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ANALYSIS OF SOLENOID FORCE IN AN AUTOMOBILE ECV

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Abstract- *Air conditioning control system is an important issue in automobiles as it is directly related to the passengers comfort. Variable capacity compressors are used for air conditioning control system in vehicles because of its low energy consumption and highly efficient characteristics. Solenoid operated electromagnetic control valve (ECV) in the compressor controls the air conditioning system by means of a pulse width modulation (PWM) input signal from an external source. The solenoid force is important for ECV operation as the force related to the movement of the internal feature i.e. plunger. Together with the solenoid force; some other forces inside the ECV are responsible for the amount of air/refrigerant flow that affects air conditioning control procedures within various pressure ports. The research paper highlights the newly developed theory and equation for solenoid force operation in ECV, and compares theoretical and experimental results.*

Keywords: Electromagnetic control valve (ECV), Pulse width modulation (PWM), Solenoid force, Plunger Bellows, Stroke

1. INTRODUCTION

At present, it is required that the automotive air conditioning system must keep the cabin temperature comfortable in spite of engine speed and improvement in fuel consumption during all seasons [1]. Compressors used for vehicle air conditioning system, consumes a lot of engine power as it is a high efficiency requiring component. Recently, automotive industries prefer variable displacement swash plate (wobble plate) type compressors instead of fixed capacity compressors because of its low energy consumption and highly efficient characteristics [2], and it is coupled with an electromagnetic control valve (ECV). The valve is solenoid operated and works in controlling different port pressure. Fig. 1 and fig. 2 shows the variable displacement swash plate type compressor and a cut way view of the compressor with main (external) control valve i.e. ECV respectively.

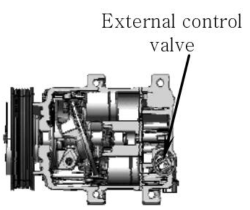

Fig. 1: Variable displacement swash plate type compressor

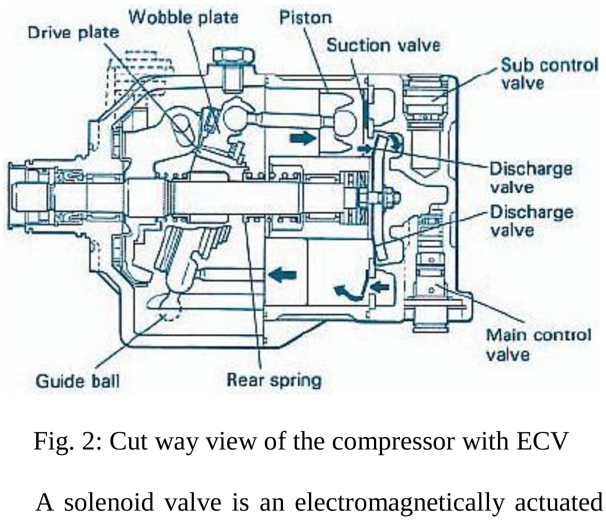

Fig. 2: Cut way view of the compressor with ECV

A solenoid valve is an electromagnetically actuated control valve that controls a plunger stroke according to the amount of current supplied from the external controller in the solenoid coil. The solenoid valve is driven by PWM input signal from an external source that is free of ripple pressure [3].

In this research, the flow of air/refrigerant from crankcase port with respect to the amount of variable supply of current is measured. This flow is controlled by setting different types of strokes such as guide, plunger and bellows stroke. These strokes result from plunger movements within the ECV, and are related to different forces acting inside it. Balance of forces is done as it affects the plunger movement. A theoretical equation of solenoid force is developed. Finally, experimental analysis of crankcase chamber pressure (P_c pressure) is carried out with an ECV sample followed by theoretical and experimental comparison.

2. THEORY AND EQUATIONS

To develop an equation for calculating solenoid force, different laws and assumptions are taken into consideration, namely Ohm's law, magneto motive force (MMF) that results from number of coil turns and supply of current, Ampere's law, magnetic field, flux density and Maxwell's pulling force formula. Considering the above issues, a simplified equation is developed for calculating the solenoid force, given as:

$$F = 0.5\,\frac{\mu_0 * N^2 * i^2 * \eta^2 * A_{c.s.}}{P_{st}^2} \qquad (1)$$

Where, μ_0 relates to magnetic flux density (B) and magnetic field (H); and is called the permeability of the medium and has a finite value about 1.257×10^{-6} Hm^{-1}. The value is constant with the magnetic field strength and temperature. In case of ECV, the gap between core and plunger is considered as non-ferromagnetic substances i.e. air/vacuum. Therefore, in practical purposes, air has a permeability that almost equals μ_0. Cross sectional area is calculated from the diameter of the static item core and the moving item plunger of the ECV. Solenoid efficiency is considered with 30% loss of energy. The energy losses include leakage loss, heating loss and eddy current loss.

Secondly, characteristics of the ECV in the steady state condition provide an important consideration in deciding the volume when designing valves. In this case, balancing of various forces in steady state condition is expressed as:

$$\Sigma F = -F_m - F_h\,(=P_s A_s) + F_{plunger\ spring} + F_{bellows\ spring} + F_c\,(=P_c A_c) + F_{aerodynamic} \qquad (2)$$

Solenoid magnetic force is induced in the valve when the electric current is supplied to it from an external source. From the suction port; as the fluid enters, it occupies the housing and thus acts in the same direction of the magnetic force. This is basically hydraulic force that is calculated from the amount of suction pressure within the area that was applied by the suction pressure. Due to this hydraulic force; plunger spring tends to move to the opposite direction of the hydraulic force by plunger spring force or pulling force.

Crankcase chamber force is calculated by the amount of crankcase chamber pressure within the area that was applied by the crankcase pressure. However, the bellows spring induced the bellows assay spring force. As the bellows effective dimension is similar to the guide (valve) cross sectional area; therefore, force acts through the axis. Both the forces act towards the direction of plunger spring force.

Finally, the valve interacts with the fluid around its surface and the fluid can change its shape and maintain physical contact at all points. Therefore, the point of contact (mechanical forces) takes place in every point on the guide surface. The forces are transmitted through the pressure, which acts perpendicular to the surface. The net force can be found by integrating (or summing) the pressure times the area around the entire surface. For a moving flow, the pressure will vary from point to point because the velocity varies from point to point. This is called aerodynamic force. Aerodynamic force also acts towards the direction of plunger spring force (opposite to the magnetic force).

Magnetic force is considered as principle force prior to all other forces. Therefore, simply it can be written as:

$$\Sigma F \propto F_m \qquad (3)$$

Fig. 3 shows the internal features of the ECV and force acting areas.

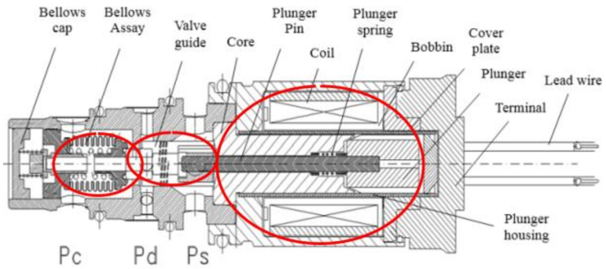

Fig. 3: Forces acting areas including ECV internal features

3. EXPERIMENT AND ANALYSIS

Similar to a vehicles' ECU module, the PWM controller generates a PWM signal which is proportional to the input current and feeds into the ECV at 400Hz. Then eventually, a magnetic force proportional to the PWM signal is generated in the ECV.

For experimental work, an air board tester is developed. The test was carried out for calculating the crankcase pressure i.e. P_c flow. In this case, some random samples of ECV, widely used in automobiles, were tested simultaneously and their range of maximum and minimum flow limit line with respect to variable supply of current (0.20Amp to 0.95Amp) was determined to obtain the crankcase pressure flow in litre per minute (lpm). Thereafter, if the flows are within the range then the flow is considered as viable results.

Fig. 4 shows the graphical result of a tested ECV sample. Guide stroke, plunger stroke and bellows stroke were measured at 0.31mm, 0.66mm and 0.45mm respectively. It is found that the result is good as all values lie within the range.

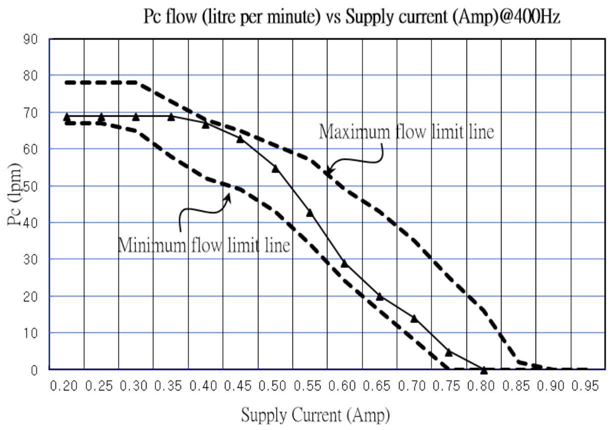

Fig. 4: Graphical result of tested ECV sample

For the analysis of solenoid force, plunger force is calculated. Actually due to supply of current the solenoid magnetic force results in moving the plunger. For the ECV, three strokes (guide stroke, plunger stroke and bellows stroke) are important as they are directly related to controlling the air/refrigerant flow. These strokes are closely related to the airflow. For the ECV, standard guide stroke and plunger stroke is considered 0~0.30mm and 0.60~0.90mm respectively.

From the graphical result shown in fig. 4, different guide stroke and plunger stroke positions are measured with respect to P_c at variable supply of current within the standard guide and plunger stroke ranges. Similarly, the plunger force is measured with respect to P_c flow at variable supply of current and it is seen that from 0.60mm to 0.90mm plunger stroke, the experimental plunger force is 1480gf to 490gf respectively. This value is calculated from the summation of plunger spring and bellows spring load test carried out by the compression load testing machine within the stroke limits. Fig. 5 shows the analysis of guide stroke, plunger stroke and plunger force of the tested ECV sample.

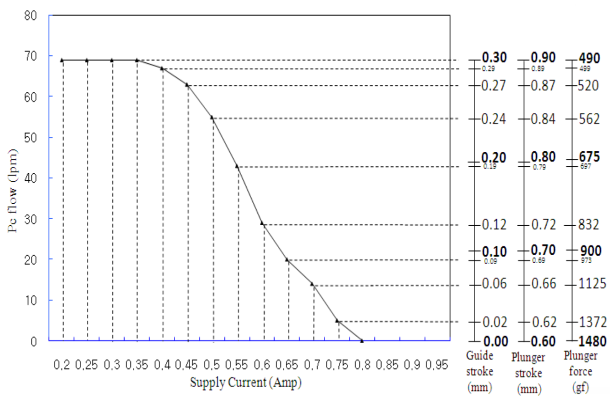

Fig. 5: Experimental plunger force analysis of ECV

4. RESULT AND DISCUSSION

Fig. 6 shows comparison between the theoretical and experimental results of solenoid force with respect to plunger stroke at variable supply of current.

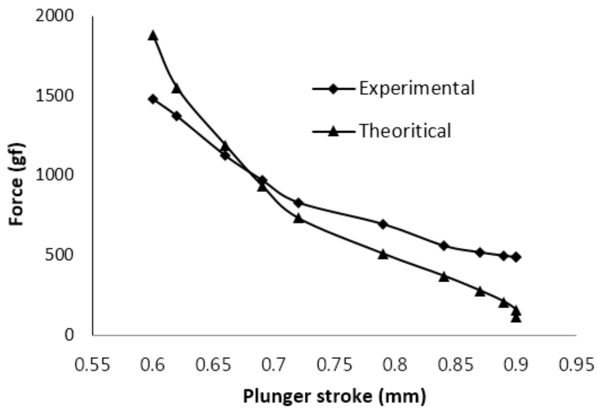

Fig.6: Comparison between theoretical and experimental results

Experimental values are obtained from fig. 5. The values are identified from the P_c flow with correspondence to variable supply of current ranges from 0.20Amp to 0.95Amp. The flow reaches 0 (zero) at 0.80Amp current supply followed by maximum plunger force of 1480gf at starting value of both the guide and plunger strokes.

Secondly, theoretical values are obtained by putting the different values in the equation (1). For the respective P_c flow points; supply of variable current (i) and plunger stroke (P_{st}) is measured and finally the theoretical result is obtained.

5. CONCLUSION

Analysis of solenoid force and balance of forces of an ECV in a variable displacement swash plate type compressor is of prime concern in this research. In this regard a theoretical equation is developed for calculating the solenoid force. Experimental work is done with a single sample of improved ECV by considering different parameter setting such as guide stroke, plunger stroke, bellows stroke, air board tester configuration etc. From the experimental P_c pressure analysis within the guide and plunger strokes, solenoid force (plunger force) is obtained. And with the help of equation developed, a theoretical result is obtained. Finally, comparison of two results indicating satisfactory performance of force analysis in the improved ECV.

6. ACKOWLEDGEMENT

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7. REFERENCES

[1] M. J. Kim, I. S. Park and G. H. Lee, "An experimental study on the performance of variable displacement swash plate type compressor with various pressure of swash plate chamber", *Korean Journal of Air*

Conditioning and Refrigeration Engineering, No. 2004-S-127, pp. 765-770, 2004.

[2] Y. J. Lee, G. H. Lee and B. E. Lim, "Design for Improving the Performance of a Control Valve in a Variable Compressor", *4th International Conference on Sustainable Automotive Technologies*, RMIT University, Melbourne, Australia, pp. 343-348, 2012.

[3] G. S. Lee, H. J. Sung and H. C. Kim, "Multiphysics Analysis of a Linear Control Solenoid Valve", *Journal of Fluids Engineering*, Transactions of the ASME, Vol. 135/011104, pp. 1-10, 2013.

8. NOMENCLATURE

Symbol	Meaning	Unit
F	(Solenoid) Force	(gf)
μ_0	Permeability of air/vacuum	(Hm^{-1})
N	Number of coil turns	-
i	Supply current	(Amp)
$A_{c.s.}$	Cross sectional area	(mm^2)
η	Eff. without energy losses	-
P_{st}	Plunger stroke	(mm)
P_c	Crankcase chamber pressure	(lpm)
P_s	Suction chamber pressure	(lpm)
A_s	Area applied by suction pressure	(mm^2)
A_c	Area applied by crankcase pressure	(mm^2)
B	Magnetic flux density	Tesla
H	Magnetic field	A-T/m
F_m	Solenoid magnetic force	(gf)
F_h	Hydraulic force	(gf)
F_c	Crankcase chamber force	(gf)
$F_{plunger\ spring}$	Plunger spring force	(gf)
$F_{bellows\ spring}$	Bellows assay spring force	(gf)
$F_{aerodynamic}$	Aerodynamic force	(gf)