Responsibility of Control System of Engine Intake Valve with Linear Electromagnetic Actuator

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Abstract: New valve driving system to control for the best volumetric efficiency at each load of an internal combustion engine within one engine cycle has been developed. The system needs to reduce pumping loss that cause by throttle valve during the intake valve is opened. In this system the intake valve is driven by a linear DC electromagnetic actuator which is controlled by personal computer. The result is compared both installed and uninstalled actuator into the cylinder head. By both of experimental and numerical calculation, the responsibility of the valve driving system to the engine speed was examined

Keywords: Electromagnetic actuator, Internal Combustion Engine, Valve, Control, Responsibility

1. INTRODUCTION

One of methods to obtain the best burning and high efficiency at each engine speed and load of automotive engine is to control valve movement to the optimum responsibility point. Peculiar both of valve timing and valve lift exist in each operating condition of engine. An electro-hydraulic valve driving system was examined for the target of valve timing and valve lift[1]. In this system phase lag due to hydraulic system give problem to control the driving system responsibility. So a newly developed intelligent variable valve timing system that continuously control cam phasing by using a electromagnetic actuator was proposed by Kreuter[2], Moriya[3], and Theobal[4] for controlling valve timing. The valve timing for opening and closing was controlled to reduce the pumping loss. The additional setting for valve opening and closing could not control lift. However, to get better burning condition, the improvement of the gas flow by valve lift control is necessary. The system to control valve lift is possible to do. Also, many problems will be solved, the increasing of parts number, the complication of the system construction, the accuracy of valve movement and the impact between valve seat and valve face that causes to wear them are remained to be solved.

Therefore, in this study to solve these problems, the experimental apparatus was tried to newly develop. The linear direct current motor (LDM), namely, electromagnetic actuator and the accuracy measuring equipment was used for feedback control. In general, under the intelligent program, the excellent responsibility and accuracy of output via the feedback control could be obtained. In this study, the characteristics of actuator, not only solitary actuator but also installed one to the cylinder head are examined.

2. EXPERIMENT AND SIMULATION

1.1 Experiment

The model of valve control system is shown in Fig. 1. LDM electromagnetic actuator shown in Fig.2 was installed onto the head of a test engine that motoring was driven by a electric motor. The samarium cobalt is used for the LDM electromagnetic actuator to get high permanent magnetic flux density. An actuator rod drove an intake valve directly maximum in 9 mm. The driving force was controlled by changed of voltage supply by computer. At the upper end of actuator rod, displacement sensor with laser beam was installed to measure valve stem movement. The valve lift data which was detected and immediately analyzed by the computer. Crank angle was detected by a rotary encoder sensor. The electric power was fed to the actuator for optimum valve lift control and the valve lift followed to the target displacement at correct engine crank angle. Meanwhile, the valve control system also analyzed the effect of cylinder internal gas pressure by pressure signal was sent back to the computer from a pressure transducer. The computer analyzed and compensated the feed back power to actuator for the optimum magnetic power. The samarium cobalt and 10.4 Ω enameled wire were used to make the electromagnetic actuator is shown in the table 1.

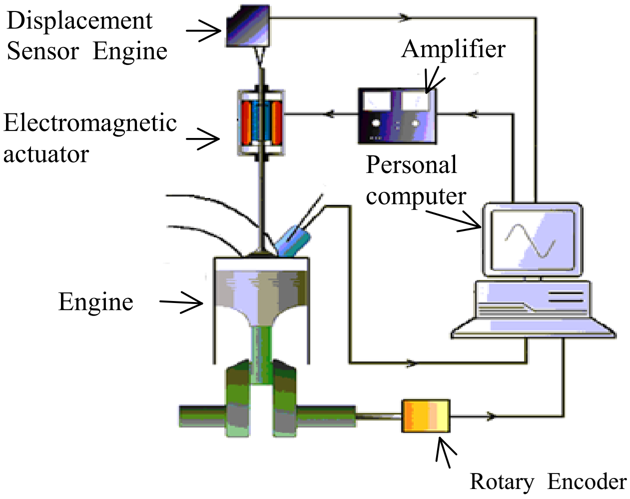


Fig.1 Valve control system

2.2 Simulation

The mobile LDM electromagnetic actuator is chilled by permanent magnet polarizes on each side of case and the axis as shown in Fig. 2. Driving force F is given by formula (1) that is based on the Fleming's left hand law. Also the characteristic equation of this system is shown by formula (2).

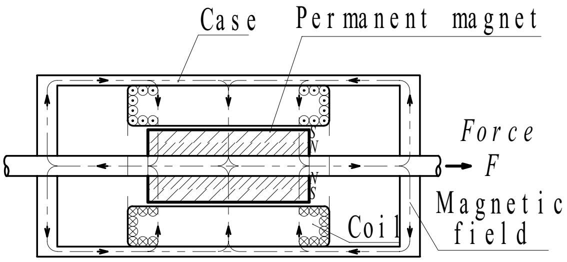


Fig.2 LDM electromagnetic actuator

Fig.2 LDM electromagnetic actuator

Table1 Specification of LDM electromagnetic actuator

Actuator	Actuator size	ϕ 40x120 mm
	Stroke	9 mm
	Moving mass	M = 0.116 kg
Magnet	Magnet size	ϕ 20x48 mm
	Magnet material	Samarium cobalt
	Magnet flux density	$B_t = 0.70$ T
Coil	Coil material	Enameled wire JIS PEW ϕ 0.5 mm
	Number of coil turns	N = 1400
	Coil resistance	R = 10.4 Ω
	Coil inductance	$L = 9.61\text{x}10^{-5}$ H
	Circumference of coil	l_c=177 mm

2.2 Simulation

The mobile LDM electromagnetic actuator is chilled by permanent magnet polarizes on each side of case and the axis as shown in Fig. 2. Driving force F is given by formula (1) which is based on the Fleming's left hand law. Also the characteristic equation of this system is shown by formula (2).

$$F = N l_c B_t I \quad \text{(N)} \qquad (1)$$

$$\begin{aligned} x(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) \qquad (2) \\ x(t) &= [\, l(t) \quad i(t) \quad I(t)] \end{aligned}$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ \dfrac{k}{m} & \dfrac{-K_F K_e}{Rm} & \dfrac{K_e}{Rm} \\ 0 & 0 & \dfrac{-R}{L} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{L} \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$

Where

N = Number of turns in coil, B = Flux density (T)
R = Resistance (Ω), L = Inductance (H)
I = Coil current (A), m = Moving mass (kg)
k = Magnetic incline force constant (N/m),
l_c = Circumference of coil (m)
K_F =Thrust constant (N/A)
K_e = Back electromotive force constant (V.s/m)

At time t, l(t), I(t), u(t), x(t), and y(t) are valve displacement, coil electric current, coil input voltage, condition variable vector and output vector respectively. A displacement deviation is output vector y(t) and target value is r(t). The expansion characteristic equation which is added the integration $x_r(t)$ is

$$\begin{bmatrix} x(t) \\ x_r(t) \end{bmatrix} = \begin{bmatrix} A & B \\ -C & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ x_r(t) \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} r(t) \qquad (3)$$

where $x_a(t) = \left[x^T(t) \quad x_r^T(t) \right]^T$

and evaluation function is

$$J = \int_0^a \left[x_a^T(t) Q x_a(t) + u^T(t) R u(t) \right] r(t) \qquad (4)$$

It demands the control input U(t) as it makes Q the smallest value and the weight coefficient of variable R control input for feedback condition.

$$\begin{aligned} U(t) &= -F_I x(t) - F_{II} x_r(t) \\ F_G &= \left[F_I \quad F_{II} \right] = R^{-1} B^{\#T} P \\ PA^{\#} &+ A^{\#T}P - PBR^{-1}B^TP + Q = 0 \qquad (5) \end{aligned}$$

where $A^{\#} = \begin{bmatrix} A & 0 \\ -C & 0 \end{bmatrix}$, $B^{\#} = \begin{bmatrix} B \\ 0 \end{bmatrix}$

F_I = Feedback gain
F_{II} = deviation gain

2.3 Force caused by suction flow

Suction force of gas flow into cylinder has effect on the valve movement control. Therefore, it needs to examine the pressure distribution around valve in each crank angle. Drag and suction force caused which acts on the valve by the flow are calculated with computer, and the program compensate magnetic force to the actuator to achieve the target lift by numerical analysis. Fig. 3 shows the engine model of fluid analysis meshes (SUBARU ROBIN-DY41), and Fig.4 shows the target lift curve of the valve movement in cases of standard (full open), 3/4 lift, and 1/2 lift at each engine crank angle.

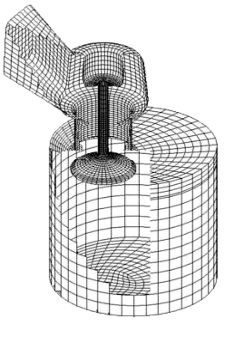


Fig.3 Computational mesh

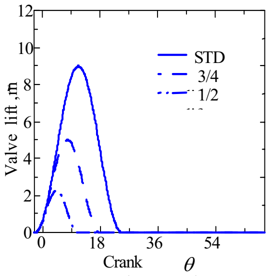


Fig.4 Target lift diagram

2.4 The simulation of valve operation

Fig. 5 is a schematic diagram of feedback control for engine simulation as shown in Fig.1. It calculates each gain from the optimal control law. Valve drag and gravity are included to compensate output gain in the simulation model. The simulation program examine valve lift curve at each revolution of the engine, then it supply optimum voltage to amplifier for exactly valve lift by magnetic flux density.

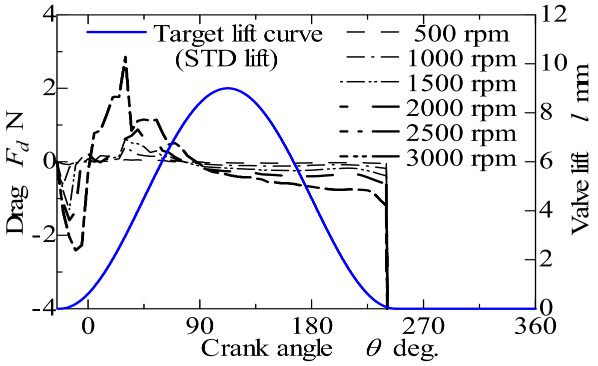
2． RESULTS AND ANALYSIS

3.1 Valve control system effect by simulation

Fig. 6 to 11 show the responsibility of electromagnetic actuator with drag and its comparison between in case of standard curve, 3/4, and 1/2 lift at any engine crank angle.

From Fig. 6, 8, and 10, the different of drag at higher engine speed is bigger than at low speed and its peak clearly occurs up to 90 degree of crank angle. At the end of drag, it continues to suction force to turn while piston moves downward. The changing point of these forces were changed from 90 degree to 180 degree and turn back to about 120 degree of crank angle when the valve lift was changed from standard lift to ¾ lift and ½ lift respectively. The less opening of valve lift causes to rebound of drag force that is clearly seen in Fig.10. If it is early closing (1/2 lift), rebound phenomenon is occurred after valve is closed. The satisfied results of valve lift control are obtained, and the curves turn to be normal valve lift by simulation, as shown in Fig. 7, 9, and 11.

For these conditions, if flux density is changed to 0.105T and 0.7T during magnetic force is constant, it can be seen that the driving force both positive voltage and negative voltage are necessary to increase when engine speed is increased, and it has highest value at 3,000 rpm. By the lower voltage driving force that cause to be higher flux density is better than the lower, Fig. 12 and 13.



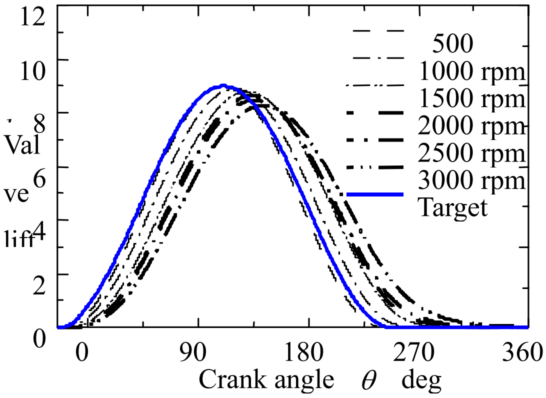


Fig. 7 Valve lift diagram of STD lift

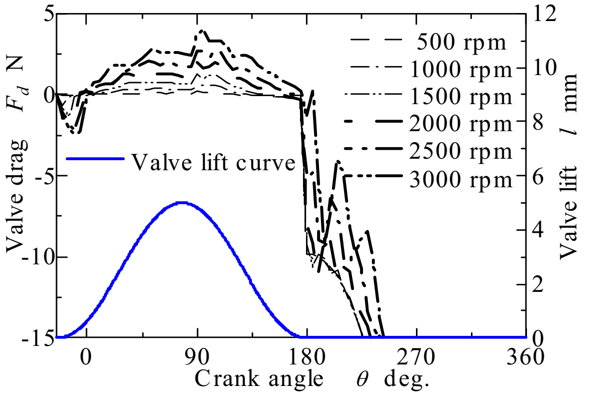


Fig. 8 Drag for intake valve of 3/4 lift

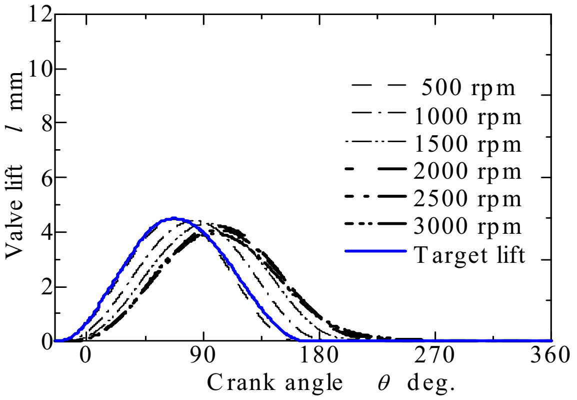


Fig. 9 Valve lift diagram of 3/4 lift

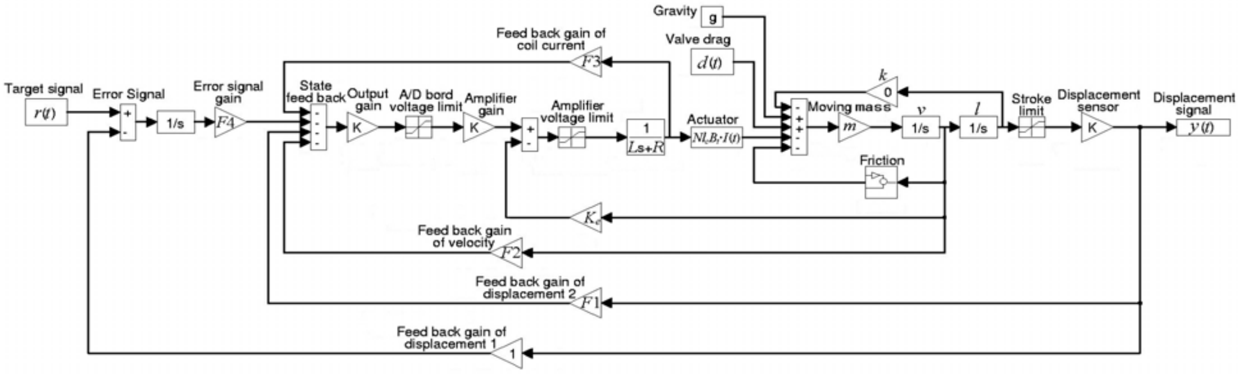


Fig.5 Block diagram of simulation

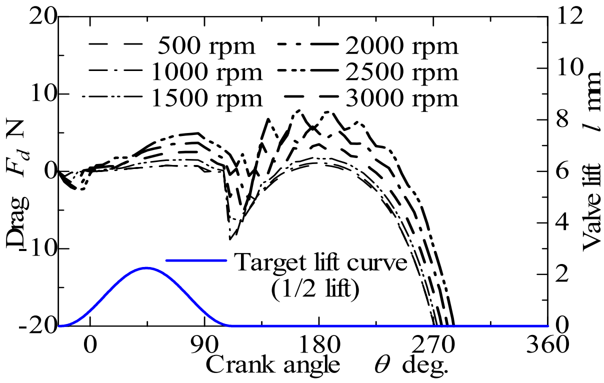


Fig. 10 Drag for intake valve of 1/2 lift

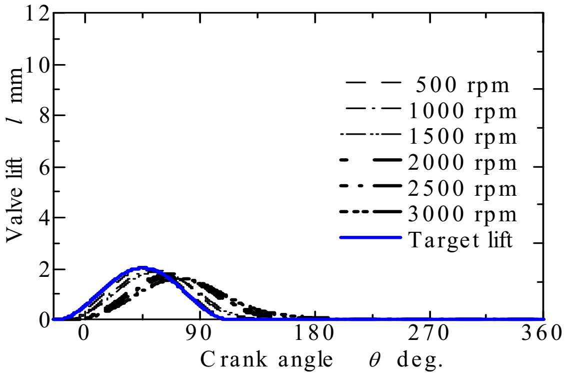


Fig. 11 Valve lift diagram of 1/2 lift

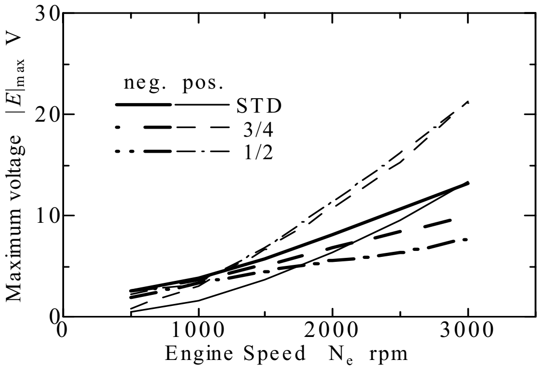


Fig. 12 Voltage diagram
(BI=0.7T)

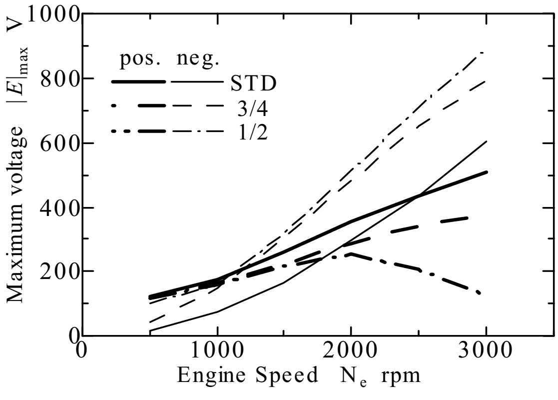


Fig. 13 Voltage diagram ($B_T = 0.105T$)

3.2 Comparison between the experiment and the simulation

By using independent actuator drives before loading into the engine, rotary encoder and computer are connected, and it corresponds to the crank angle. It controls an actuator at the target value of standard lift. By some adjustment for obtain better responsibility, the result is shown in Fig. 14, phase lag can be seen from lower engine speed, 200 rpm, and it become more phase lag at higher speed. Until around 1,500 rpm and more, the actuator is out of control, while the good valve lift can be controlled with the nearly constant of phase lag is shown by simulation without drag in figure15. By loading the actuator drive into the engine cylinder head, the actuator can control valve lift at only low engine speed up to approximately 1,000 rpm. And it still has a little bit of phase lag, after computer gain is adjusted and magnetic flux density at 0.7T is used, shown in Fig. 16. By this experiment, valve drag is analyzed too.

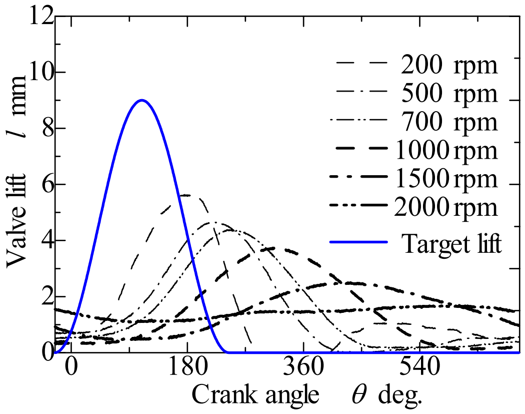


Fig. 14 Valve lift diagram (Experiment)

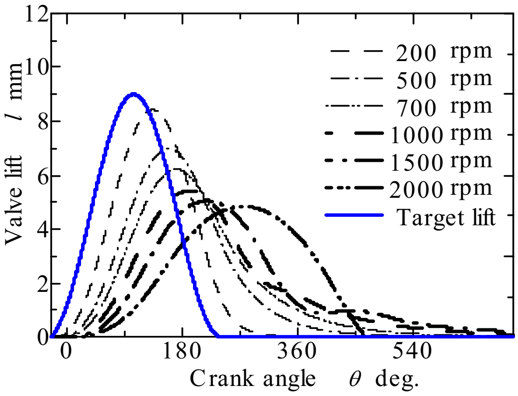


Fig.15 Valve lift diagram (Simulation)

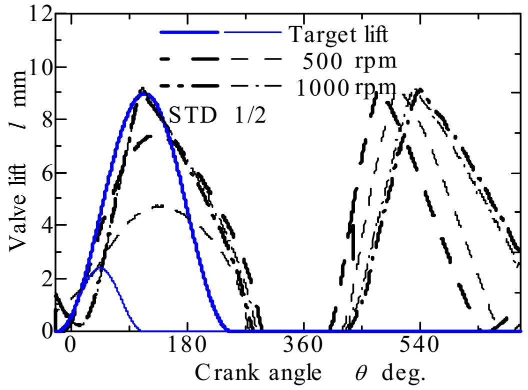


Fig. 16 Valve lift diagram (Experiment.)

Fig. 17 shows the valve lift curve compare to the standard by simulation. The driving system can control valve lift at low speed as same as the former and still have more phase lag at higher speed. But around more than 1,500 rpm, it can be clearly seen that the system is difficult to control the valve closing. Both experimental and simulation show the second valve opening by suction force during the expansion stroke as shown in Fig16 and 17. But this phenomenon has no problem in the actual engine, because the positive gas pressure during an expansion stroke will automatically close the intake valve.

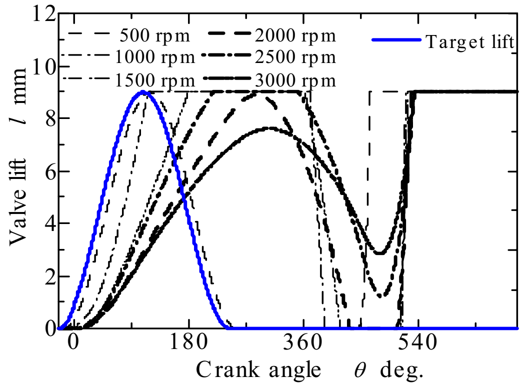


Fig. 17 Valve lift diagram (Simulation)

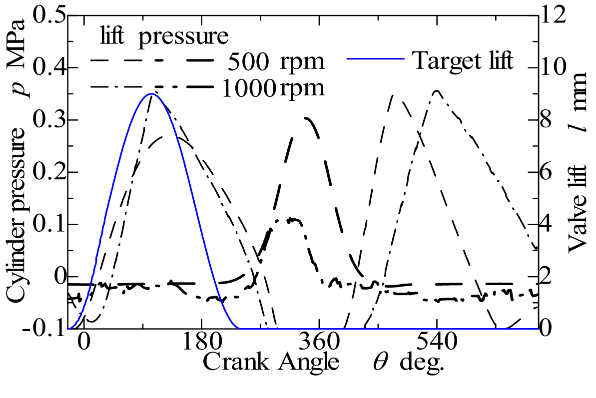


Fig 18 Pressure diagram (Experiment)

Fig. 18 shows the internal cylinder gas pressure at each engine crank angle during low speed motoring and expansion stroke, the internal gas pressure is very small and the same phenomenal is occurred during compression stroke. At the expansion stroke around 440 degree of crank angle, it become to negative pressure, and it cause to be the second time valve opening.

During the experiment, volumetric efficiency was calculated to compare between cam drive and actuator. The same behavior can be seen but a little lower is occurred by an actuator than cam, shown in fig 19. By more program improvement and higher flux density of electromagnetic, it is to be possible that the electromagnetic actuator can be used in the valve drive system.

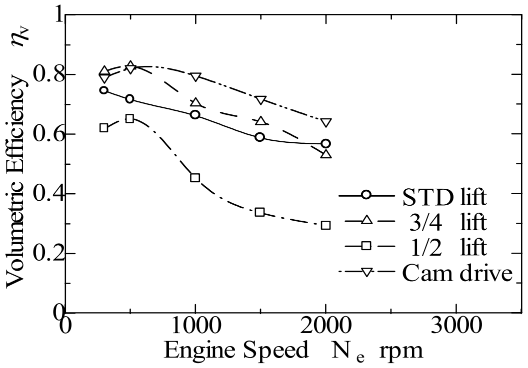


Fig 19 Volumetric efficiency at any speed (Simulation)

4. CONCLUSIONS

From both experimental and simulation, the results are summarized as follows.

1) An electromagnetic actuator system can control valve movement.

2) By strengthening magnetic flux density LDM actuator it can control valve at higher engine speed.

3) From analysis of the drag that acts to the valve, it found that the gas pressure in the engine cylinder has big effect on the valve movement and also it disturbs the accuracy of valve movement driven by electromagnetic actuator.

4) By this system, the higher accuracy of valve control can be done, but it needs more powerful electromagnetic actuator. And that causes to wear at valve seat and valve face.

5) Actuator of high magnetic flux density is more suitable to control the valve opening than lower flux density. Especially it can use lower voltage of power supply.

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