P 34

Ultrafast Switching Rotary and Linear Actuators

S. Biwersi*, G. Loussert, J. Ríos Quesada, M. Delbaere, G. Andrieux**
Moving Magnet Technologies, 1 Rue Huygens, 25000 Besançon, France
(*) : corresponding author: sbiwersi@movingmagnet.com
(**) : now with Sonceboz SA, CH-2605 Sonceboz, Switzerland

Abstract:

Moving Magnet Technologies has developed innovative solutions of ultrafast rotary and linear electromagnetic actuators.

Such actuators are able to travel several millimeters or tens of degrees in a few milliseconds and can be used for various very demanding applications including control of fast switching flaps or valves used in new solutions dedicated to lower consumption and emissions of combustion engines. They are based on optimization of a mass-spring system associated to a specific magnetic circuit, and can be either of solenoid or polarized type.

Keywords: fast displacement, electromagnetic actuators, spring-mass system

Introduction

As a specialist in the development of innovative electromagnetic actuators, Moving Magnet Technologies has been involved for several years in the development of highly efficient actuator technologies able to achieve ultrafast travel times (typically a few milliseconds for a few millimeters or several tens of degrees) [1, 2].

Such actuators are required for very demanding applications like control of flaps or valves in the intake or exhaust manifold of combustion engines where they are used for innovative consumption and emission reduction solutions, or also industrial applications like mail sorting. These actuators are built up on a mass-spring principle, and sized according to optimized design rules allowing to find the best trade-off between size, travel time and electric power consumption.

After describing general working principle of such actuators, the paper will detail linear and rotary structures and prototype results based on application examples will be provided.

General principle

Although fast actuation can be obtained using various kind of direct drive actuators (voice coil, voice magnet, solenoid), these can hardly comply with the extremely demanding requirements of some specific applications to be found for example in automotive engine management applications like electric valve actuation for camless engine or flap control for pulse charging of the intake cylinder.

As such applications also require a flap or valve to hit a seat at the end of the stroke, control of the landing speed is also an issue that can not easily be achieved by using these actuator types.

In such case, a well-known solution is to use a mass-spring system associating an electric actuator with elastic means [Figure 1] that fits well with the requirement of such application to have a fast switching from one end of the stroke to the other without maintaining intermediate positions.

Typically, a ferromagnetic stator part driven by electric coils interacts with a ferromagnetic moving part associated with springs and driving a load. The system part can be of polarized type (i.e. including permanent magnets) or not.

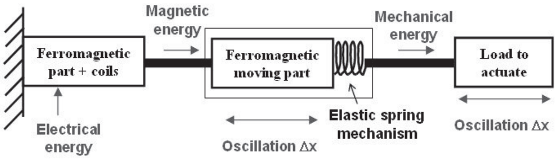


***Fig. 1:** Overall actuation principle*

The travel time T of such a system is given by :

$$T = \pi.\sqrt{\frac{J_a + J_l + J_s}{K}}$$

Where :

- J_a is the mass (or inertia) of the armature
- J_l is mass (or inertia) of the load
- J_s if the apparent mass (or inertia) of elastic mechanism
- K is the stiffness of the springs

A high stiffness is obviously a way to reduce travel time, but will induce a higher apparent mass or inertia of the springs and will also increase the force to be provided by the actuator and therefore its active mass or inertia, especially for large strokes, due to higher forces to be generated to overcome opposite spring forces.

As a consequence, the design of such an actuator is in general the result of a trade-off between antagonistic parameters.

Standard symmetric solenoid structure

A well-known structure using this general principle is the symmetric solenoid using two E-shape stators having each one coil with a ferromagnetic armature moving between these two stators (see for example [3, 4]) :

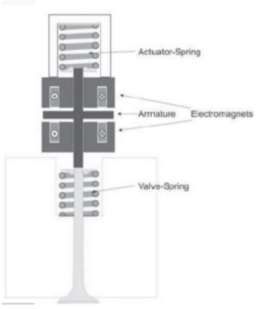


Fig. 2: *Symmetric solenoid structure*

Such actuator is typically associated with a symmetric spring system that will hold the armature in the middle of the stroke when the coils are not supplied. Further, it is made of two phases (one per coil) driven each by a half H-bridge.

The actuator operating cycle will then begin with a starting sequence (Figure 3) where at least one of phase is supplied with a predetermined duty cycle so as to allow the moving part to oscillate and reach one end of the stroke where it is maintained against springs force using a residual current in one phase. Once the current is released, the spring system drives the moving part to the other side of the stroke where it will be attracted by the other phase through a catching current and then hold by a residual current (Figure 4).

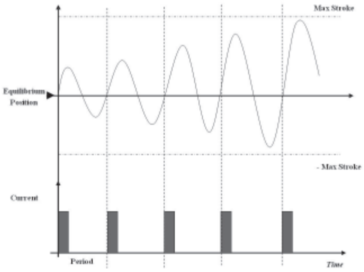


Fig. 3: *Typical actuator starting sequence*

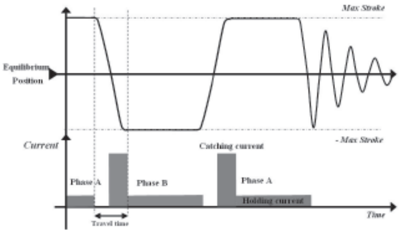


Fig. 4: *Typical actuator switching sequence*

Although well known through numerous variants of such principle developed over the last twenty years ultrafast actuation still offers challenges as for example the need for efficient and robust rotary actuators or for bistable linear actuators, and generally speaking simplified structures adapted to mass production requirements.

In that scope, MMT has investigated and developed specific linear and rotary actuators structures that will be presented hereafter.

Control strategies

Several advanced control strategies to provide especially closed-loop control of the landing speed having been developed (see for example [5]). Note however that MMT mainly focuses on actuator structures development validated by prototypes driven by open loop controllers. However, the proposed structures are of course definitely compatible with various closed loop control principles.

MMT rotary solenoid structure

One of the challenges of fast switching rotary actuators is to ensure high life time and to reduce effects of load and unbalance on the guiding elements while keeping reduced friction. Another is of course to have reduced armature inertia.
Considering this, MMT has developed a fully symmetric structure as described in Figure 5.

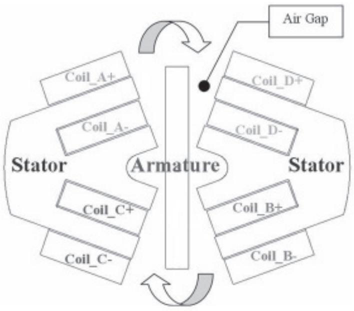


Fig. 5: *Rotary solenoid structure*

This actuator is made of two electric phases each having one coil placed on each of two separate stators.

A ferromagnetic armature is symmetrically rotating between the stators with its extremities contacting opposite sides of each stator at the end of the stroke.

The actuator operating mode is similar to the linear solenoid structure presented before.

Linear polarized actuator structure

Some applications require the moving mass to be held in the end position without a residual current.

This can not be achieved with the structure described in Figure 2 and requires the use of permanent magnets, usually located in the stator circuit. In that scope, various structures are known (see for example [6, 7]).

MMT has therefore developed a structure based on optimized used of permanent magnets and offering a simple stator construction, as described here below:

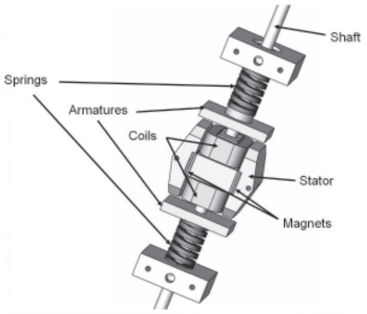


Fig. 6: *Polarized linear actuator structure*

This structure is made of two linked moving armatures activated on both sides of a stator circuit integrating permanent magnets and coils.

Using the attracting force of the magnets, one of the armatures can be held at the end position against springs force without current so that there is no need for an oscillating starting sequence. Typically, a negative current is applied to cancel the magnet attracting force so that the armature can be released until the other armature reaches the other end of the stroke with the help of a catching current and is then also held without current also using the attracting force of the same magnets.

Of course, it is possible to adapt upper armature and/or stator shape to have a non-symmetric actuator behavior if required.

Actuators sizing

As previously mentioned the main challenge in the sizing of such actuators is to find trade-off between antagonistic parameters like increase of spring stiffness that reduces the travel time on the one hand and the related increase of springs apparent mass as well as of the force – and therefore the actuator moving mass - required to displace the load against these springs that will tend to increase the travel time, on the other hand.

One also has to take into account non linearity of the magnetic circuit since at the end of the stroke it generally operates in the saturated part of the ferromagnetic material's (B-H) curve.

MMT has therefore developed calculation tools using actuator force or torque analytic model [8] connected with experimental feedback allowing to define best dimensions associated to a specific application and following examples will illustrate some specific development results.

Linear actuator for electric valve actuation

Electric actuation of engine valves and suppression of the camshaft to achieve full variability of valve lift and timing is one of the most ambitious solutions to reduce emissions and consumption of combustion engines. Various structures using symmetric solenoids with holding currents have been proposed over the last twenty years ([1],[2]).

Although electric control of the exhaust valve is a critical case because of high pressure forces, control of the intake valve is considered as the most contributing solution and is still a major focus. It also appears that the possibility to have valves fully closed at rest using a locking magnetic force generated by permanent magnets is of high interest (no initialization sequence, optimized power consumption, easy cylinder deactivation, anti-theft function for the vehicle at key-off).

In accordance, MMT developed a prototype according to the following specifications and to the basic principle of Figure 6:

* Stroke : +/- 4.5 mm

* Moving load (valve + other components) : 70 g

* Holding force (springs force deduced) > 100 N over the last 0.2 mm of displacement

* overall dimensions (including armatures & without suspension): 40 x 61 x 50 mm^3
* switching time (7.5 % – 92.5% of the stroke): 2.5 ms
* magnet weight (sintered NdFeB): 25 g
* overall actuator mass (iron + copper + magnet): 440 g
* Power supply: 24V / 20A

Fig. 7: *Electric Valve Actuator sample*

The actuator is made of one phase driven by a full H-bridge. Next figure shows a typical switching sequence. A negative current is applied to cancel magnet force, while at the end of the stroke a positive current is applied to brake the armature that is attracted by the magnet force on the other side.

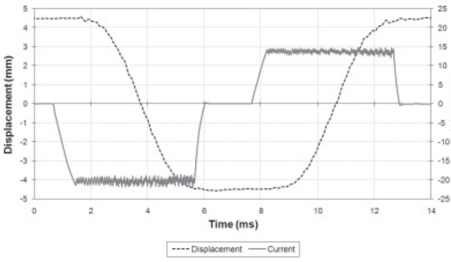
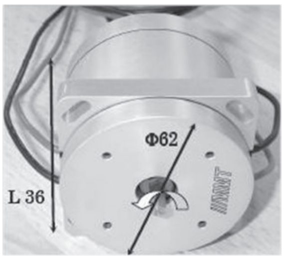


Fig. 8: *Linear actuator typical switching sequence*

Rotary actuator for impulse charging

An other solution to improve combustion engine behavior, and especially engine torque at low speed is to use a fast switching valve generating pressure waves in the intake manifold [9,10].

Next figure shows a sample specifically developed for such application and for a stroke of +/- 20° based on the principle described at Figure 5:



* overall dimensions (including springs): ϕ62 x H 36 mm
* overall actuator mass (iron + copper + magnet): 290 g
* switching time (5 % – 95 % of the stroke): 2.2 ms
* Power supply: 36V / 40A

Fig. 9: *Fast switching flap rotary actuator sample (solenoid type)*

For an optimized integration and life time, classical compression springs are used. Next figure shows typical starting and switching sequences.

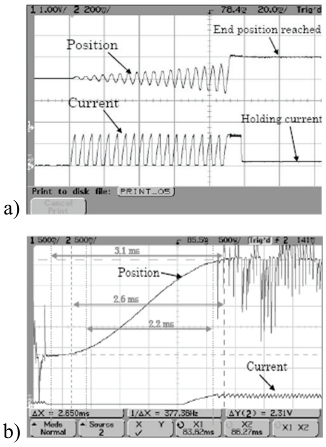
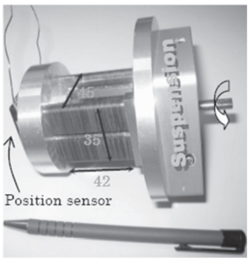


Fig. 10: *Rotary actuator typical initialization (a) and switching (b) sequence*

MMT also recently developed bistable rotary variant using permanent magnets also allowing to hold end stroke positions without current and having similar dynamic response (Figure 11):



* overall dimensions (without suspension): 35 x 45 x 42 mm^3
* magnet weight (sintered NdFeB): 13 g
* overall actuator mass (iron + copper + magnet): 392 g
* Power supply: 24V / 20A

Fig. 11: *Fast switching flap rotary actuator sample (polarized type)*

Conclusion

In this paper, MMT introduced several innovative structures of linear and rotary actuators dedicated to ultrafast actuation. Polarized and non-polarized types were proposed, and prototype results related to demanding automotive applications were demonstrated.

Although these have shown their abilities through intensive testing in realistic operating conditions, their future application in mass production is directly depending on the cost and reliability of a global system and the will of car manufacturers to invest in the development of completely new engine control systems that also require highly efficient and powerful electronic controllers as well as new engine mechanical configuration.

References

[1] MMT, French patent FR 2834119
[2] MMT, French patent FR 2884349
[3] Isuzu, European patent EP 0376716
[4] PSA, French patent FR 2799302
[5] Siemens-VDO, European patent EP 0959479
[6] General Motors, US Patent 4,779,582
[7] Valeo, French Patent FR 2894390,
[8] “High speed electric actuators designs for improved air intake”, Loussert, G. et al, 2007 SAE International Congress
[9] “Development of an actuator for a fast moving flap or impulse charging”, Findeisen H. et al, 2003 SAE International Congress
[10] “Study on impulse charger for enhancement of volumetric efficiency of SI engine”, Takahashi, H. et al, 2006 SAE International Congress