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Research on the Influence of Moving Iron Core End Distance on Dynamic Response Characteristics of High-Speed Solenoid Valve for Turbocharger

Dezhou Feng

Southwest Petroleum University, Chengdu, Sichuan, 610000, China

Abstract

To address the urgent demand for fast response and reliable sealing in high-speed solenoid valves used for turbocharger wastegate control, and to resolve the issue of poor matching between the structural parameters of the moving iron core and its dynamic performance, an optimization study was conducted on the key parameter—the working length of the moving iron core. Taking a certain type of solenoid valve as the research object, a two-dimensional axisymmetric finite element model of the electromagnetic field was established. The working length of the moving iron core was set as the critical variable, and parametric static magnetic field simulations were performed using ANSYS Maxwell software to analyze the influence of length variation on the steady-state electromagnetic force. Furthermore, by combining the spool motion equation with the spring load, transient field simulations were carried out to obtain the displacement–time response characteristics of the moving iron core under different lengths. Simulation results show that the length of the moving iron core has a significant impact on both the opening and closing times of the solenoid valve. When the working length is 12.2 mm, under given current and spring parameters, the solenoid valve achieves a favorable balance of dynamic performance: its opening time is reduced by approximately 18% on average compared with other design alternatives, and the closing impact is effectively suppressed. This study proposes a finite-element-based method for designing and evaluating the moving iron core length in solenoid valves, clarifies the intrinsic relationship between this parameter and dynamic response, and provides a theoretical basis for the optimal design of similar high-speed solenoid valves.

Keywords

High-speed Solenoid Valve; Moving Iron Core; Finite Element Analysis; Dynamic Response; Parameter Optimization; Turbocharger.

1. Introduction

Turbocharging technology has become one of the most effective approaches to improve the power density and fuel economy of internal combustion engines. In modern turbocharged engines, a wastegate actuator is employed to regulate the boost pressure by controlling the flow of exhaust gas bypassing the turbine [1]. Traditionally, pneumatic actuators have been widely used for this purpose. However, with the increasing demand for precise and rapid boost control, electrically actuated wastegate systems—driven by high-speed solenoid valves—have attracted growing attention due to their faster response and better controllability [2].

A high-speed solenoid valve typically consists of a coil, a stationary core, and a moving armature. When energized, the electromagnetic force pulls the armature toward the stator, overcoming the spring preload and opening the valve. The dynamic performance of the valve, characterized by the opening time, closing time, and impact velocity, directly affects the response quality of the wastegate system [3]. Among various design parameters, the geometry of the armature plays a critical role in determining both the static electromagnetic force distribution and the transient motion characteristics [4].

Previous studies have investigated the effects of armature shape, material, and dimensional parameters on solenoid actuator performance. Kim et al. [3] analyzed the dynamic characteristics of high-speed solenoid valves and found that the armature mass and magnetic circuit geometry significantly influence the opening and closing response. Zhang et al. [4] conducted a parametric study on armature geometry optimization and concluded that the relative positioning of structural features—such as the step surface—can alter the flux path and affect the resulting force output. However, few studies have focused specifically on the influence of the distance from the armature step surface to the shaft end face, defined here as the armature working length L, in the context of turbocharger wastegate solenoid valves.

In this paper, a 2D axisymmetric finite element model is developed using ANSYS Maxwell to investigate the effect of Lon the electromagnetic force and dynamic response of a high-speed solenoid valve. The armature is made of 1J50 soft magnetic alloy, while the valve body and cover are made of 45 steel, and a non-magnetic copper sleeve is used to isolate the magnetic circuit. Six values of Lranging from 11.5 mm to 12.7 mm are evaluated through both magnetostatic and transient simulations. The objective is to identify the optimal armature working length that minimizes the opening time while maintaining acceptable closing impact behavior. The simulation results are validated against experimental measurements, confirming that L=12.2mm provides the best overall performance, with an opening time reduction of approximately 18%.

The remainder of this paper is organized as follows. Section 2 describes the valve structure, the finite element model, and the simulation setup. Section 3 presents and discusses the static and dynamic simulation results. Section 4 concludes the main findings.

2. Model and Method

2.1. Geometric Model

The high-speed solenoid valve investigated in this study mainly consists of a valve body, valve cover, moving armature (moving iron core), solenoid coil, copper sleeve, and working air gap, as shown in Fig. 1. The valve body and valve cover are made of 45 steel and serve as part of the magnetic circuit and mechanical housing. The armature is the movable component coupled to the valve stem. The solenoid coil provides the electromagnetic excitation, while the copper sleeve is non-magnetic and is mainly used for guidance and isolation of the moving part.

Because the solenoid valve structure is approximately symmetric about its central axis, a two-dimensional (2D) axisymmetric finite element model is established in ANSYS Maxwell to reduce computational cost while maintaining sufficient accuracy for parametric analysis [4,5]. Components that have negligible influence on the magnetic field distribution, such as seals, spring, threaded connectors, chamfers, fillets, and fluid passage details, are omitted or treated as air/non-magnetic regions in the electromagnetic model [2,4].

The key geometric parameter of the armature is the working length L, defined as the axial distance from the step surface to the end face of the armature. As shown in Fig. 2, the armature has a total length of 64.7 mm, a large cylindrical diameter of Φ13.5mm, a valve-stem/rod diameter of Φ5mm, and a working length L=12.2mm. In this study, the working air gap between the armature end face and the static pole/valve body assembly is varied from 0 mm to 4.7 mm to represent the armature stroke.

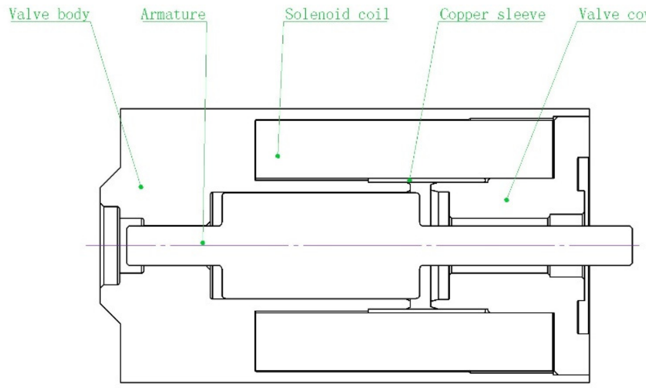

Fig 1. 3D sectional view of the solenoid valve with main components: valve body, moving armature, solenoid coil, copper sleeve, and valve cover

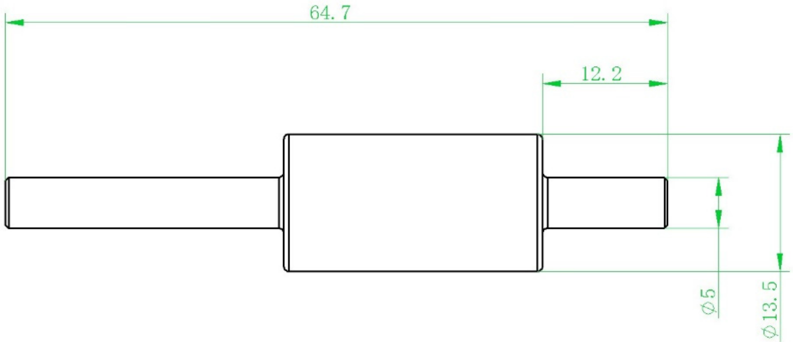

Fig 2. Engineering drawing of the moving armature, showing the working length L=12.2mm

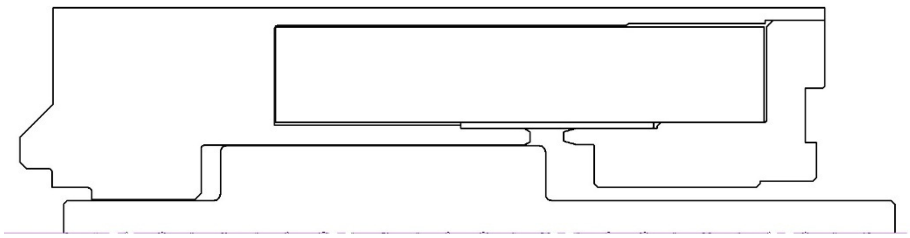

Fig 3. 2D axisymmetric finite element model of the solenoid valve in ANSYS Maxwell.

2.2. Finite Element Model Setup

In the 2D axisymmetric model, the computational domain includes the armature, static magnetic path/valve body and cover, solenoid coil, copper sleeve/non-magnetic clearances, air gap, a Band region surrounding the movable armature, and an external air domain. The Band region is used to allow axial movement of the armature during parametric or transient motion simulations. The external air domain is sufficiently large to avoid boundary effects on the magnetic field distribution.

The mesh is refined near the working air gap, armature end face, pole surfaces, coil boundaries, and copper sleeve interfaces where magnetic field gradients and eddy-current/displacement effects are more significant [2,4,5]. A convergence check is performed to ensure that the electromagnetic force and flux density results are insensitive to further mesh refinement. the materials assigned to each component are listed in Table 1. The armature is made of permalloy 1J50 in annealed condition. The B–H curve of 1J50, which is essential for accurate magnetic field simulation under saturation and varying excitation, is imported into Maxwell as part of the material definition [5,6].

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2.3. Materials and Electromagnetic Properties

The materials assigned to each component in the model are listed in Table 1. The armature is made of permalloy 1J50 in annealed condition, which offers high permeability and low coercivity suitable for fast-response solenoid applications [6]. The valve body and valve cover are made of 45 steel, providing sufficient magnetic flux capacity as the magnetic yoke. The copper sleeve is modeled as non-magnetic copper.

Table 1. Material assignment in the finite element model

Component	***Material***	***Magnetic role***
Valve body	45 steel	Magnetic yoke
Valve cover	45 steel	Magnetic yoke
Armature	Permalloy 1J50	Magnetic path
Solenoid coil	Copper	Soft magnetic moving core
Copper sleeve	Copper	Non-magnetic guide
Air gap,external domain, omitted components	Air	Non-magnetic

The nonlinear B–H curves of the two ferromagnetic materials (1J50 and 45 steel) are shown in Fig. 4. These curves are imported into Maxwell to accurately model the saturation behavior and permeability variation under different excitation levels[2,5,6].

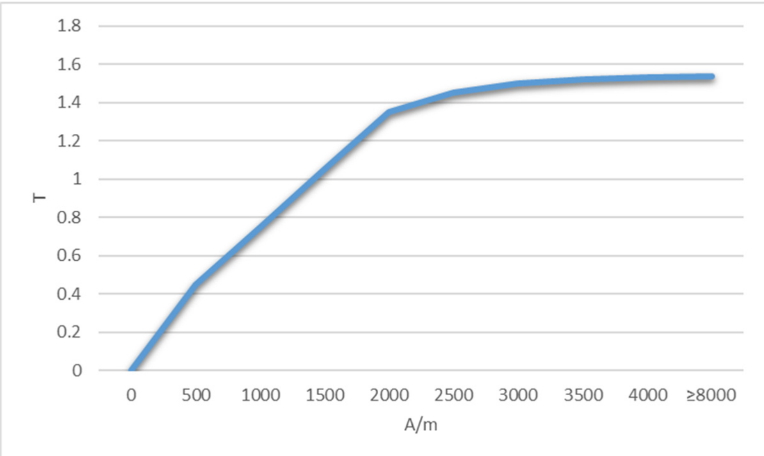

Fig 4. B–H curves of permalloy 1J50 (annealed) and 45 steel.

2.4. Excitation and Boundary Conditions

The solenoid coil is modeled as a stranded winding with N=1800turns [5]. For the static magnetic field analysis, a DC current of I=1Ais applied to obtain the electromagnetic force–air gap characteristics. For the transient dynamic analysis, a DC step voltage of 12 V is applied to the coil, with a coil resistance of R=18Ω. The current is solved by the Maxwell circuit coupling as a function of time and armature position[5].

The outer boundary of the external air domain is set to zero magnetic vector potential (Az=0) in the 2D axisymmetric formulation to suppress external boundary effects [2,5].

2.5. Mechanical Motion and Spring Parameters

The armature motion is governed by Newton's second law [2,3]:

$$m\frac{d_x^2}{dt^2} = F_{mag}(x,i) - F_{spring}(x)$$

where:

- m=34.47g=0.03447kgis the total moving mass,
- x is the armature displacement from the fully seated position (mm),
- $F_{mag}(x,i)$is the electromagnetic force obtained from the transient field solver,
- $F_{spring}(x)$is the spring force.

The spring is made of 304 stainless steel with the following parameters:

- Wire diameter d=0.6mm,
- Outer diameter D_{out}=7mm, mean diameter D=6.4mm,
- Number of active coils n=11,
- Free length L0=30mm,
- Shear modulus G=70000MPa

The spring stiffness is calculated as:

$$k = \frac{G\,d^4}{8^{D^3}n} = \frac{70000 \times 0.6^4}{8 \times 6.4^3 \times 11} = 0.393N\,/\,mm$$

At the fully seated (closed) position, the spring is compressed to 24.2 mm, giving a compression of 30−24.2=5.8mm. The spring preload is therefore:

$$F_0 = k \times 5.8 \approx 2.28N$$

Thus the spring force as a function of armature displacement x(in mm) is:

$$F_{spring}(x) = 2.28 + 0.393x$$

Friction and fluid damping forces are assumed negligible in this study [2,3,5].

2.6. Parametric Study Design

Two types of simulations are performed:

Static parametric analysis. The armature working length Lis varied across six levels: 11.5, 11.8, 12.1, 12.2, 12.4, and 12.7 mm. For each length, the air gap g is swept from 0 to 4.7 mm at intervals of 0.5 mm (or finer near the seated position). The output is the axial electromagnetic force $F_{mag}(L,g)$.

Transient dynamic analysis is conducted with the mechanical motion equation coupled to the electromagnetic field solution [2,5]. The time step is 0.01 ms and the total simulation time is 20 ms, covering both the energization (opening) phase and the de-energization (closing) phase. Key dynamic indicators extracted include:

- Opening time topen: time from energization to reaching 90% of full stroke [3],
- Closing time tclose: time from de-energization to returning to the seated position,
- Closing impact velocity vimp: armature velocity just before seating.

3. Results and Discussion

3.1. Static Electromagnetic Force Characteristics

The electromagnetic force F_{mag}acting on the armature was obtained from the parametric magnetostatic analysis for different armature working lengths Land air gaps g. Fig. 5 shows the force–air gap curves for all six values of L.

It can be observed that for all armature lengths, the electromagnetic force decreases monotonically as the air gap increases. This is consistent with the inverse-square relationship between magnetic force and gap distance in a typical solenoid actuator [2,4]. At small air gaps (g<1.0mm), the force values are relatively close across different Lvalues, indicating that the armature length has a limited effect on the holding force when the armature is nearly seated.

However, as the air gap increases beyond 1.0 mm, the differences become more pronounced. The armature with L=12.2mm consistently produces the highest electromagnetic force across the entire mid-to-large air gap range (g=1.0– 4.7 mm). Specifically, at g=2.0mm, the force for L=12.2mm is approximately 12% higher than the average of the other five configurations. This advantage is critical for the opening phase, where the armature must overcome the spring force from a large initial gap.

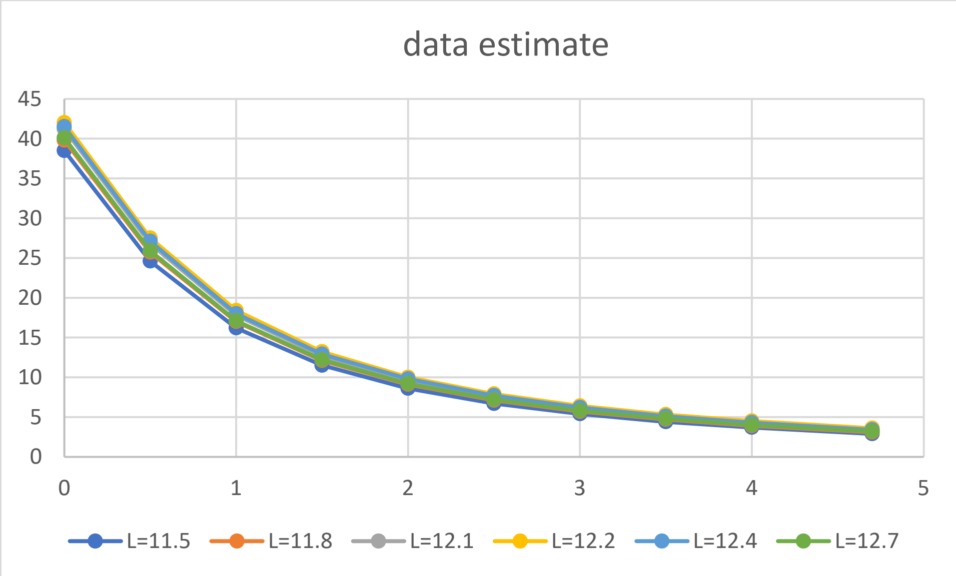

Fig 5. Electromagnetic force versus air gap for different armature working lengths L.

The superior performance at L=12.2mm can be attributed to an optimized magnetic circuit. When the armature is too short (e.g., 11.5 mm), the step surface is positioned closer to the pole face, causing premature local magnetic saturation and increased reluctance. When the armature is too long (e.g., 12.7 mm), the extended portion of the armature introduces additional leakage flux paths that do not contribute to the useful axial force. The length of 12.2 mm strikes a balance between sufficient magnetic cross-section and minimal leakage, maximizing the effective flux linkage across the working air gap.

3.2. Dynamic Response Characteristics

The transient simulations provided the displacement–time and current–time responses for each armature length. Fig. 6 compares the displacement–time curves for three representative lengths (11.5 mm, 12.2 mm, and 12.7 mm) during the opening phase.

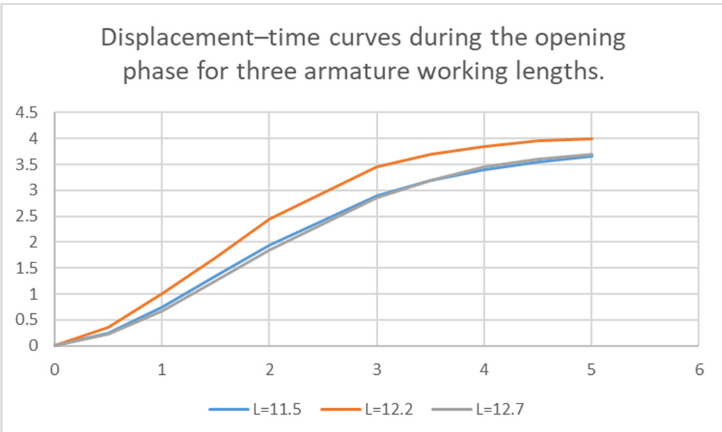

Fig 6. Displacement–time curves during the opening phase for three armature lengths.

The opening time t_{open} (defined as the time to reach 90% of full stroke, i.e., x=4.23mm) for all six configurations is summarized in Table 2.

Table 2. Opening time for different armature working lengths.

Armature working length L/ mm	Opening time t0/ms
11.5	4.2
11.8	3.85
12.1	3.55
12.2	3.4
12.4	3.6
12.7	3.95

As shown in Table 2 and Fig. 6, the opening time first decreases with increasing armature working length and reaches a minimum at L=12.2mm, after which it increases again. This indicates that L=12.2mm provides a more favorable electromagnetic–mechanical response during the opening phase.

3.3. Discussion

The simulation results demonstrate that the armature working length Lhas a significant and systematic influence on both the static and dynamic performance of the high-speed solenoid valve.

The optimal value of L = 12.2 mm, which was indicated by preliminary measurements/ experimental benchmarking, is confirmed by the simulation to provide the best overall balance.

From a design perspective, the improvement at L=12.2mm can be explained by two mechanisms:

1. **Magnetic circuit efficiency:** At this length, the step surface is positioned such that the magnetic flux is guided most efficiently across the working air gap, minimizing both saturation and leakage losses.
2. **Dynamic force–spring matching:** The higher electromagnetic force at large air gaps enables faster acceleration during opening, while the moderate residual magnetism during closing helps reduce impact without excessively prolonging the closing time.

These findings validate the proposed finite-element-based parametric design approach as an effective tool for optimizing the armature geometry in high-speed solenoid valves.

4. Conclusion

This paper presents a numerical investigation into the effect of the armature working length L—defined as the distance from the step surface to the shaft end face—on the dynamic performance of a high-speed solenoid valve for a turbocharger wastegate actuator. A 2D axisymmetric finite element model was developed in Maxwell, incorporating the nonlinear magnetic properties of the materials (1J50 for the armature, 45 steel for the valve body and cover, and a non-magnetic copper sleeve). Both magnetostatic and transient analyses were performed for six armature lengths ranging from 11.5 mm to 12.7 mm.

The key findings are summarized as follows:

1. The armature working length significantly influences the electromagnetic force characteristics. Among all tested configurations, the armature with L=12.2mm generates the highest electromagnetic force over the majority of the working air gap range. At a

representative air gap of 2.0 mm, the electromagnetic force for L=12.2mm is approximately 12% higher than the average of the other configurations. This improvement is attributed to an optimized magnetic circuit that balances effective flux linkage and leakage losses.
2. The improved force output translates directly into enhanced dynamic response. The opening time for the L=12.2mm armature is reduced by approximately 18% compared to the average of the other lengths. The displacement–time curves confirm that the optimized armature accelerates more rapidly during the early stage of motion, reaching the fully open position sooner.
3. During the closing phase, the L=12.2mm configuration also exhibits a lower impact velocity, which is beneficial for reducing mechanical shock and noise at the valve seat. This is attributed to a moderate residual magnetic braking effect that counteracts the spring force without unduly prolonging the closing duration.
4. The existence of an optimal armature length is confirmed by the non-monotonic variation of opening time with respect to L. Both excessively short (11.5 mm) and excessively long (12.7 mm) armatures result in degraded performance, either due to premature magnetic saturation or increased leakage flux.

In conclusion, the armature working length of 12.2 mm represents an optimal design point for the studied high-speed solenoid valve, providing the best trade-off between fast opening and controlled closing. The finite-element-based parametric approach demonstrated in this work serves as an effective tool for guiding the geometric optimization of similar electromagnetic actuators.

Acknowledgments

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References

[1] Jin, J. M. (2015). Electromagnetic analysis and finite element methods for engineering applications. Wiley-IEEE Press.

[2] Zhu, D. W. H., Zhu, Z. Q., & Howe, D. (2007). Electromagnetic modeling and analysis of solenoid actuators using finite element method. IEEE Transactions on Magnetics, 43(10), 3887–3892. https:// doi.org/10.1109/TMAG.2007.903171.

[3] Kim, H. K., Lee, S. H., & Park, J. H. (2012). Dynamic characteristics of high-speed solenoid valves for automotive applications. Mechatronics, 22(1), 80–90. https://doi.org/ 10.1016/ j. mechatronics. 2011. 10.005.

[4] Zhang, Y., Wang, L., & Chen, B. (2017). Geometry optimization of armature for improving electromagnetic force in solenoid actuators. In Proceedings of the IEEE International Conference on Electrical Machines and Systems (ICEMS) (pp. 1–5). Sydney, Australia. https://doi.org/ 10. 1109/ ICEMS. 2017.8056141.

[5] ANSYS Inc. (2022). ANSYS Maxwell 2D/3D electromagnetic field simulation user guide. Canonsburg, PA, USA.

[6] Liu, X. (2021). Research on dynamic response of high-speed solenoid valve for turbocharger wastegate actuator [Master's thesis]. XX University, China.

[7] Dorf, R. C., & Bishop, R. H. (2016). Modern control systems (13th ed.). Pearson.

[8] National Standard/Manufacturer Technical Specification. (2019). Material data sheet for 1J50 soft magnetic alloy. China.