, the size of the inner yoke and the related parameters are

TABLE 1. Preliminary design parameters of gearshift actuator.

Parameter	Value
Total length/L	99 mm
Outer radius/H	62.5 mm
L_1	32 mm
L_2	15 mm
L_3	91 mm
L_4	10 mm
L_7	7.5 mm
H_1	7 mm
H_2	6 mm
δ	0.5 mm
Resistance/R	1.4 Ω
Inductance/$L_{\rm m}$	1.32 mH

determined, so the optimized parameters are $L_1, L_2, L_4, L_7, H_1, H_2$.The fitness function can be written as:

$$f = pqF_{\rm m} + (1 - pq)F_{\rm e} \tag{3}$$

where p and q represent the axial weight coefficient and the radial weight coefficient, respectively, Fm is the mean maximum output force at the initial displacement of each stage, Fe is the mean terminal force at the end displacement of each stage. The selection of the weight coefficient will be explained in detail later. FM and FE represent global maximum output force and global terminal output force of gearshift actuator, respectively.

The variation of the weight coefficients and the handling gearshift force in each stage will reduce the fluctuation rate of the gearshift force at each stage of DAMT and increase the output force and output force density of the gearshift actuator.

The magnetization direction and size of the permanent magnet determine the magnetomotive force of the whole circuit. The space size of the coil determines the effective number of currents in the air gap magnetic field, but an excessively large permanent magnet size increases the loop reluctance. The length of coil will generate the opposite electromagnetic force during the movement of coil, which further increases the degree of damping of the shifting force. The inner yoke, external yoke and the cover function to transmit the magnetic flux, if the size is too small, magnetic saturation will occur and the overall output force density will be reduced.

In order to obtain more accurate optimization results, the static forces of each parameter were obtained by 3D-FEA. In the case of considering the static field and ignoring the displacement current, the Maxwell equation based on the magnetic field strength is given, where the magnetic field strength is denoted as $\boldsymbol{H}$, the current density is denoted as $\boldsymbol{J}$, the magnetic flux density is denoted as $\boldsymbol{B}$, and the material permeability is denoted as μ. In general, the magnetic flux density can be expressed by the magnetic vector $\boldsymbol{A}$: (The differential form of Maxwell's equation under the

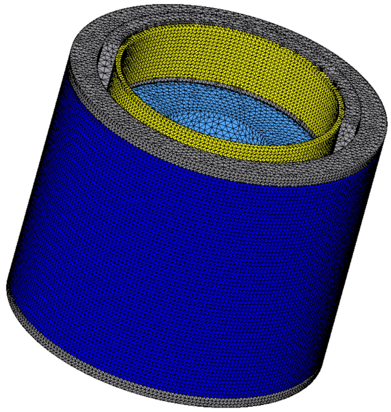

FIGURE 7. 3D Mesh model.

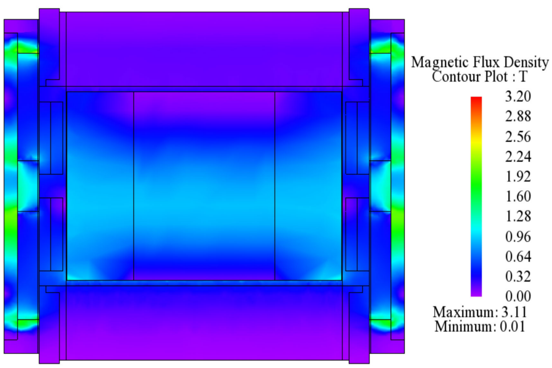

FIGURE 8. Magnetic Flux Density in 3DFEA.

Coulomb specification).

$$B = \nabla \times A \tag{4}$$

$$\nabla^2 A = -u_0 u J \tag{5}$$

In addition, since the coil and other components are meshed separately, a longer calculation time is required for 3DFEA analysis. The gap between the armature and the stator is small, so a denser grid is required when calculating. Fig.7 shows the mesh division of the gearshift actuator; the nonlinear characteristics of the magnetic material are also considered in the numerical calculation process. Fig.8 shows the magnetic flux density of the gearshift actuator in neutral position

IV. VARIABLE WEIGHT COEFFICIENT OPTIMIZATION PROCESS

A. WEIGHT COEFFICIENT

In order to solve the problem of excessive gearshift force fluctuation and increase the output force density in the optimization process, this paper proposes an variable weight coefficient optimization method, in which F_{m} and F_{e} represent the maximum output force and terminal output force of gearshift actuator in the gearshift process, respectively. p and q represent the axial weight coefficient and the radial weight coefficient, respectively.

The value ranges of p and q are determined according to the range of the target parameters. Since the magnetization directions of the two permanent magnet rings of the gearshift actuator are opposite, the winding directions of the two sets of coils are opposite in the winding process, which makes opposite current coil in the opposite magnetic flux. The gearshift force in the same direction is obtained in the gap magnetic field, and the magnetic flux mostly passes through the coil winding vertically.

When the axial length of the gearshift actuator is too large and the radial dimension is too small, the length of the magnetic or permanent magnet ring is small, so that the opposite current coil will be in the same magnetic flux direction, generating the opposite shifting force and increasing the degree of gearshift force fluctuation. When the axial dimension is too small and the radial dimension is too large, there will be a case where the thickness of the permanent magnet and external yoke are small. In such case, the magnetomotive force of the magnetic circuit is small and severe magnetic saturation occurs, which directly affects the output force of the gearshift actuator. To this end, reducing the radial weight coefficient interval and increasing of the axial weight coefficient properly allow the fitness of individual to develop in the desired direction. Therefore, the method of changing the weight coefficient can make the optimization process develop in a suitable direction. The selection of weight coefficients in the optimization process is shown in Fig.9.

B. OPTIMIZATION PROCESS

Compared with the constant coefficient optimization method in the monostable optimization process of the electromagnetic driving devices, the variable coefficient optimization method can further optimize the fluctuation rate of gearshift force and output force density. In this work, the simulated annealing –particle swarm optimization algorithm (SA-PSO) with variable coefficients is adopted, which has a good global search ability under the premise of ensuring the convergence speed, and prevents the fitness function from converging too fast or falling into the local optimum. The schematic representation of the optimization process is shown in Fig. 10. All the steps of the proposed algorithm are presented as follows:

Step1: Initialization parameters. Initialize population size ($n = 20$), maximum iteration algebra ($N = 25$), inertia weight (ω), particle maximum velocity ($v_{\max}$), initial velocity (v_0), acceleration constants ($c_1 c_2 = 2$) initial temperature (T), temperature change rate ($\mathrm{d}T$), position variation value ($\mathrm{d}x$).

Step2: Generate the initial population randomly.

Step3: Calculate of F_{m} and F_{e} by 3D FEA.

Step4: Calculate of individual weight coefficients.

Step5: Calculate the fitness values of all particles, rank them on the basis of the fitness f_{i}.

Step6: Update the particles' velocities and positions using the individual best position (p_{id}) and global best position (p_{gd})

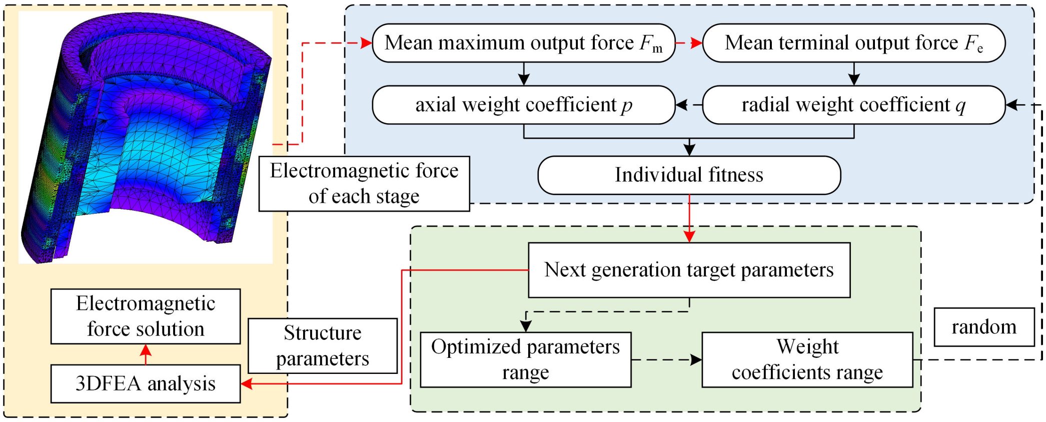

FIGURE 9. Variable weight coefficient in optimization process.

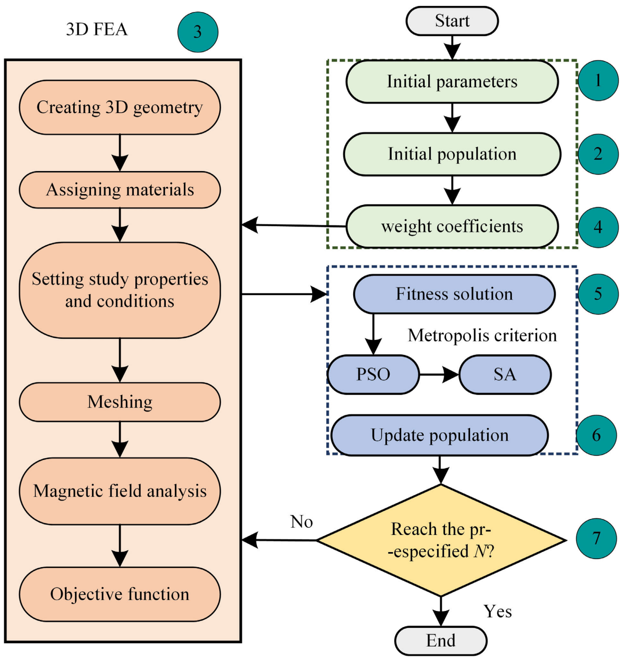

FIGURE 10. The schematic representation of SA-PSO algorithm with Variable weight coefficient and 3D FEA.

according to the following equations.

$$x_i(t+1) = x_i(t) + v_i(t) \tag{6}$$

$$v_i(t+1) = \omega(t)v_i(t) + c_1r_1(p_{id}(t) - x_i(t)) + c_2r_2(p_{gd}(t) - x_i(t)) \tag{7}$$

The variable inertia weight ([0.95, 0.4]) and constriction coefficient are applied to enhance the search ability of the particles and improve the convergence of the algorithm [24].

$$\omega(t) = 0.95 - 0.55t/N \tag{8}$$

Update particle displacement and calculate fitness f_j, calculate the probability of accepting fitness f_j according to the Metropolis criteria. Accept new fitness and update p_{gd}, p_{id}.

$$P = 1 \quad \text{if } f_j \geq f_i \tag{9}$$

$$P = \exp(f_j - f_i)/-T \quad \text{if } f_j \leq f_i \tag{10}$$

Step7: The algorithm will return to Step 3 until a pre-specified number of iterations is satisfied.

V. OPTIMIZATION RESULTS AND ANALYSIS

A. VARIABLE WEIGHT COEFFICIENT OPRIMIZATION RESULTS

Based on the above analysis, the gearshift actuator of the DAMT is optimized by different methods such as 3D FEA, SA-PSO algorithm and variable weight coefficient. 3D FEA is used as a calculation tool for electromagnetic field of gearshift actuator under different currents and different gearshift displacements. The main program generates the current individual fitness based on the individual generating the axial weight coefficient and the radial weight coefficient; and the optimal solution is continuously iterated in the algorithm. The population size (n) is 20, the maximum number of iterations (N) is 25.

The optimization results are shown in the Fig.11. With the iteration of population algebra, the weighted average fitness and the optimal weighted fitness of the population were improved to different extents. The variance values of various group weighted fitness were shrunk and eventually approached to zero. The first ten generations of the population converged faster, and the initial optimal weighted fitness of the population was improved by 20.7%.

The evolution process of the optimization target is shown in Fig.12. The maximum output force F_M and the terminal output force F_E of the gearshift actuator were continuously increased, and the density of maximum output force was also increased. The maximum output force F_M of the optimal fitness particle converged to 1263.4 N in the 25th generation; the terminal output force F_E converged to 984 N; the density of maximum output force was optimized to 2.69 × 106 N/m3. These FEA results obtained when the coil current was 15 A.

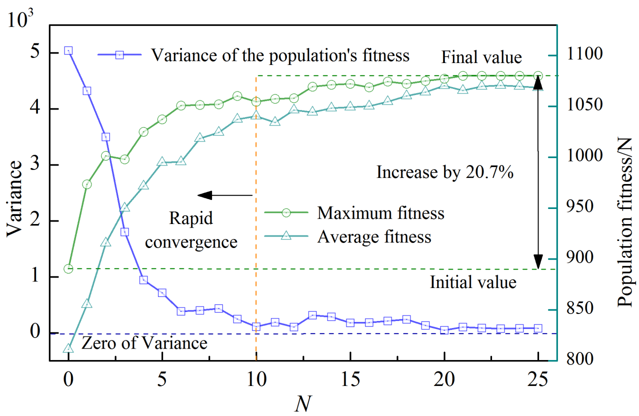

FIGURE 11. Convergence of optimization process.

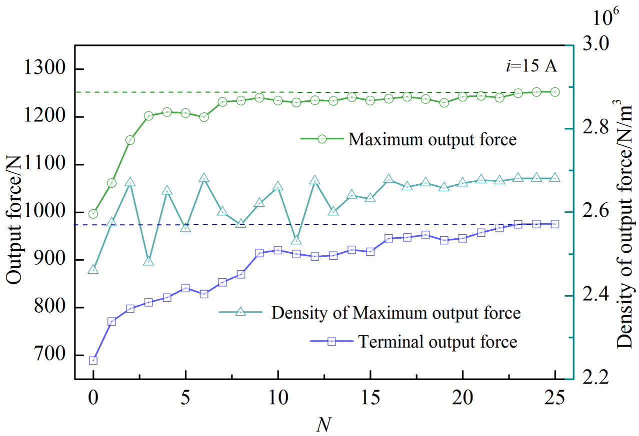

FIGURE 12. The evolution process of each optimization objective.

TABLE 2. Parameter optimization results.

Parameter	Value	Value range
L_1	33.75 mm	[20,37]
L_2	10.8 mm	[5,20]
L_4	9.5 mm	[6,10]
L_7	7.6 mm	[5,10]
H_1	7.9 mm	[2,8]
H_3	5.8 mm	[2,7]

Since the design displacement of the gearshift actuator was 10 mm, the terminal output force was equal to the electromagnetic force of the gearshift actuator at ±10 mm displacement, while the gearshift displacement of the first and second gears in the DAMT was 8.2 mm, so the true gearshift force effective range was within the range of 0 to 8.2 mm. The parameter optimization results are listed in Table 2.

Fig.13 and Fig.14 show the variations of different parameters during the optimization process. H_1^i, H_2^i. $L_1^i L_2^i$ are the parameters of the optimal individual at the i-th generation. H_{10}, H_{20}, L_{10}, L_{20} are the initial values of each parameter. The curve in the figure shows the comparison of various parameters with the initial values during the process.

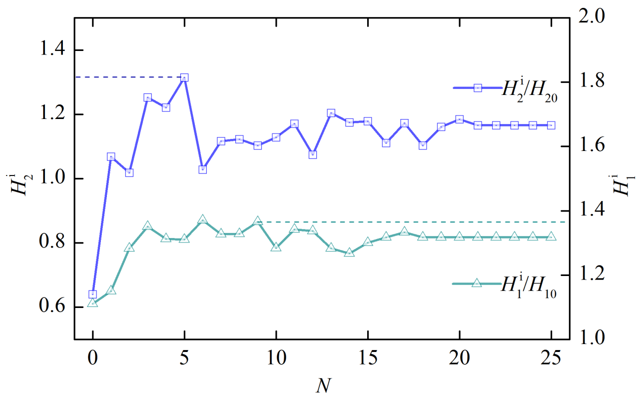

FIGURE 13. Optimization process of H_1, H_2.

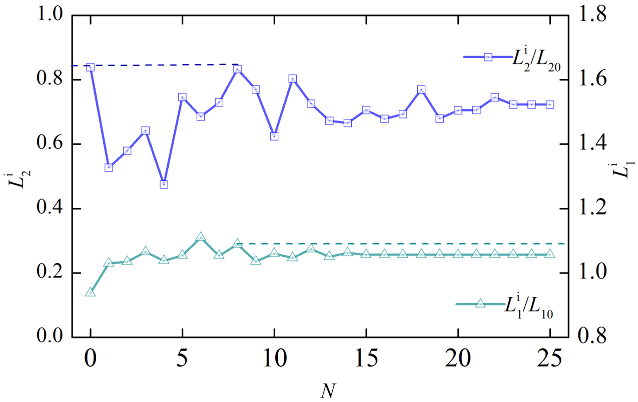

FIGURE 14. optimization process of L_1, L_2.

B. COMPARISON OF OPTIMIZATION METHODS

For the general optimization method, the fitness function only includes the maximum output force F_M and the terminal output force F_E, without considering the gearshift process of the transmission or the weight coefficients of F_M and F_E. In contrast, the fitness function of the proposed method is the average of F_M and F_E with constant weight coefficient, that is:

$$f = 1/2F_M + 1/2F_E \tag{11}$$

The comparison of the two optimization methods is shown in Fig. 15. The maximum gearshift force of the two optimization results was almost the same, but the optimization result with the variable weight coefficient improved the terminal output force by 102N. Compared to the optimization method with the constant coefficient, the optimization method with the variable coefficient reduced the gearshift force volatility by 27.5%. Since the output force in different stages was considered in the fitness function, the volume of the gearshift actuator was also reduced. This shows that the optimization method with variable weight coefficient has certain advantages in optimization of electromagnetic linear actuator.

VI. EXPERIMENTAL VERIFICATION

In order to verify the optimization results, a DAMT is made and a static experiment is performed on the gearshift actuator.

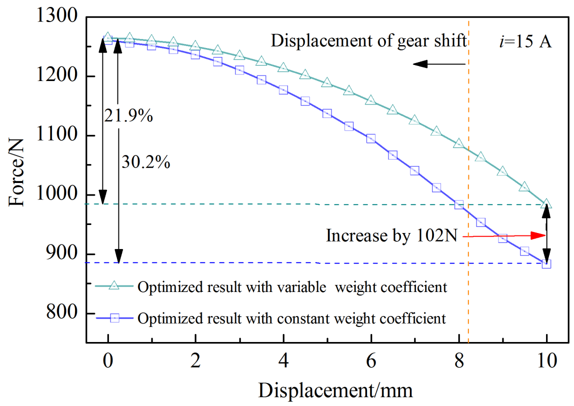

FIGURE 15. Comparison of the two methods.

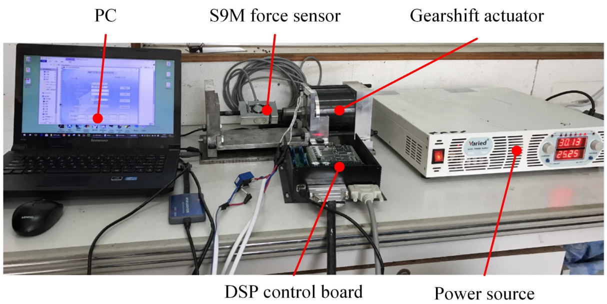

FIGURE 16. Experimental setup.

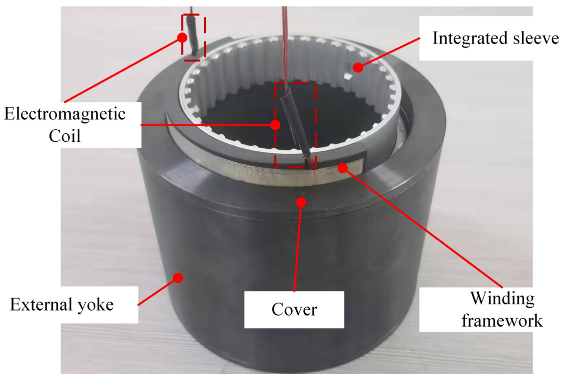

FIGURE 17. Gearshift actuator prototype photo.

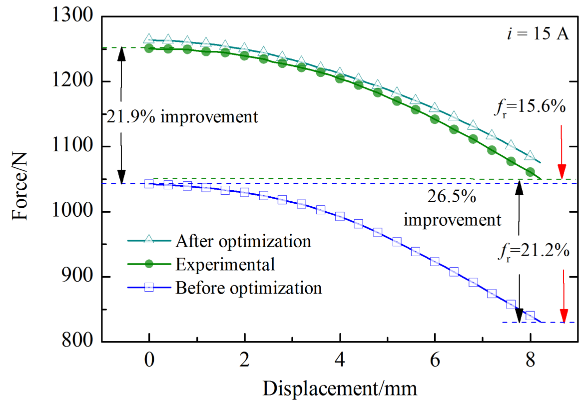

FIGURE 18. Comparison after optimization.

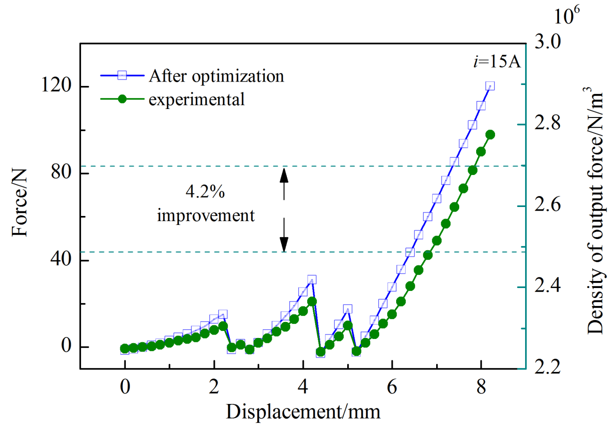

FIGURE 19. Comparison of gearshift force error.

The experimental setup and prototype of gearshift actuator is shown in Fig.16 and Fig.17, respectively. The static test system is used to measure the electromagnetic force during the formation of the gearshift actuator. A S9M "S"-type force sensor equipped with a CLIP analog amplifier with a range of 2000 N and a sampling frequency of 10 HZ is selected. The controller integrates a DSP control board, interface circuit, power amplifier and current sensor. The PC side acquires sensor data through the controller.

In Fig. 17, a threaded hole is reserved for the winding frame work to obtain the experimental data. External power transmission is completed by installing a power shaft. In actual applications, the winding frame directly pushes the sleeve to complete the gearshift, and a displacement sensor is installed in the threaded hole to detect the gearshift displacement. The power source provides a constant voltage to the actuator as shown in Fig. 16. Due to the coil inductance, the current reaches a predetermined value after a period of fluctuation. The test current loading time is 6.2 ms. After the current reaches a stable value, the force sensor data is obtained. Under this displacement, the output force of the gearshift actuator under a certain current state. By adjusting the dynamic position, the output force of each point during the while gearshifting stroke is obtained, and then the force-displacement curve is obtained.

The comparison of electromagnetic force-displacement curve after optimization is shown in Fig.18. The experimental value is slightly lower than the simulated value. This is because the anaerobic adhesive used for pasting the permanent magnet during the installation process caused the displacement of the permanent magnet, the interference of the motion gap, and the failure to obtain number of coil turns when winding by the preset value. The maximum error between experimental result and simulation result reached 2.1%. The maximum output force F_M increased from 1041 N to 1267 N after optimization, with an increasing rate of 21.9%; the terminal output force F_E was increased by 26.5% after optimization. The variability f_r of the gearshift force before optimization was 21.2%, which was reduced to 15.6% after optimization, with a decreasing rate of 26.4%.

As shown in Fig.19, the gearshift force during the gearshift process exhibited a certain decline compared with that after optimization. In the gearshift process, the maximum error value was reduced from 120 N to 96 N after optimization, with a decreasing rate of 20%. The maximum output force density of the gearshift actuator was increased by 4.2%.

After analysis, the maximum output force and the terminal output force of the gearshift actuator wre both increased by more than 20%. For the electromagnetic linear actuators, the optimization of the volatility is of particularly important significance. In this paper, the variable weight coefficient optimization method proposed via the innovation of the fitness function reduced the volatility of the gearshift actuator by more than 25% and increased the output force density to a certain extent.

VII. CONCLUSION

This paper proposes a new transmission form DAMT by integrating an electromagnetic linear actuator with AMT. Aiming at the complex problems such as the output force and the large fluctuation rate of the gearshift actuator, a variable weight coefficient optimization method is proposed. In order to obtain a more accurate fitness function, the gearshift displacement process is divided into five stages and then optimized. By comparison, the proposed method improved volatility and terminal output force compared with the constant coefficient optimization method. In the fitness function, the mean output force formed by the output force at different stages will make the actuator obtain a smaller volume, thus further reducinge the volatility

Compared with the initial value, the maximum output force of the gearshift actuator was increased by 21.9%, the end output force was increased by 26.5%, and the volatility was reduced by 26.4% when the current was 15 A. Moreover, the volume changed from 0.962×10^{-3} m^3 to 0.953×10^{-3} m^3.

Based on the electromagnetic field calculation results of 3D FEA, the proposed method has high calculation accuracy and optimization efficiency. In addition, the compact structure of gearshift actuator makes the DAMT lightweight and miniaturized, which has certain significance and value for the development of electric vehicles.

REFERENCES

[1] P. Walker, Y. Fang, and N. Zhang, "Dynamics and control of clutchless automater manual transmissions for electric vehicles," *J. Vib. Acoust.*, vol. 139, no. 6, pp. 1–13, Dec. 2017.

[2] H. Song, Y. S. Yoon, K. Kim, S. J. Kim, and C. Song, "Economic hybrid transmission system using clutchless geared manual transmission," in *Proc. 28th Electr. Vehicle Symp. Exhib.*, Goyang, South Korea, May 2015, pp. 3–6.

[3] B. Gao, Q. Liang, Y. Xiang, L. Guo, and H. Chen, "Gear ratio optimization and shift control of 2-speed I–AMT in electric vehicle," *Mech. Syst. Signal Process.*, vols. 50–51, pp. 615–631, Jan. 2015.

[4] H. Cheng and G. Tian, "Modeling and simulation of gear shifting in cluthless coupled motor-transmission system," *J. Tsinghua Univ. (Sci. Techology)*, vol. 56, no. 2, pp. 144–151, May 2016.

[5] X. Zhu, H. Zhang, J. Xi, J. Wang, and Z. Fang, "Robust speed synchronization control for clutchless automated manual transmission systems in electric vehicles," *Proc. Inst. Mech. Eng., D, J. Automobile Eng.*, vol. 229, no. 4, pp. 424–436, Mar. 2015.

[6] L. Li, Z. Zhu, X. Wang, Y. Yang, C. Yang, and J. Song, "Identification of a driver's starting intention based on an artificial neural network for vehicles equipped with an automated manual transmission," *Proc. Inst. Mech. Eng., D, J. Automobile Eng.*, vol. 230, no. 10, pp. 1417–1429, Sep. 2016.

[7] G. Kong, N. Zhang, and B. Zhang, "Novel hybrid optimal algorithm development for DC motor of Automated Manual Transmission," *Int. J. Automot. Technol.*, vol. 17, no. 1, pp. 135–143, Feb. 2016.

[8] S. Fang, J. Song, H. Song, Y. Tai, F. Li, and T. Sinh Nguyen, "Design and control of a novel two-speed uninterrupted mechanical transmission for electric vehicles," *Mech. Syst. Signal Process.*, vol. 75, pp. 473–493, Jun. 2016.

[9] P. Jin, S. Fang, H. Lin, X. Wang, and S. Zhou, "A novel linear and rotary Halbach permanent magnet actuator with two degrees-of-freedom," *J. Appl. Phys.*, vol. 111, no. 7, Apr. 2012, Art. no. 07E725.

[10] R. Payri, F. Salvador, M. Carreres, and J. De La Morena, "Fuel temperature influence on the performance of a last generation common-rail diesel ballistic injector. Part II: 1D model development, validation and analysis," *Energy Convers. Manage.*, vol. 114, pp. 376–391, Apr. 2016.

[11] B. Li, W. Ge, X. Yu, S. Shao, and H. Liu, "Innovative design and gearshift control for direct-drive electromagnetic gearshift system equipped with servo synchronizer," *Proc. Inst. Mech. Eng., D, J. Automobile Eng.*, vol. 233, no. 5, pp. 1115–1124, Apr. 2019.

[12] L. Liu and S. Chang, "Improvement of valve seating performance of engine's electromagnetic valvetrain," *Mechatronics*, vol. 21, no. 7, pp. 1234–1238, Oct. 2011.

[13] C. Tan, S. Chang, and L. Liu, "Dynamic performance design and analysis of hybrid excited linear actuator for on-off valve," *Int. J. Appl. Electromagn. Mech.*, vol. 54, no. 2, pp. 199–209, May 2017.

[14] H. Guo, L. Liu, X. Zhu, S. Chang, and Z. Xu, "Design of an electromagnetic variable valve train with a magnetorheological buffer," *Energies*, vol. 12, no. 20, p. 3999, Oct. 2019.

[15] N. Takahashi, S. Okamura, T. Sasayama, and Y. Yamagami, "Optimization of 3-D magnetic circuit of linear oscillatory actuator for diaphragm blower," *IEEE Trans. Magn.*, vol. 49, no. 5, pp. 2125–2128, May 2013.

[16] I. Mazhoud, K. Hadj-Hamou, J. Bigeon, and G. Remy, "The electromagnetic actuator design problem: An adapted interval global optimization algorithm," *IEEE Trans. Magn.*, vol. 48, no. 2, pp. 387–390, Feb. 2012.

[17] C. Tan, S. Chang, and L. Liu, "Hierarchical genetic-particle swarm optimization for bistable permanent magnet actuators," *Appl. Soft Comput.*, vol. 61, pp. 1–7, Dec. 2017.

[18] W. Li, Z. Y. Ren, Y. W. Jeong, and C. S. Koh, "Optimal shape design of a thomson–coil actuator utilizing generalized topology optimization based on equivalent circuit method," *IEEE Trans. Magn.*, vol. 47, no. 5, pp. 1246–1249, May 2011.

[19] Z.-Y. Sun, G.-X. Li, L. Wang, W.-H. Wang, Q.-X. Gao, and J. Wang, "Effects of structure parameters on the static electromagnetic characteristics of solenoid valve for an electronic unit pump," *Energy Convers. Manage.*, vol. 113, no. 1, pp. 119–130, Apr. 2016.

[20] I. Yatchev, M. Rudnicki, K. Hinov, and V. Gueorgiev, "Optimization of a permanent magnet needle actuator," *COMPEL—Int. J. Comput. Math. Elect. Electron. Eng.*, vol. 31, no. 3, pp. 1018–1028, May 2012.

[21] M.-T. Pham, Z. Ren, W. Li, and C. S. Koh, "Optimal design of a Thomson–coil actuator utilizing a mixed-integer-discrete-continuous variables global optimization algorithm," *IEEE Trans. Magn.*, vol. 47, no. 10, pp. 4163–4166, Oct. 2011.

[22] M. Bortolozzi, C. Bruzzese, F. Ferro, T. Mazzuca, M. Mezzarobba, G. Scala, A. Tessarolo, and D. Zito, "Magnetic optimization of a fault-tolerant linear permanent magnet modular actuator for shipboard applications," in *Proc. 9th IEEE Int. Symp. Diagnostics Electr. Mach., Power Electron. Drives (SDEMPED)*, Aug. 2013, pp. 27–30.

[23] J. Dai, S. Chang, and L. Liu, "Optimization analysis of electromagnetic linear actuator's radial array permanent magnets," *Int. J Appl. Electromagn. Mech.*, vol. 47, no. 2, pp. 441–451, Feb. 2015.

[24] M. Clerc and J. Kennedy, "The particle swarm—Explosion, stability, and convergence in a multidimensional complex space," *IEEE Trans. Evol. Comput.*, vol. 6, no. 1, pp. 58–73, Feb. 2002.

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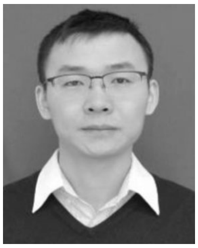

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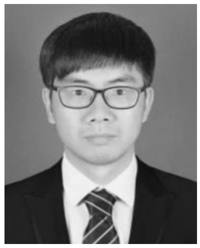

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