Energy Conversion and Management 113 (2016) 119–130

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Effects of structure parameters on the static electromagnetic characteristics of solenoid valve for an electronic unit pump

Zuo-Yu Sun [a], Guo-Xiu Li [a,*], Lan Wang [a], Wei-Hong Wang [a], Qing-Xiu Gao [b], Jie Wang [b]

[a] School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China
[b] China North Engine Research Institute, Tianjin 300400, China

ARTICLE INFO

Article history:
Received 6 November 2015
Accepted 14 January 2016

Keywords:
Electromagnetic energy conversion
Static electromagnetic force
The effect of structure parameters
Solenoid valve
Numerical simulation

ABSTRACT

In the present paper, the effects of driving current and solenoid valve's structure parameters (including iron-core's length, magnetic pole's cross-sectional area, coil turn, coil's position, armature's thickness, damping hole's position, damping hole's size, and width of working air–gap) on the static electromagnetic characteristics have been numerically investigated. From the results, it can be known that the electromagnetic energy conversion will be seriously influenced by driving current for its effects on magnetic field strength and magnetic saturation phenomenon, an excessive increase of current will weak electromagnetic energy conversion for the accelerating power losses. The capacity of electromagnetic energy conversion is also relative to each solenoid valve's parameter albeit it is not very sensitive to each parameters. The generated electromagnetic force will be enhanced by rising iron-core's length, equalizing the cross-sectional areas of major and vice poles, increasing coil turn within a moderate range, closing the coil's position towards armature's centre, enlarging armature's thickness, pushing the damping holes' positions away from armature's centre, reducing the sizes of damping holes, and reducing the width of working air–gap; but such enhancements won't be realized once the driving current is excessively higher.

1. Introduction

Fuel injection system plays one utmost important role in diesel engine's general performance, high-pressure direct injection associated with electronic control system has been widely regarded as one promising injection manner to modern diesel engines for its superiorities in dynamic power and raw emissions [1–4], and electronic unit pump (abbreviated as EUP) is one most common modular high-pressure fuel delivery device of a high performance diesel fuel injection system for heavy duty diesel engine owing to its high pressure capability, robust design, proven reliability, dynamic trimming capability, etc. In EUP, solenoid valve is one essential and crucial component, it has significant effects on both the capabilities of response and discharge. Due to its focal role, more and more scholars have been following the scientific studies on the electromagnetic issues of solenoid valve [5,6]. Heretofore, a substantial amount of literatures have reported the fundamental characteristics of solenoid valve [7,8,5,9,10] but the effects on the static electromagnetic characteristics hardly be considered into. Therefore, more works on the effect mechanism of static electromagnetic characteristics of solenoid valve should be conducted [11–14].

Hitherto, some scholars have made valuable contributions to the understanding on solenoid valve's static electromagnetic characteristics, and the effects on static electromagnetic force is always one important research object. Since the works done by Seilly [15,16], accelerating solenoid valve's response time has been one hot topic, the nexus between solenoid valve's response capability and its configuration manner have been deeply studied [17,18]. As the factor directly determines response capability, the variation regulation of static electromagnetic force of solenoid valve have attracted more and more scholars' attentions. Topçu et al. [19], Luharuka et al. [20], and Al-Jaber [21] respectively studied the effects of driving current on static electromagnetic force of electro-pneumatic valves and/or solenoid valves with different configuration manners; Nitu et al. [22] and Taghizadeh et al. [23] respectively studied the effects of driving voltage and pulse width modulation frequencies on the static electromagnetic force of solenoid valve; the reported conclusions indicate that driving parameters have significant effects on solenoid valve's dynamic behaviour. Aimed at further enhancing solenoid valve's general performance, the nexus between solenoid valve's structure parameters and static electromagnetic force has been focused in the recent decade. Miller et al. [24] studied the effects of coil's parameters on the

* Corresponding author. Tel.: +86 010 51684484; fax: +86 010 51638684.
E-mail address: Li_guoxiu@yahoo.com (G.-X. Li).

http://dx.doi.org/10.1016/j.enconman.2016.01.031
0196-8904/

electromagnetic performance of a novel solenoid valve for heavy vehicles' pneumatic emergency brake systems, Wang et al. [5] studied the effects of magnetic circuit's structure on the magnetic characteristics of a solenoid valve with Al–Fe soft magnetic alloy material, Liu et al. [25,26] studied the magnetic circuit's partial structure parameters on static electromagnetic force; and those reported results indicate that structure parameters of magnetic circuit are essential and crucial to solenoid valve's electromagnetic energy conversion. Besides solenoid valve's dynamic behaviour, the energy losses during the electromagnetic energy conversion on solenoid valve also have been concerned by several scholars (such Angadi et al. [27,28] and Chen et al. [29]), their results indicate that the certain structure parameters have significant effects on the distributions of magnetic and thermal fields in solenoid valve, but more detailed and quantitative information are still insufficient.

From the aforementioned literatures, solenoid valve's static electromagnetic characteristics are closely related to its structure parameters (especially in the magnetic circuit); however, systematic and in-depth investigations are still scare. For providing more valuable information on the understanding of electromagnetic energy conversion in solenoid valve, a systematic investigation has been conducted, the effects of driving current and eight essential structure parameters in magnetic circuit on static electromagnetic force have been numerically studied and analysed.

2. Description of models and methodology

2.1. Models and calculation setup

In the present investigation, the static electromagnetic characteristics of solenoid valve have been numerically studied by three dimensional simulation, and one E-type two-way solenoid valve has been adopted for it is widely employed in EUP for modern heavy-duty diesel engines. As demonstrated in Fig. 1, the valve is composed of electromagnet (associated with excitation coil) and valve body (including armature, valve spool, reset spring, spring seat, and seal ring). Considering just magnetic components (including iron-core, excitation coil, and armature) have effects on electromagnetic energy conversion, and thus the nonmagnetic components haven't been considered into the model for reducing calculation time cost. Furthermore, the iron-core has been dealt into a mono block with laminated silicon steel sheets. The intuitive simplified model of magnetic structure is also demonstrated in Fig. 1, and the related physical parameters have been marked on the model.

Since the electromagnetic energy conversion in solenoid valve is a complex situation that hardly can be solved by general analytical method or difference method, finite element analysis (FEA) method has been employed [31]. Learnt from previous literatures [22,24,28–30], ANSYS Maxwell has been employed for the calculations. The calculated domain has been meshed by unstructured tetrahedral mesh, and the method of multiple block grid (as shown in Fig. 1) has been adopted as the mesh strategy for obtaining a better topological property. Adaptive Mesh Refinement (AMR) approach has been adopted for boundary element mesh for the following reasons: (1) The studied model is relative simple and highly symmetrical, AMR can be well suitable as suggested by software's tutorial. (2) Different from manual refinement approach that needs rich experience and a relative longer time, AMR approach can automatically refine meshes with simple settings. (3) If manually refine meshes, more numbers of meshes are always preferred with a hope of more accurate calculations. The detailed information about physical properties, initial boundaries, model selections, and mesh elements have been listed in Table 1. It should be emphasised that, in the present investigation, the driven condition is current-driven, the driving current adopts Direct Current (abbreviated as DC), and the driving current on the validation experiment is also DC. Different to Alternating Current (abbreviated as AC), the distribution of DC in conductor's cross-section is uniform, no obvious behaviours about skin effects could be obtained, and thus skin effects are oughtn't to be considered in the present investigation.

2.2. Validation on the calculation results

For proving the accuracy of the adopted model, the calculation data should be validated by experimental results. Since it is the utmost essential and crucial indicator reflecting electromagnetic energy conversion, electromagnetic force (F_e) has been taken as the validation object.

The validation experiments have been conducted on static electromagnetic force test bench. The test bench is composed of five essential and crucial components (as most common test bench for the measurement of electromagnetic force): (a) clamping and positioning devices, (b) faint adjustment element for air–gap, (c) fast lifting mechanism, (d) displacement measurement element, and (e) force measurement element. The air–gap has been adjusted by a pair of differential bolts (one is M16 $\times$ 1.75, and the other is M16 $\times$ 1.50) according to Differential Principle, an inductorsyn has been taken to measure the displacement, and a precision resistance strain pressure sensor (CZLYB series) has been taken to measure F_e.

Procedurally, the electromagnet has been fixed at the free-end of test bench while the armature and its connected S-type pressure sensor have been fixed at the fixed-end of test bench, the both axial lines of armature and electromagnet should be adjusted to a same level line by adjusting the height of test bench's free-end, and the distance between the free-end and the fixed-end would have been adjusted by feeler-gauge blades. Once the width of working air–gap has reached to the set value (0.28 mm for all the cases in the validation experiment), the free-end would have been locked, and subsequently a constant current will have been loaded into the excitation coils. Undergoing electromagnet's pull-in force, a voltage signal would have been formed in the resistance strain pressure sensor which is connected with the armature, the signal would have been enlarged via high-precision amplifier (AMPV series), then the enlarged signal has been measured by oscillograph (Ageilent series), and F_e would have been calculated according to the conversion chart. With the variations of driving current and working air–gap's width, the variation regulation of F_e would have been obtained. In the validation experiments, the driving current is respectively set as 4.0–15.0 A with an interval value of 1.0 A. And the obtained experimental data have been listed in Fig. 2.

Fig. 2 shows the comparison on F_e between the calculated data and the experimental results. As can be seen, with the increase of I, the difference on F_e (ΔF_e) between the calculated and the measured first rises and then declines, the maximum difference is attained near 9.0 A, and the difference turns negative once I has beyond 13.0 A (the standby current for the tested solenoid valve). When I rises from 4.0 A to 13.0 A, the effects of I on hysteresis becomes too stronger to be neglected in the actual measurement, but such effects are usually neglected in the simulation of static electromagnetic force [29]; and thus ΔF_e is positive and monotonously rises. When I has beyond 13.0 A, there will induce local magnetic saturation which has been sufficiently considered within the simulation, and hence the calculated F_e is less than the measured F_e. Generally, the calculated data are consistent with the actual situation and have a good agreement with the experimental results, the maximum error (which defined as the ratio of ΔF_e to F_e) is less than 5%; therefore, it can be believed that the established model and the adopted models are scientific and reasonable.