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Synthesis of studies on polarized valve actuators for internal combustion engine

J. P. YONNET*, C. CHILLET, C. FAGEON*
Laboratoire d'Electrotechnique de Grenoble (UMR 5529 CNRS / INPG-UJF) BP 46, 38402 St Martin d'Hères Cedex, France
**PSA Peugeot Citroën, 18 rue des Fauvelles, 92250 La Garenne Colombes, France*

A very promising technique to reduce fuel consumption in spark-ignition engine is to control the load by means of variable valve timing with electromagnetic valve train systems. So far, such concepts use actuators based on electro-magnets systems only. The best configurations are polarized actuators, in which magnetic flux of permanent magnets is in series or in parallel with the main flux circulation. Compared with non polarized actuators, the addition of permanent magnets in the magnetic circuit allows important operation improvements. The motion can be controlled more easily, allowing us to achieve a better soft-landing and to reduce the energy consumption. In addition, when the valve is not moving (either closed or open), it can remain in its position by the magnetic attraction, without any energy. Polarized actuators with permanent magnets are the best solution for electromagnetic valves.

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1. Introduction

The targets of future car efficiency, and in particular the average CO_2 limit of 140 g/km on NMVEG cycle in 2008, bring the automotive industry to take up new technological challenges. Fully variable valve timing has been identified as one of the most promising technologies, in particular for its benefits towards fuel economy and low end torque increase, this without any negative on after treatment. The fully variable valve timing is obtained by driving electromagnetic valve actuators. This concept allows reaching 20% of fuel consumption and CO_2 emissions reduction for gasoline engine. Moreover, these results can be gained towards easier pollutant emissions reduction.

Such concepts use actuators based on electro-magnets systems only. Basic electromagnetic valves are equivalent to two electromagnets attracting a moving part at each end of its stroke. The moving part operates by the use of springs and creates a type of harmonic oscillator. The moving part stays in a static position in the high or low point, then go to the other position in less then 3 ms. The valve opening time is obtained by adjusting the interval between the up and down motions. The landing noise of the moving part is a key issue for this type of actuator. To reduce it and to obtain a longer lifetime, a soft-landing must be achieved.

Different configurations can be used for electromagnetic valve actuator. By adding the polarization flux of permanent magnet, the flight control is easier, the energy consumption is lower. The magnet flux can be either in series or in parallel in comparison with the flux created by the current.

2. Engine improvement with electromagnetic valve actuation

The following results have been obtained with EVE Concept engine (Electromagnetic Valve Engine), which means that the internal combustion engine was equipped with intake electromechanical actuators and exhaust camshaft with mechanical valve deactivation device that can allow cylinder deactivation.

2.1 Vehicle performance

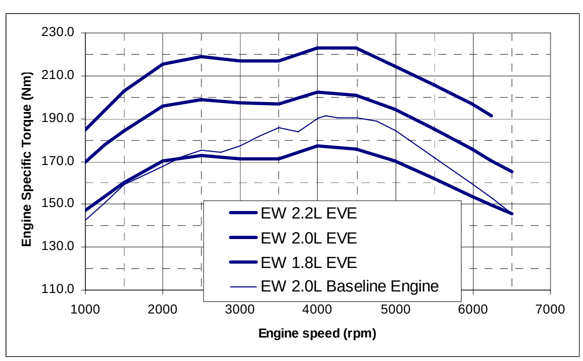

Fig. 1. Engine specific torque versus speed, comparison between a 2.0l baseline engine and 3 similar engines equipped with electromagnetic intake valves (EVE).

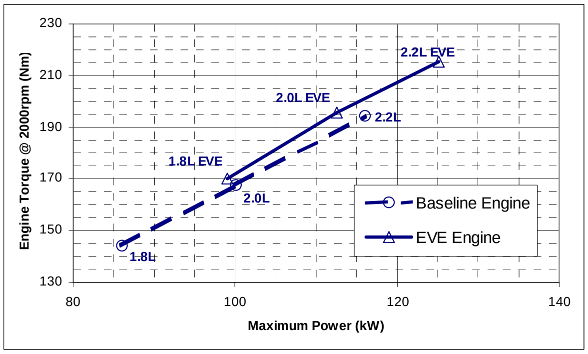

Fig. 2. Engine specific torque versus maximum power, comparison between a 2.0l baseline engine and 3 similar engines equipped with electromagnetic intake valves (EVE).

Fig. 1 shows a first evaluation of full load performance that could be gained for each feasible application of EVE engine on PSA Peugeot Citroën 4 cylinder middle range engine: 1.8L, 2.0L and 2.2L

Comparing torque curve of 1.8L EVE engine with 2.0L baseline engine led us to the conclusion that due to improvement of low-end torque as well as peak power some downsizing could be achieved for same vehicle performance. This is more than evidence if we compare low-end torque (represented by torque @ 2000 rpm) versus maximum power for baseline engine and EVE engine (Fig. 2).

Summary of this results are shown in the table below:

	Middle Range Car					
	1.8L		2.0L		2.2L	
	NEDC fuel consumption (L/100)	NEDC CO_2 emissions (g/km)	NEDC fuel consumption (L/100)	NEDC CO_2 emissions (g/km)	NEDC fuel consumption (L/100)	NEDC CO_2 emissions (g/km)
Baseline Engine	7.7	182	8.3	197	8.8	210
EVE Engine	6.5	155	6.9	164	7.3	175
	-15%		-17%		-17%	

2.2 Vehicle consumption

For this analysis, vehicle consumption and CO_2 emissions on NEDC have been updated for 2.0L EVE engine with baseline gear ratio, and projected for 1.8L and 2.2L EVE engine.

Vehicle consumption benefit appears to be directly comparable for 2.0L and 2.2L engine, but a bit lower for 1.8L engine. This can be explained by higher load experienced during driving cycle due to smaller displacement of the engine.

3. Electromagnetic valve actuators

3.1 Conventional valve actuators

Fig. 3 shows a conventional electromagnetic valve actuator. The moving part is attracted by the two electromagnets. The stroke is relatively high, about 8 mm. The fast motion is obtained by the two springs. The neutral position is in the middle, and the two electromagnets mainly operate by holding the moving part at the two ends of the stroke.

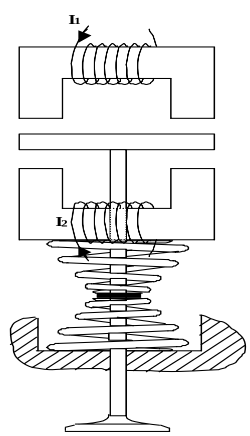

Fig. 3. Conventional valve actuator operating with two electromagnets.

This system works correctly, it is very rugged and inexpensive. However it has several disadvantages. Because the forces they produce are proportional to the inverse square value of the airgap for a given current, the control of the landing is difficult, giving a very noisy operation. Moreover maintaining the low and high position needs permanent electric consumption. To solve these problems, polarised actuators can be used [1,3].

3.2 Polarized actuators

By adding the flux of permanent magnet to the flux created by the coils, it is possible to obtain permanent attraction forces and linear behaviour for small airgap. In the actuator shown on Fig. 4 the flux created by the magnets is in series with the flux created by the coils. It owns many advantages:

- at the high and low position, the permanent magnet flux creates an attraction force which can maintain the moving part without current consumption,
- the force variation is relatively linear for small airgap, allowing a best control of the landing of the moving part.

However some drawbacks must be taken into account. For the coil the magnet thickness is an additional airgap and must be as reduced as possible. The magnet must create an important induction, but it can be submitted to high inversed magnetic field created by the coil. For such a configuration, Rare Earth magnets are well adapted.

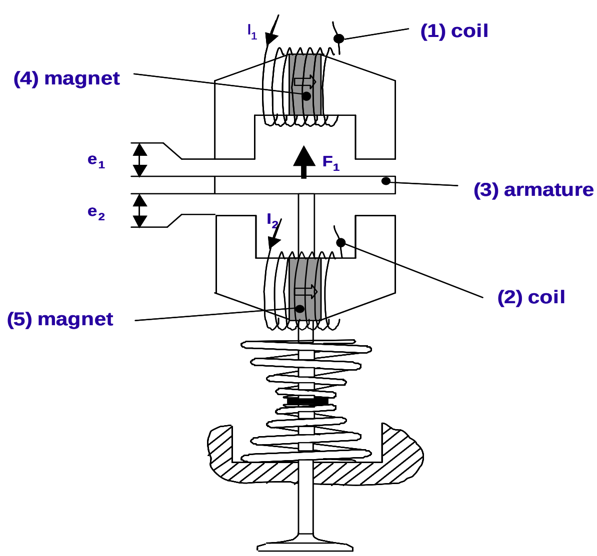

Fig. 4. Polarized valve actuator. The magnet flux is in series with the flux coil.

For a given vertical position, the permanent magnet creates the induction B_0 in the aigaps. The coils give a variation of induction ΔB proportional to the current I. It can be demonstrated that the force is given by [3]:

- for the non polarized system

$$F_{np} = k \, . \, \Delta B^2 = \alpha \, I^2$$

- for the polarized system

$$F_p = k \, . \, B_0 \, . \, \Delta B = \beta \, . \, B_0 \, . I$$

These two expressions show that the polarized actuator has a linear response as a function of the current I, and consequently can be more easily controlled.

3.3 Different types of polarized actuators

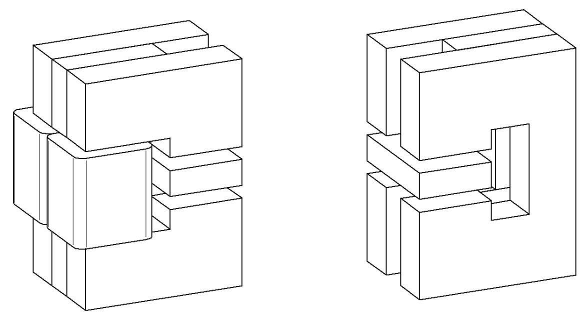

Fig. 5. An actuator structure with parallel polarization. Electromagnetic parts of actuator (all parts on the left, without coils and on the opposite face on the right).

Different configurations can be used. They can be divided into two categories, series or parallel, according to the respective position of the coils and the magnets.

- In a series configuration, the coil and the magnet are in series in the magnetic circuit (Fig. 4). The magnet thickness must be as small as possible because it is an additional airgap for the coil. However, a too thin magnet will give a reduced polarisation for a large airgap. Consequently an optimum magnet thickness exists.
- In a parallel polarization actuator, the magnet flux is added to the flux coil in the airgap, but the magnet does not interfere with the coils. The parallely polarized configuration which is shown on Fig. 5 is very compact [7]. Two ferrite magnets are located between the two C-shaped magnetic pieces. The soft iron circuit canalizes the magnetic flux to the air-gaps. The moving part (armature) is made with soft iron in a cuboïdal shape. It is located between the extremities of the iron pieces and can vertically move. The magnetic flux generated by the permanent magnet flows from the right airgaps to the left one through the armature. If the armature is located higher than the neutral position, the flux in the upper airgaps is more important, and then generates a vertical force on the armature increasing until the contact with the magnetic circuit. An important force is then permanently generated in the two extreme positions of the armature without current in the coils.

The actuator design owns a very small vertical length. Additionally, it can be stacked easily on the motor top. It is very interesting when the space is limited around the ICE motor.

2.4 Comparison between polarized and non polarized actuators

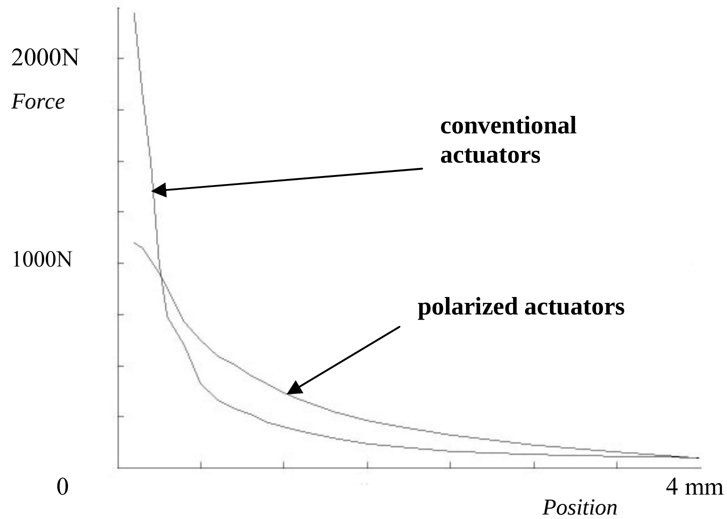

Fig. 6. Comparison between non polarized and series polarized actuator: force measurement as function of the position for a given current.

Several series of actuators have been built and measured. Figs. 6 and 7 presents the force variations measured on prototype with and without polarization. For conventional actuators at a given current, the force becomes very high for small airgap (Fig. 6). Comparatively, the force variation of the polarized actuator is more linear. It is very important for the landing control.

For a given airgap, the conventional actuator force increases very fast with current (Fig. 7), but it is limited by the magnetic circuit saturation. In comparison, the polarized actuator owns a relatively linear response.

Other parameters are also very important in the comparison between non polarized and polarized actuators. As example the polarized actuator is less sensitive to the mechanical clearance and to the initial settings of the actuator. It is less sensitive to the variation of all the mechanical parameters, particularly caused by the temperature. The polarized actuator is very robust for the parametric variations.

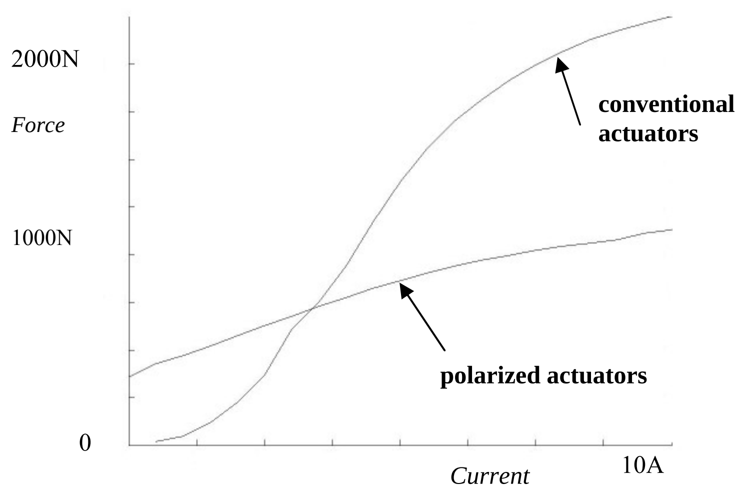

Fig. 7. Comparison between non polarized and series polarized actuator: the force measurement as function of the current for a given airgap.

4. Measurements on a series polarisation actuator

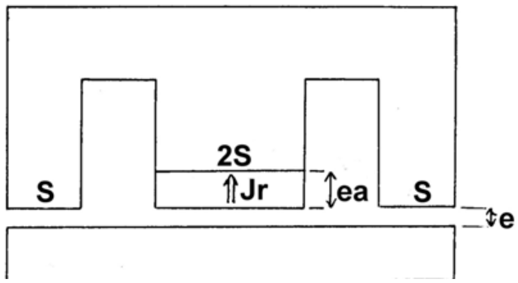

Fig. 8. Actuator with series polarization.

Fig. 8 shows the upper half of the actuator which has been used for the tests. The magnet thickness is about 2 mm. It is made in Rare Earth material (Nd Fe B). The outer legs of the magnetic circuit have a 8 cm^2 section, and the central leg section is 16 cm^2. The stroke is 8 mm.

Fig. 9A shows the simultaneous measurements of the position, the speed and the currents during a movement from the high to the low position. The first curve is the position and the second is the speed (vertical scale: 1ms^{-1}/square). The maximum speed is 3.2 m/s when the mobile part is close to the intermediary position. The travel time is 3.5 ms for the stroke of 8 mm.

The two lower curves (Fig. 9B) are the currents in the two coils. The current in the high coil varies in three steps. First step: when the moving part is the high position (starting position), the current in the low coil is null. Then the control system reverses the current to about -10 amperes for 2 milliseconds (second step) to decrease the polarisation induction in the airgap; this allows to increase the starting speed of the moving part. In a third step, the high coil current is null.

For the low coil, the current is null at the beginning of the displacement. When the moving part arrives at about 2 mm of its final position, the coil is supplied by a current which is controlled by the speed and the position. The control system is designed to obtain the soft landing of the moving part, by avoiding the shock. The good indicator of the quality of the landing is the noise, which remains relatively low when the polarized system is correctly controlled.

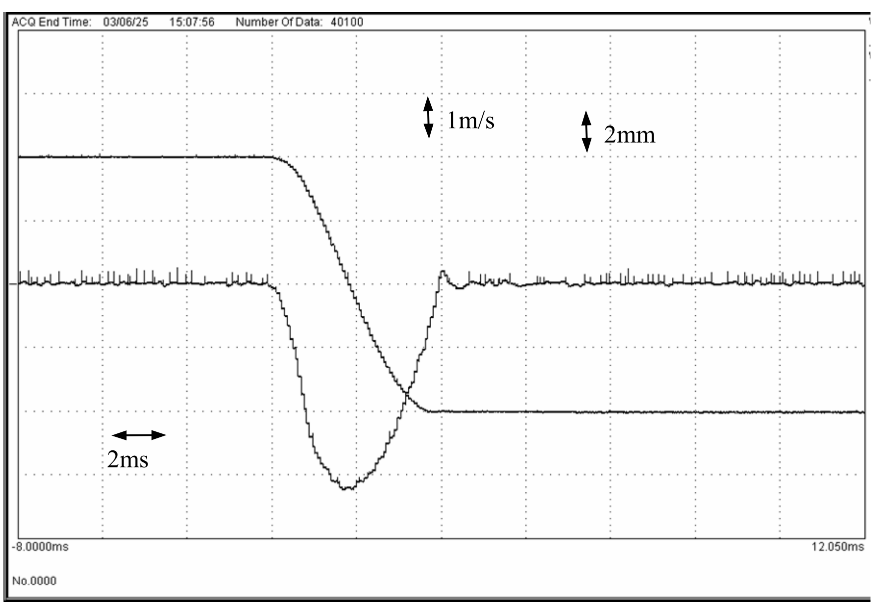

Fig. 9A. Position and speed measurement for a valve opening. The moving part goes from the high to the low position.

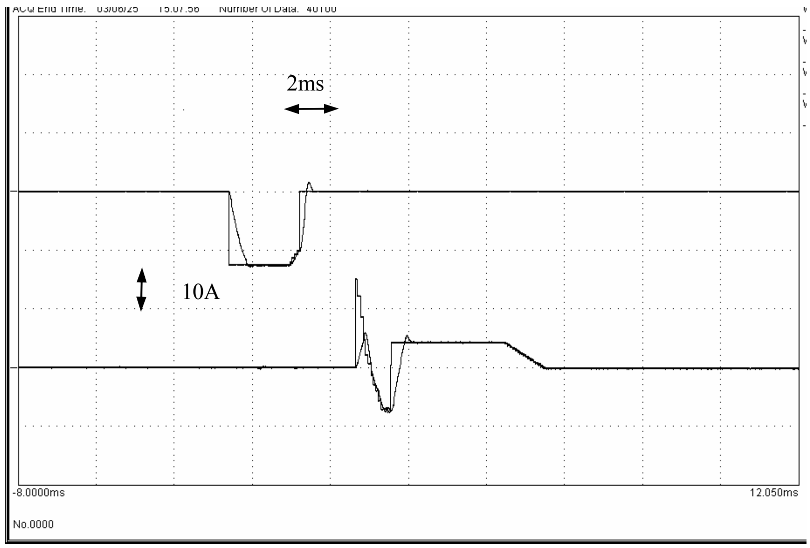

Fig. 9B. Signal given by the command and real current in the upper coil (first curve) and lower coil (second curve).

5. Materials and actuator construction

The magnetic circuit is crossed by magnetic flux which has very fast variation. It produces important losses by eddy currents. More precisely, the moving part is submitted to very important shock stresses; consequently its building with iron sheets is almost impossible. Only bulk materials can be used. To reduce the eddy current losses, some alternative solutions are tested, using less conductive materials than soft iron.

For the magnets, the situation is different for series or parallel polarization. In series polarization devices, the magnets are submitted to very high demagnetization field, and the magnet section is limited. It leads to the use of high coercive NdFeB magnets. For parallel polarization, the magnet sections can be large in comparison with the coil flux section. Additionally the magnets are not submitted to high demagnetizing field, so that low grade magnets can be used. Ferrite magnets are a good choice.

6. Synthesis and conclusion

By adding magnetic flux of permanent magnets in series with the main flux circulation, it has been demonstrated on polarized prototypes that the motion can be more easily controlled, allowing us to achieve a better soft-landing. Moreover the energy consumption can be lower. In addition, when the valve is not moving, either closed or opened, it can remain in its position by the magnetic attraction. Consequently, this static position does not consume any energy.

After a presentation of different types of polarized actuators, the measurements made on a prototype show that it is more easily controlled, well adapted to obtain soft landing and low electric consumption.

On a more general point of view, it has to be underlined that electromagnetic valves have made huge progress and improvement. For engine performance itself, innovative valve opening strategies have allowed to improve as well as low-end torque, peak power and pollutants emissions. The electromagnetic valve concept appears to allow now reaching a 20% CO_2 emissions reduction for given vehicle performance, becoming in that way the most effective technology for gasoline engine in that area. This result can be gained toward easier pollutant emissions control. For all this reason, taking in account constant need of CO_2 and pollutants emissions reduction, electromagnetic valve concept is now a very well placed candidate for next generation of gasoline engines.

References

[1] C. Morin, C. Baldi, E. Sedda, M. Vienne, C. Fageon, “EVE Concept: additionnel improvement of potentiel and major breakthrough in NVH area”, SAE Essen Congress, march 2002.
[2] C. Maerky, E. Nicole, A. Dulac, SVA “Electromagnetic valve actuation”, SAE Essen Congress, march 2002.
[3] E. Sedda, C. Fageon, J-P. Yonnet, “Permanent magnet actuators for electromagnetic valve in automotive applications”, LDIA 03, Birmingham, sept. 2003.
[4] M. A. Theobald, B. Lequesne, R. Henry, “Control of engine load via electromagnetic valve actuator”, SAE conference, Detroit (Michigan), Feb 28 - Ma 3 1994, paper 940816.
[5] B. Lequesne, “Fast acting, long stroke solenoids with two springs”, IEEE Trans on Indus Appl, **26**(5), 848-856 (1990).
[6] T. Redarce, J-P. Yonnet, “L’utilisation des aimants dans les paliers magnétiques”, RGE 10/84, oct 1984, p 648-653.

[7] S. Guérin, E. Sedda, C. Fageon, J-P. Yonnet, C. Chillet « An original configuration of linear actuator with parallel polarization », LDIA 03, Birmingham, sept. 2003.
[8] C. Chillet., J-P. Yonnet, C. Fageon, C. Baldi « Very compact actuator for camless system », LDIA 05, Awaji-Kobe (Jap), sept. 2005.
[9] J-P Yonnet, C. Chillet, C. Fageon, E. Sedda, C. Baldi « Polarised actuators for electromagnetic valve », High Performance Magnets and their Applications, HPMA'04, Annecy, 29 Aug – 2 Sept 2004, Proc. p 756 – 763.

*Corresponding author: Jean-Paul.Yonnet@inpg.fr