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Design and sizing of electromagnetic linear actuators for valve applications

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Abstract: In this paper, various structures of linear motion actuators are described. These structures have been studied in order to drive the valves of a car motor. According to general specifications, a description of the design and sizing of variable reluctance or permanent magnet devices is given. The main qualities of each structure are enhanced.

Keywords: Linear motion actuator, variable reluctance, permanent magnet, valves.

1. Introduction, general specifications

The valves which can be found in thermal engines are actuated by means of devices such as camshafts, tippers, belts, etc. These ways of driving valves involve many disadvantages. For instance, the displacement speed cannot be modified, the valve cannot be stopped in an intermediate position (the full stroke is necessarily utilised), neither can be chosen the moments when the valve opens and shuts. In order to improve the general working of these engines it may be useful to have a better control of the valve's movement. An electromagnetic actuator can solve all these problems. As a matter of fact, if the valves are driven with such an actuator associated with a controller, the opening and shutting instants, the displacement length and the displacement speed can be adjusted according to various criteria depending on mechanical specifications: fuel consumption, pollution problems, comfort, noise and so on. In order to solve these problems, an easy to drive actuator must be utilised. At the present time, electromagnetic actuators seem to be the simplest and the best adapted solution. We can find two main sorts of actuators: rotating or linear. Obviously, linear actuators will be easier to implement when a linear displacement is required. So it is not necessary to settle anything between the actuator and the valve.

In a thermal motor, we can find two kinds of valves: inlet valves and exhaust valves. The constraints are stronger for exhaust valves; so it was decided to take into account the specifications relative to exhaust valves for the actuator's design. If such an actuator is able to drive an exhaust valve, it'll be able to drive an inlet one.

The specifications for an exhaust valve are given hereafter:

Force value when the valve is shut: 120 N
Maximal value of the force when the valve opens: 300 N
Average value of the force when the valve opens: 100 N
Maximal diameter for the actuator: 48 mm
Height of the actuator: around 70 mm
Stroke: 10 mm

2. Variable reluctance actuators

2.1 Various structures

A first structure is given in **figure 1**. This structure is axis symmetrical.

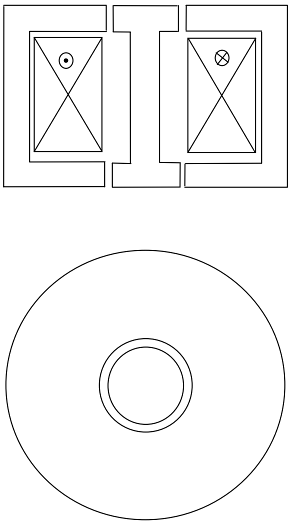

Figure 1: Cylindrical variable reluctance actuator

As it is shown in the upper part of **figure 1**, the currents turn around the mobile part of the device and the coils are located in a slot situated in the motionless part. The two main advantages are: the coil is entirely located inside the magnetic core of the actuator and, due to the cylindrical outline, the shaft which is mechanically connected to the valve and the valve itself can rotate around their symmetry axis. Thus the guiding of these elements will be simpler than if it was necessary to avoid that movement.
Among the disadvantages, it must be noticed that the flux density goes vertically through the shaft; a consequence of this phenomenon is that this part will have to be laminated in the right direction in order to

avoid eddy currents. Such a lamination is not easy to realize. Moreover, concerning magnetic saturation, the section of this shaft will have to be greater than a minimal value. So the mobile part could become too heavy and too voluminous.

A second structure is represented in **figure 2**.

On this structure, the coils turn around the external legs of the motionless part of the actuator. This avoids the presence of flux density in the mobile shat, hence, it has not to be laminated and its section will be only determined according to mechanical considerations. Among the disadvantages we must notice the global volume of this actuator will be more important and that the shaft will have to be guided in such a way its rotation cannot be made possible.

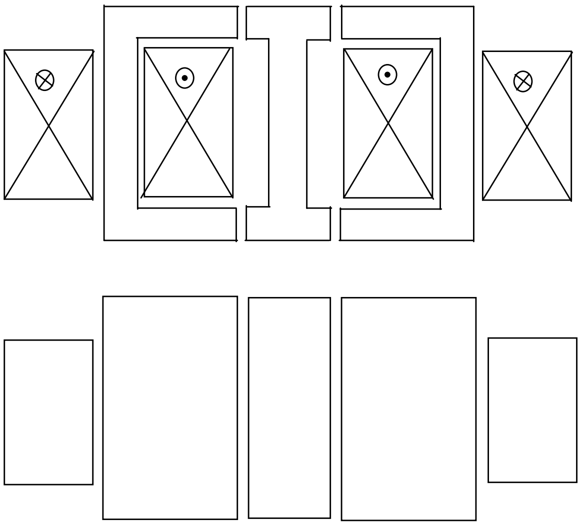

Figure 2: parallelepiped variable reluctance actuator

At last, a third configuration is shown in **figure 3**. This configuration may be more interesting as regards the length of the coils. It also allows obtaining a structure whose ratio width/length is closer to that of a cube.

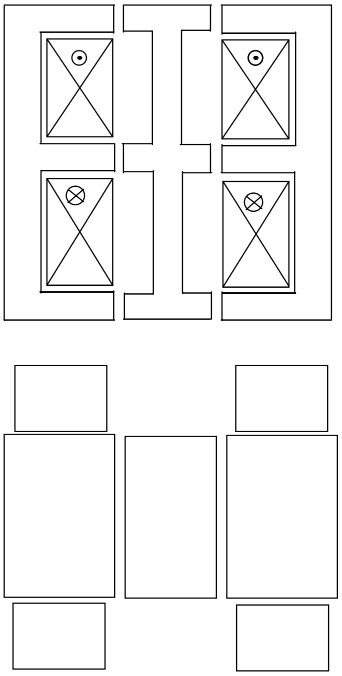

Figure 3: parallelepiped variable reluctance actuator (2nd type)

These structures do not allow the rotation of the valve shaft. If this rotation must be made possible a device such as that represented in **figure 4** may be chosen.

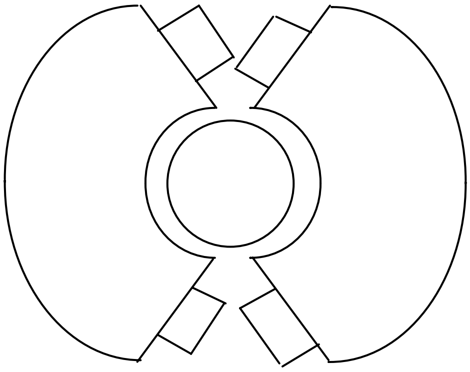

Figure 4: variable reluctance actuator allowing shaft's rotation

2.2 Numerical data

The **figure 5** hereafter shows a cross section of the cylindrical structure represented in figure 1.

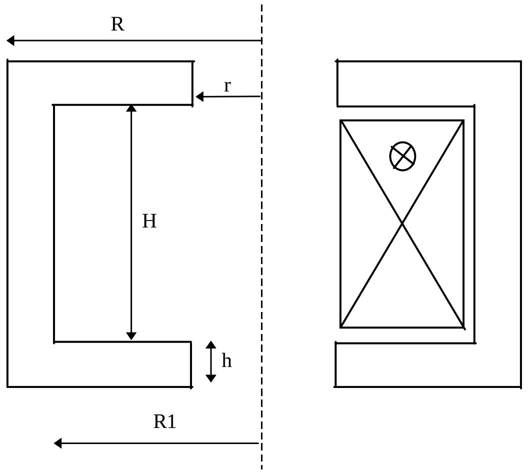

Figure 5: main dimensions of the cylindrical structure

The force which this actuator can develop is given by the following equation; ***e*** is the value of the air-gap and ε the sum of the currents flowing in the slot:

$$F = \frac{1}{2}\varepsilon^2 \frac{\mu_o 2\pi r}{2e}$$

The mechanical dimensions are those given hereafter:

r = 10 mm
R = 24 mm
R1 = 20 mm
h = 10 mm
H = 30 mm

If the current density is equal to 2.6 A/mm², ε will be equal to 800 At and the developed force will be 65 N for a 10 mm's stroke. This value is not important enough; in order to increase it, the area of the air-gap must be made wider. Another solution can be developed by using several structures as shown in figure 3 or by slotting the magnetic core as shown in **figure 6**. This solution requires a variable frequency voltage supply whose frequency depends on the number of slots.

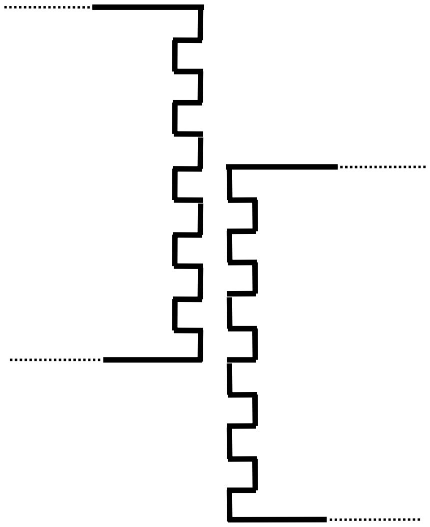

Figure 6: slotted air-gap

2.3 Conclusions on variable reluctance structures

The force that is developed by the cylindrical actuator was calculated for a 2.6 A/mm² current density. The forces given by the permanent magnet actuators studied thereafter will be calculated for 10 A/mm² current densities. It may be believed, considering the equation of the force, that the value obtained by the variable reluctance actuator, for a 10 A/mm² current density, should be sixteen times as important. Actually, when the current density is equal to 2.6 A/mm², the flux density is equal to 2.2 T; so the magnetic core is already saturated. As soon as the magnetic core is saturated, the force does not any longer vary in a quadratic way; in those conditions, the force varies in a linear way.

In order to obtain better values of the force the air-gap's area should be increased. This is made possible by increasing the value of the air-gap's radius. This solution has two main disadvantages. First, the weight of the mobile part is more important and moreover the coil's room decreases.

Another important disadvantage of variable reluctance actuators is that they can develop forces only in one direction. Thus, we'll have to implement two similar devices: one to move the valve upwards and another to move it downwards.

These considerations make us think that variable reluctance actuators must not be the best solution. In the following pages, we are going to describe and study the properties of permanent magnet actuators.

3. Permanent magnet actuators

3.1 Introduction

Concerning these structures, the same actuator can be utilised to move the valve upwards and downwards. The permanent magnets will be NdFeB type whose values of remanent flux density and relative permeability are B_r = **1.25 T** and μ_r **= 1.13**. The magnetic core will be called "steel", its values of remanent flux density and relative permeability are 1.4 T and 8000.

3.2 Slotless structures

A slotless structure is given in **figure 7**.

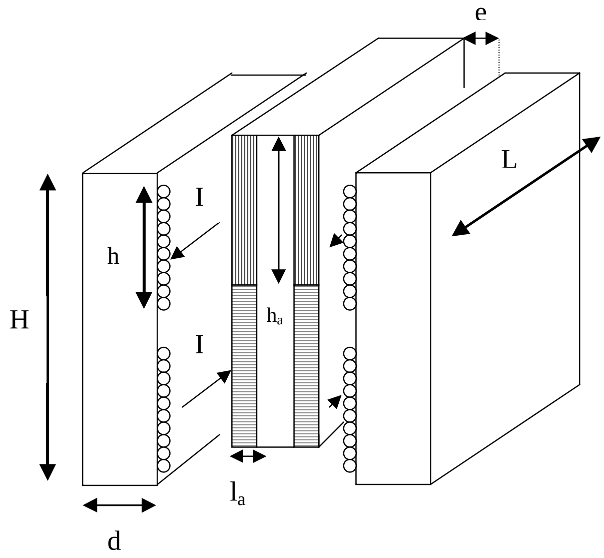

Figure 7: slotless structure

The vertically hatched parts are permanent magnets whose North pole is on their right hand side. The horizontally hatched parts are permanent magnets whose North pole is on their left hand side. The currents flow in the wires as shown in the figure. The wires can be stuck to the motionless part of the device.

The force which is developed by this actuator is given by:

$$F = 4nI.BL$$

The values of the parameters are:

B (flux density in the air-gap): **1 T**
L (active wires' length): **50 mm**
F (maximal force): **500 N**

In order to check these specifications, nI must be equal to:

$$2nI = 5{,}000\ \mathrm{A}$$

Geometrical data: According to the specifications, H is taken equal to **70 mm**.
In order not to create conflicting actions, each group of wires relative to a sense of current must always been situated in front of a same polarity magnet. Thus the height of the magnets will be equal to $H / 2$, i.e. **35 mm**. The mobile part is supposed to travel along a **10 mm** path. So, it is not necessary to put windings in front of parts which sometimes are not occupied by magnets, then h will be taken equal to **25 mm**. Concerning this slotless structure, the **air-gap** will be equal to **5 mm**.
If the magnetic core is considered perfect, we can write:

$$H_e.4e + H_a.4l_a = 0$$

H_e is the magnetic field in the air-gaps and H_a that in the magnets.
It is considered that the section area of the permanent magnets and that of the air-gap are nearly equal, thus we can write:

$$B = -\mu_0 H \frac{l_a}{e}$$

And:

$$B = \frac{B_r}{1 + \mu_r . \frac{e}{l_a}}$$

If we want to obtain a flux density value that is nearly equal to 0.8 B_r, we must have:

$$1 + \mu_r . \frac{e}{l_a} = 1{,}25$$

This leads to:

$$\mu_r . \frac{e}{l_a} = \mathbf{0{,}25} \quad \Rightarrow \quad l_a = \mathbf{4}\mu_r e$$

And:

$$l_a = 22\ \mathrm{mm}$$

We must avoid reaching saturation in magnetic cores; the flux density value will be limited to 1.6 T.
The flux conservation law allows writing:

$$d = \frac{B_a h_a}{B_{fer}}$$

Then:

$$d = 22 \text{ mm}$$

So, the total width of this structure will be equal to:

$$D = 2d + 2e + 2l_a = 98 \text{ mm}$$

Constraints on electrical windings: The air-gap is equal to 5mm, so the room devoted to the windings on each side of the actuator is given by:

$$(2 \times 25) \times 5 = 250 \text{ mm}^2$$

Hence the current density equals:

$$5{,}000 / 250 = 20 \text{ A/mm}^2$$

This result is obtained with a 100% filling coefficient. As a matter of fact, the value of this coefficient varies between 50 and 75%. Taking into account these values, the current density varies between **27 and 40 A/mm²**.

3.3 Possible improvements, slotted structure

The main default of slotless structures is the important value of their air gaps. In order to minimise this value, a slotted structure can be realized as shown in **figure 8**.

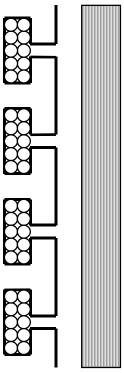

Figure 8: slotted structure

The main difficulty which appears when this sort of device is implemented is the fact the flux density is more important in the part of the magnetic core situated between slots. The core material must be chosen in order to avoid this phenomenon.

3.4 Conclusion

We didn't carry on any longer studies on slotted structures because we thought that there were almost as many advantages as drawbacks.

The various advantages have been evoked here above.

Among the disadvantages, we can notice:

For a same current, the current density value will be more important due to the localisation of the windings in slots. Moreover, the heat resulting from the power dissipation is more difficult to evacuate. At last, it was thought that the presence of slots would make the magnetic core more fragile.

4. Various permanent magnet structures

4.1 Introduction

Other slotted structures have been studied. They are described hereafter according to design simplification order. Different ways of calculating the forces developed by the actuators have been carried out: analytical calculation or finite elements method modelling (FEM).

Concerning the FEM, two situations are taken into account; the first one utilises a linear magnetic material whose permeability is equal to 10,000, in the second one, we have a non-linear material such as the one described in 3.1.

4.2 Structure with full size and half size magnets

This sort of actuator is represented in **figure 9**.

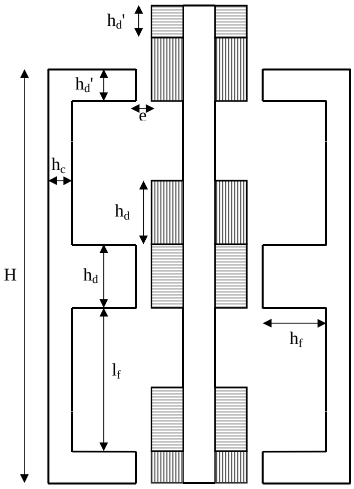

Figure 9: actuator with full and half size magnets

The main geometrical dimensions are the same as those of the actuator studied in part 3. The windings are located in the four slots. The magnets are more numerous than in other structure but it must be noticed that they can be thinner. There are eight full size and four half size magnets

Weight of magnets:
10 full size magnets (8 + 4x1/2)
thickness: **l_a = 2.2 mm**
volume: **11 cm^3**
weight: **55 g**

Forces' values for a 5000 At mmf:
analytical calculation: **560 N**
FEM with linear core: **440 N**
FEM with non-linear core: **350 N**

Flux density: **1.5 T** (non-linear FEM)

The differences between the analytical calculation and the FEM one can be explained because the analytical calculation does not take into account any leakage fluxes. The analytical calculation is carried out considering that we only have flux density in the parts of the air gaps which are in front of the magnetic core's teeth. The FEM calculation takes into account the presence of flux density in the whole field. The presence of ½ size magnets leads to a dissymmetrical configuration of the upper and lower parts of the actuator which may enhance the effect of the leakage flux.

The 90 N loss between linear and non-linear calculations is due to the saturation of the magnetic core. A greater value of force can be obtained by using thicker cores. If the external dimensions cannot be modified, this will be done by reducing the area of the slots and, then, increasing the current density.

In order to minimize the effects of the dissymmetry alluded here above it was decided to study centralized magnet structures.

4.3 Structures with centralized magnets

Various structures have been studied. They are detailed hereafter. The first one is given in **figure 10**.

In this case, the magnets of the lower and upper part have been replaced by a mobile magnetic core. The dimensions of this device are exactly the same as those of that studied in 4.2. This modification leads to symmetrical conditions for both extremities of the mobile part. The suppression of magnets is counterbalanced by using thicker magnets. Their main characteristics are given below.

Weight of magnets:
4 full size magnets
thickness: **l_a = 3.2 mm**
volume: **6.5 cm^3**
weight: **33 g**

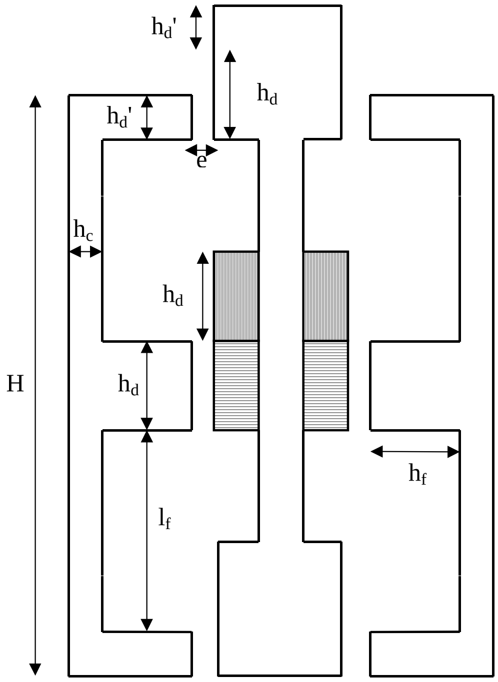

Figure 10: actuator with centralized magnets

The developed forces have been calculated according to the three methods which have been evoked in 4.1. The different results are as follows.

Forces' values for a 5000 At mmf:
analytical calculation: **476 N**
FEM with linear core: **292 N**
FEM with non-linear core: **223 N**

Flux density: **1.5 T** (non-linear FEM)

The differences between the three different ways can be justified by the same reasons as those given in 4.2.

The values of the forces are less important because the magnets are not thick enough. It would be possible to obtain higher values by reducing either the space of the windings or the thickness of the shaft. The space of the windings cannot be reduced because it would lead to lower values of developed forces. Concerning the shaft's thickness, it was decided to study another structure which is described hereafter. This structure was named: actuator with centralized magnets without mobile magnetic core. It is shown in **figure 11**.

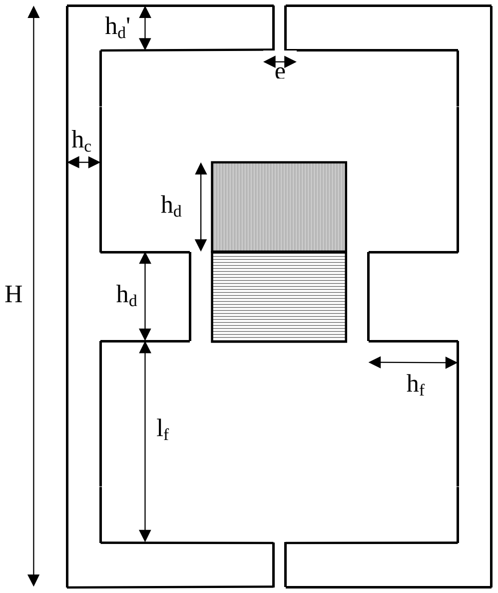

Figure 11: actuator without mobile magnetic core

The first advantage of this structure is that it allows using thicker magnets; the second one is that we can use a shaft as light and thin as required. So, the weight of the mobile parts can be minimized. Two air gaps have been represented in figure 11 but only one may be necessary according to the location of the shaft connected to the valve.

The main characteristics of this device are:

Weight of magnets:
- 2 magnets
- thickness: **$l_a = 8.8$ mm**
- volume: **$8.8\ \text{cm}^3$**
- weight: **44 g**

Forces' values for a 5000 At mmf:
- analytical calculation: **560 N**
- FEM with linear core: **330 N**
- FEM with non-linear core: **250 N**

Flux density: **1.52 T** (non-linear FEM)

Forces' values for a 2500 At mmf:
- analytical calculation: **280 N**
- FEM with linear core: **165 N**
- FEM with non-linear core: **163 N**

Flux density: **1.15 T** (non-linear FEM)

The absence of a mobile magnetic core increases the leakage flux that's why the differences between the analytical and the linear FEM calculations are more important than those of the previous cases.
The developed forces are more important, this is due to the thickness of the magnets.

It was noticed that the leakage flux was to be reduced in order to obtain better performances. One way to reduce this leakage flux is to settle cladding magnets.

4.4 Structures with cladding magnets

Such a structure is shown in **figure 12**.

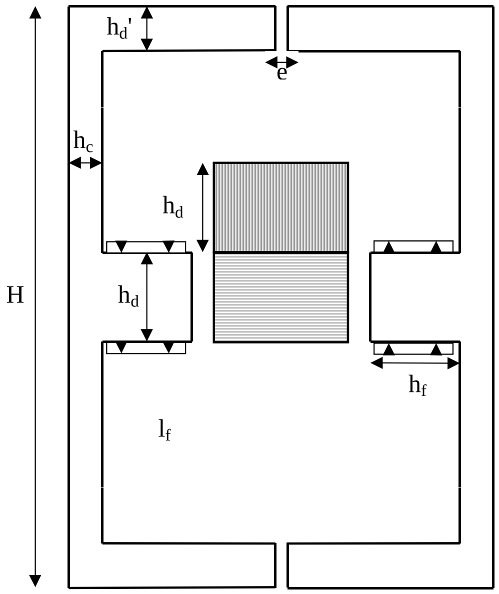

Figure 12: actuator with cladding magnets

The cladding magnets take place on the main teeth of the motionless part. The flux density they create is oriented as the arrows show. These magnets are supposed to concentrate the magnetic flux inside the magnetic core and to diminish the leakage flux.
The developed forces are not better than those obtained previously. The leakage flux is less important but, on the opposite, the motionless magnets create forces that are against the main forces. The thickness of these cladding magnets should be optimised. It may be supposed that certain values allow combining both effects.

5. Half-step structures

4.1 Introduction

Concerning the various above-mentioned devices, the magnets are situated on a rather little part of the mobile element. This mobile element consists of magnets, on one hand, and a magnetic (or non-magnetic) core, on the other hand. This core does not create any force but it has to be moved and its weight can be compared to that of the magnets. In order to optimise the working of the actuator, two solutions may be carried out. The first one consists in using as light as possible materials. In these conditions, the results are those obtained for the actuator without mobile magnetic core (4.3).
Another solution consists in using a more important number of magnets which are one beside another. In such a way the whole part of the mobile shaft is used to create forces. This kind of actuator is shown in **figure 13**.

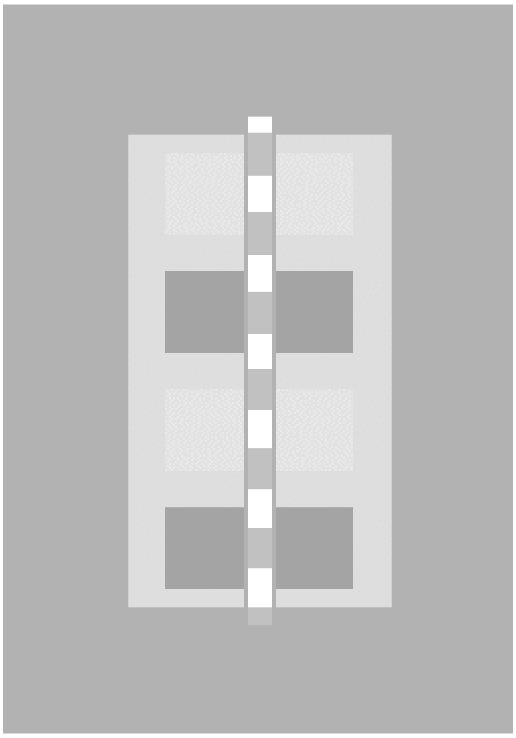

Figure 13: actuator with cladding magnets

The mobile shaft consists of a succession of magnets of different polarities. The motionless part is made of slots in which are situated the coils. The polarities of the currents change in every second slot. Whatever the position of the shaft may be; if a current flows in the slots, a force will always be developed by the actuator. That was not the case with the previous actuators. The orientation of the developed force (upwards or downwards) depends on the polarity of the magnets that are in front of the teeth of the motionless part. So, if the orientation of the force has to be the same when the mobile part moves, the polarity of the currents must change when the polarity of the magnets in front of the teeth changes. The main magnet's length is equal to 5 mm, that of the first and last ones is only 2.5 mm.

The dimensions are the same for the teeth (5 mm and 2.5 for the upper and the lower ones). When a current flows in the slots, the shaft will move downwards (or upwards) according to the polarity of the currents. That will carry on as far as the polarity of the magnets changes (5 mm), then in order to have the same orientation of the force, we must change the polarity of the currents. If we did not do so, the mobile part would tend to move in the wrong direction. The usual stroke is equal to 10 mm, so the polarity of the currents must be changed as soon as the half length has been reached, that is why this kind of actuator was named "half step" structure.
Compared with the previous cases, we can approximately expect close values of forces if the values of the m.m.f. are the same. So, as we have twice more slots, the sum of the currents in each slot will be twice as small. It will be the same for the magnetic field and for the flux density (if we neglect the material's saturation). The thickness of the vertical parts can be reduced. This can be exploited either to reduce the total weight or to have wider slots. If wider slots are realised, we can obtain either higher values of forces for a same current or lower copper losses for a same force.

The values of the developed forces are given in **figure 14**. They depend on the value of the total m.m.f. indicated on the right.

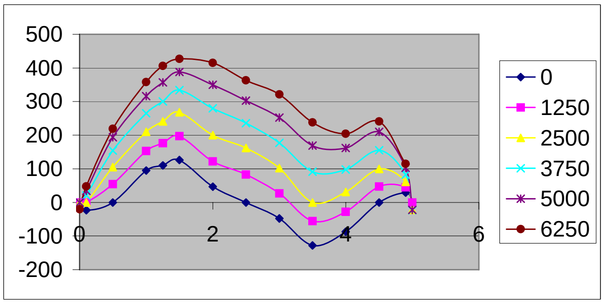

Figure 14: forces versus displacement

For an m.m.f. equal to 0, the force is only due to the magnets' action; that's why we obtain symmetrical values. For a value greater than 5,000 At the developed forces are always over 150 N

6. Conclusion

The calculations carried out here above show that the choice of a structure depends on the main criteria relative to the utilisation of the device. In the field concerned by these studies, many different criteria may be taken into account: total cost, realization cost, volume, total weight, weight of the mobile parts, values of developed forces, easiness of control for the supply currents, and so on. In this paper, we only tried to reach general conclusions; the real choice of one structure needs a better knowledge of the constraints of the specifications which are very different from one application to another. For instance, for a popular car, the cost and the volume might be the more important constraints, for other ones, a better control of the supply currents could be used in order to obtain better mechanical performances or more comfortable cars, etc.

Among the various devices described here above, the last one (half step) allows an acute control of the currents, the device without magnetic core is the lightest one; that studied in 4.2 is both robust and easy to build.

As a matter of fact, the knowledge of the main required properties allows choosing the best adapted structure.

7. References

[1] M. Kadiri, D. Valette, J-C Vannier : "Fast electromechanical actuator with linear displacement" Proc of 6th international conference on optimisation of electrical and electronic equipement – Brasov, 1998, p87

[2] J-C Vannier, M. Kadiri, D. Valette : "Etude d'un actionneur linéaire" Rapport interne 97/98 Supélec – Gif-sur-Yvette

[3] J-C Vannier, P. Vidal : "Analyse et modélisation d'un moteur à réluctance variable à circuit magnétique toroïdal" Électrotechnique du futur 99 – Lille

[4] F. Binet, J-C Vannier, P. Vidal : "Conception et simulation d'un moteur-roue" La conversion électromagnétique directe, 4 février 1999 - ENS Cachan - SEE

[5] B Bonafos, F Dugué, J-C Vannier, Pierre Vidal : "Actionneur linéaire rapide, conception, simulation et essais" Électrotechnique du futur 01 - Nancy

[6] A. Arzandé, F. Dugué, J-C Vannier, P. Vidal : "Actionneur électrique rapide de pompe à carburant : modélisation, simulation dynamique et système de commande"
Aerospace energetic equipment 2002 - Avignon

[7] A. Arzandé, F. Dugué, J-C Vannier, P. Vidal, B. Bonafos[1] "Optimisations du volume et de la séquence de commande d'un actionneur électrique rapide de pompe à carburant" Électrotechnique du futur 03 – Supélec Gif-sur-Yvette