

Design and Analysis of VCA for fuel pump in Automobile

Se-Myung Park¹, Jin-Ho Kim

Abstract—Solenoid diaphragm fuel pump, which to replace mechanical fuel pump system by utilizing cam-shaft driving force, is in the spotlight for being a high efficient green car component. However, there is a drawback in power consumption as a solenoid diaphragm fuel pump only relies on solenoid for its flux needed in reciprocating motion. Therefore, this research proposes permanent magnet type VCA (Voice Coil Actuator) actuated fuel pump system to minimized power consumption. Furthermore, the study compares and analyzes power consumption and dynamic performance between the current and the former solenoid diaphragm pump by conducting finite element analysis with the commercial electromagnetic solver, MAXWELL

Keywords—Fuel Pump, Diaphragm, Solenoid, Voice Coil Actuator

I. INTRODUCTION

FUEL pumps as a devices that provides fuel to the carburetor or fuel injection nozzle, are currently used a mechanical pump, a solenoid pump and electric pump in automobiles. Mechanical diaphragm pump mounted on the side of the cylinder block or head camshaft is driven by the rotational movement of the camshaft. The mechanical diaphragm pump including the additional device is a drive system of the dual structure, which has a complex system configuration, and the energy loss and the noise is caused by friction action. Moreover, there are limits to improve efficiency and it is difficult to control the precise position. The mechanical diaphragm pumps rely on the shape of the camshaft will change the vibration characteristics. Therefore optimization of the shape of the camshaft design is required. However, the cams are just optimized for a short range of engine driving conditions. Recently, in automobile industry, green car are becoming an increasingly important trend of modern cars as people realize the value of lower fuel consumption and high efficiency. Even in common fuel pump, recently, mechanical diaphragm pump is rarely used because of limitations in terms of engine efficiency, almost is used electric fuel pump or solenoid diaphragm pump. Compared with the mechanical diaphragm fuel pump, electric fuel pump can supply more fuel than its required. Electric fuel pump using a rotary type mechanism including a impeller, however, has a drawback of power consumption. Besides,

electric pump has weakness in high power consumption, large space occupancy and additional energy conversion system required in comparison with other linear actuator due to the rotary type mechanism. Electric fuel pump currently, all modules in the form of an integral fuel pump contained Float, Intake, Fuel/Vapor Line is supplied. If there are flaws in the part you need to replace the entire module, so the replacement cost will rise.

Solenoid diaphragm pump has two main advantages. First, it has more simple structure than electric fuel pump, so it doesn't require additional devices. Second, there is no energy loss due to mechanical friction, and the noise can be reduced. However, the flux required to reciprocate only rely on the solenoid, so to get enough driving force, it required a lot of power consumption.

Recently, in automobile industry, it is important to reduce power consumption per electric devices because the automobiles use a lot of electric devices. Therefore to overcome the problems which solenoid diaphragm pump and electric fuel pump have a lot of power consumption, some electric devices including permanent magnet have been developed.

In this study, to overcome the problems which solenoid diaphragm pump and electric fuel pump have, and in order to minimize the power consumption, using permanent magnets and electromagnets for driving fuel pump, Voice Coil Actuator (VCA) is proposed.

In order to characterize the dynamic performance of the VCA, finite element analysis is performed using a commercial electromagnetic analysis software, Maxwell. Based on the simulation results, we compare the dynamic performance of the solenoid diaphragm with the dynamic performance of the VCA, and finally we verify the reduction of power consumption of the VCA.

II. ACTUATOR FOR FUEL PUMP IN AUTOMOBILE

A. Structure and operation principle of the Solenoid Actuator

It consists of springs, yoke, armature, diaphragm, one solenoid and an pump device. The armature that moves between the diaphragm and the yoke is connected to an diaphragm and they are rigid body. To drive the actuator, a current source is applied to the solenoid and the magnetic flux of the electromagnet forms a closed magnetic loop between the yoke and the armature, and the armature is pulled down. As a result, the diaphragm is pulled down too.

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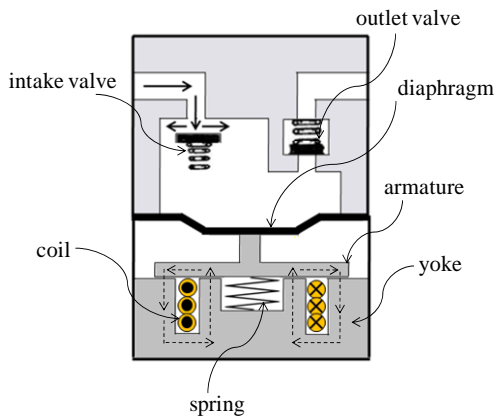


Fig. 1 Schematic diagram of solenoid diaphragm pump

Fig. 2 shows the input current profiles to the solenoid diaphragm pump versus time.

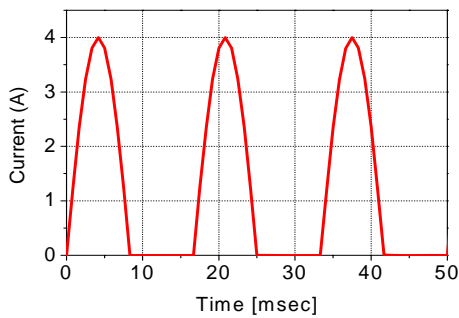


Fig. 2 Input current profiles versus time

In the case of solenoid diaphragm pump, it requires about 30N driving force to get the smooth pumping operation, and the current applied to the solenoid is maximum 4[A].

When a current source is applied to the solenoid, the magnetic flux generated by electromagnet forms a closed magnetic loop between the yoke and the armature, so the armature and diaphragm is pulled down, and the spring is compressed. As a result, fuel enters to the pump chamber through the inlet valve, because volume of pump chamber is increased. The current source applied to the solenoid is periodic.

B. The structure and operation principle of the Voice Coil Actuator

Fig. 3 shows a schematic diagram of the voice coil actuator.

It consists of yoke, a permanent magnet (PM), coil, spring, and coil housing around the coil. We used steel 1010 in the yoke, neodymium in the PM and aluminum in the coil housing. The PM is located between the upper and lower yoke and spring is located between the diaphragm and upper yoke. There are two types of methods for actuator operation. One is the moving magnet method and the other is moving coil method. In this research, we applied the moving coil method. While PM and yoke are fixed, the coil and the coil housing reciprocate due

to the Lorentz force generated by the interaction of magnetic flux line in the air gap and the current flowing through the coil. The Lorentz force is expressed as the equation below (1)

$$F_{Lorentz} = n B_g i l_{eff} \quad (1)$$

In the Lorentz force, n is the number of coil turns, B_g is the flux density in the air gap generated by PM, I is the input current and l_{eff} is the effective length of coil in the air gap.

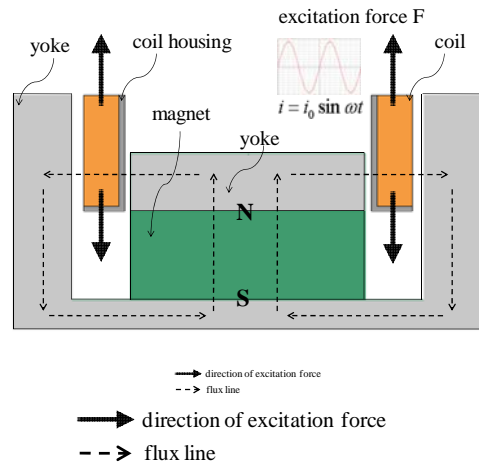


Fig. 3 Schematic diagram of VCA

Fig. 4 shows the combined image of the pump chamber and Voice Coil Actuator, and represents driving principle.

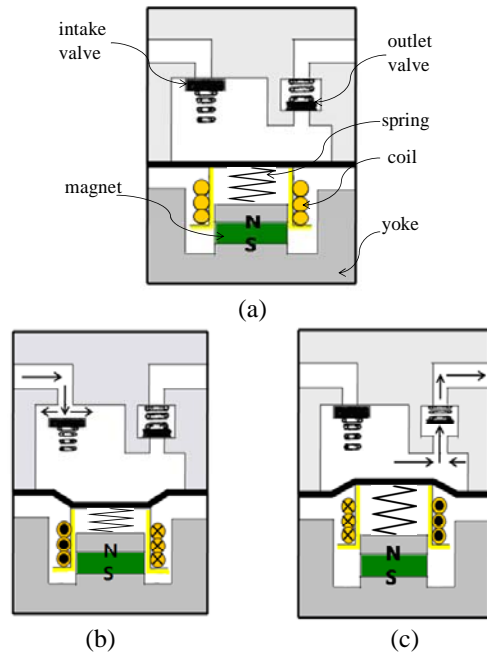


Fig. 4 Operation principle of VCA actuated fuel pump (a) at initial position (b) at the lower position (c) at the upper position

Rigid body consisting of a coil housing and the diaphragm causing a reciprocating motion by the Lorentz force vibrates up and down, and as a result, the pump chamber pressure is

increased or decreased because of changing the volume of pump chamber. Therefore, the fuel enters to pump chamber through the intake valve, and then the fuel is emitted from pump chamber through the outlet valve.

III. FINITE ELEMENT ANALYSIS

To characterize the performance of the newly proposed design, VCA, finite element analysis is performed using a commercial electromagnetic analysis program, Maxwell.

Table. II shows the magnetic properties of NdFeB35.

Table. II gives the specification about mass, spring stiffness, natural frequency and damping coefficient of the mechanical subsystem. Table. III gives the specification about input current, input frequency, and the number of coil turns of the electric subsystem.

TABLE I
MAGNETIC PROPERTIES OF NdFeB35

Relative Permeability (Mu)	1.1
Residual Induction (Br)	1.3 T
Coercivity (Hc)	-890,000 A/m

TABLE II
SPECIFICATION OF MECHANICAL SUBSYSTEM

Mass	0.12kg
Spring stiffness	12 KN/m
Natural frequency	50hz
Damping coefficient	0.76kg/ms

TABLE III
SPECIFICATION OF ELECTRIC SUBSYSTEM

Input current (VCA actuated pump)	1 A
Input current (Solenoid diaphragm pump)	4 A
Input frequency	60 hz
Number of coil turns	350 turns

In order to simulate the newly proposed design, the cross-section of model in cylindrical coordinate is used in Fig. 5.

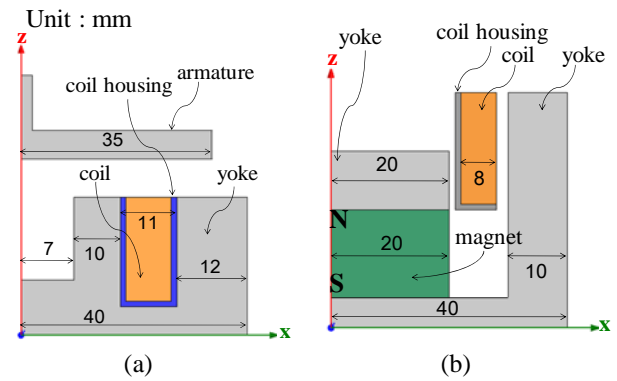


Fig. 5 FE model specification (a)VCA actuated pump2-D model specification (b)solenoid diaphragm pump2-D model specification
The motion equation of the mechanical subsystem is expressed as the equation below (2)

$$m \ddot{x} + c \dot{x} + kx = F_{Lorentz} = n B_g i l_{eff} \quad (2)$$

The mechanical subsystem includes a moving mass, and external forces and it is governed by the second-order equation.

The current flowing in the electromagnet coil is given as a sine waveform described by the equation (3), in electric subsystem.

$$i = i_0 \sin \omega t \quad (3)$$

The amplitude of input current i_0 and input frequency is given by Table. III. So the magnetic force also has a sine waveform and oscillates the moving mass in the same pattern. This actuator is composed of three subsystems, i.e. a mechanical subsystem, an electrical subsystem, and a magnetic subsystem those are coupled to each other.

A 2-D dynamic finite-element model was created to assist in modeling these coupled systems. The simulation of FE model with triangle elements is conducted.

IV. SIMULATION RESULTS

Fig. 6 shows flux distribution of solenoid diaphragm pump model at initial position and lower position of armature. Fig. 7 shows flux distribution of VCA model at initial position and the moving mass is pulled down due to lorentz force.

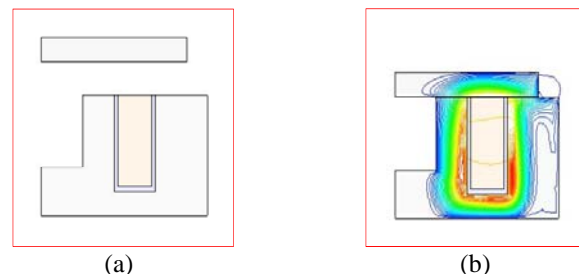


Fig. 6 Position of armature and flux distribution in solenoid diaphragm pump (a) initial position of armature (b) at lower position of armature and flux distribution

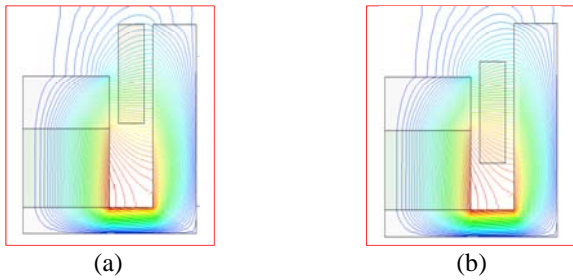


Fig. 7 Position of moving coil and flux distribution in VCA actuated pump (a) initial position of moving coil and flux distribution (b) at lower position of moving coil and flux distribution

Fig. 8 shows the plot result of the VCA and solenoid actuator by FEA; excitation force at the input current frequency of 60 Hz.

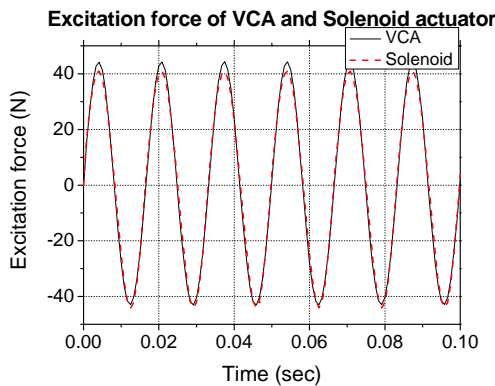


Fig. 8 The excitation force of VCA actuated pump and Solenoid diaphragm pump

In general, the required force in mechanical diaphragm pump in order to drive the device is approximately 30N. As shown in the simulation results, VCA and solenoid actuator have enough excitation force to pump the fuel.

Fig. 9 shows the input current profile for VCA and solenoid actuator.

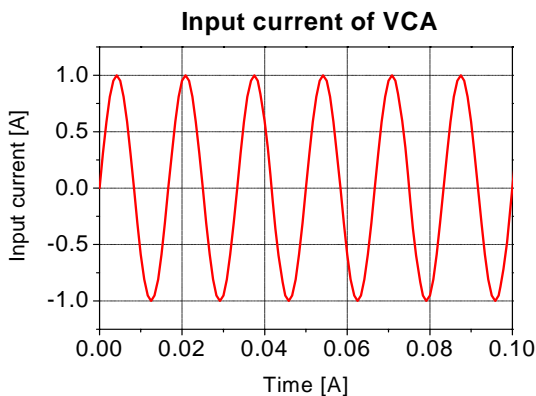


Fig. 9 Input current profile for VCA actuated pump and Solenoid diaphragm pump

As shown in the simulation results, between the two systems in terms of dynamic performance shows very similar results.

However, there is so large difference in power consumption between the two systems. Under the similar dynamic performance, when comparing the power consumption between VCA and solenoid actuator,

The power consumption of the VCA was saved about 87.5% when we compared to Solenoid Actuator in the similar dynamic performances.

V.CONCLUSIONS

A novel design of the Voice Coil Actuator is introduced and built in this study.

To overcome the high power consumption of the other fuel pump, both the permanent magnet and the electromagnet were simultaneously used in the newly designed Voice Coil Actuator for fuel pump.

Models of the VCA and Solenoid Actuator was designed simply for 2-dimensional finite element analysis, which was carried out by the Maxwell electromagnetic analysis software. The results of the analysis demonstrated that the VCA and Solenoid Actuator produced a suitable excitation forces to operate the fuel pump. The power consumption of the VCA was saved about 87.5% when we compared to Solenoid Actuator in the similar dynamic performances.

In the recent automotive industry uses a lot of electronic components, the expected value of the proposed VCA which saves power consumption, is expected to be higher.

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