

# Design, control, and comparison of low-energy solenoid valve actuators

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**ABSTRACT BODY:**

**Digest Body:** Introduction

An automotive, fluid-control solenoid valve is composed of an electromagnetic reluctance actuator and a near-constant-force spring. Reluctance actuators are applied as electromagnetic brakes in aerospace applications [1], as valves that perform fast sorting tasks by means of short air-pulses in the manufacturing industry [2], as accurate fluid-control valves in petrochemical processes [3], and in the automotive industry to achieve variable valve timing in camless engines [4]. Common desires are a fast switching and low noise upon impact. Preferably, these objectives are met with minimized energy consumption, especially during constant position operation. In addition, minimizing the impact velocity improves valve lifetime and reduces the audible noise, vibration, and harshness (NVH).

This paper considers cylindrical reluctance actuators due to their low cost. However, this complicates the use of laminations to minimize eddy current effects in a cost-effective manner. Proper analysis, design, and optimization of the reluctance actuator can, therefore, only be performed if these dynamic effects in the actuator are accounted for. This paper will focus on incorporating the eddy current effect in the models and their effect on performance, as well as control methods to improve the performance and minimize energy consumption. The performance of a classical reluctance actuator (Fig. 1a) is compared to a PM-biased topology (Fig. 1b) which reduces the energy consumption. Modeling is performed using transient, axisymmetric, nonlinear finite element (FE) simulations, coupled to Matlab-Simulink.

Actuator topology and constraints

Two single-coil reluctance actuators are shown in Fig. 1. One is a classical reluctance actuator with a stationary coil and a moving plunger (CLA). A second actuator includes a permanent magnet atop the core (PMB) to allow zero-power latching by means of a passive attraction force [1],[3],[5]. In addition, the actuator height and diameter are 16 and 13 mm, with a stroke of 0.25 mm. Moreover, the plunger of mass 1.2 g experiences an opposing force of 4 to 12N. Finally, the closed-to-open transition can last maximally 4 ms, with a typical valve-open time of several seconds.

Open-loop simulation results

In an open-loop co-simulation between Simulink and FE software, predefined voltage profiles are applied to the actuators, while the current is limited. In Fig. 2a, the electromagnetic force develops 0.075 ms slower in cases with eddy currents, and the final position is reached 0.115 ms later. This indicates the inherent eddy current damping in the device, slowing down the plunger. In addition, once the movement commences and the airgap closes, the developed electromagnetic force increases rapidly while the opposing force decreases, resulting in a quickly moving plunger. As a result of applying the voltage profiles in Fig. 2b, the corresponding coil currents develop. Note that equal voltages are applied to CLA and PMB until 1.15 ms, after which CLA requires a small hold voltage (1V) to hold the valve open (latch), whereas PMB achieves this passively. Therefore, the hold power can be reduced to zero using PMB. Fig. 2c shows the (in)ability of the actuators to passively latch the valve. The plunger in CLA retracts quickly after (<0.2ms) the supply voltage is removed, as the developed electromagnetic force drops below the opposing force. On the other hand, PMB latches indefinitely, under equal operating conditions, because of the passive attraction force provided by the PM.

In general, the predefined voltage profiles produce unnecessarily high forces, indicating that additional control can greatly improve the energy efficiency. Moreover, a significant energy consumption reduction can be achieved by

latching passively, and, therefore, reducing to zero the coil current and the hold power using PMB. In addition, plunger closed-to-open movement takes under 0.3ms without achieving a soft landing, while 4ms is allowed. Together, these considerations require to investigate closed-loop feedback control.

#### Conclusions and future work

Analyses on two reluctance actuators have shown that open-loop control using predefined voltage profiles results in high energy consumption and no soft-landing. Furthermore, the eddy current effects further deteriorate the timing performance and increase the losses. To achieve soft-landing and further minimization of energy consumption during movement and holding, the final paper will consider cascaded closed-loop control. Inner and outer feedback loops are considered to control the current and position, respectively. Simulations are performed using a closed-loop co-simulation using Simulink and transient FE software incorporating eddy current effects. These simulations will be performed on both actuator types and analysis will target possible reduction of energy consumption and the ability to achieve soft-landing.

#### Acknowledgments

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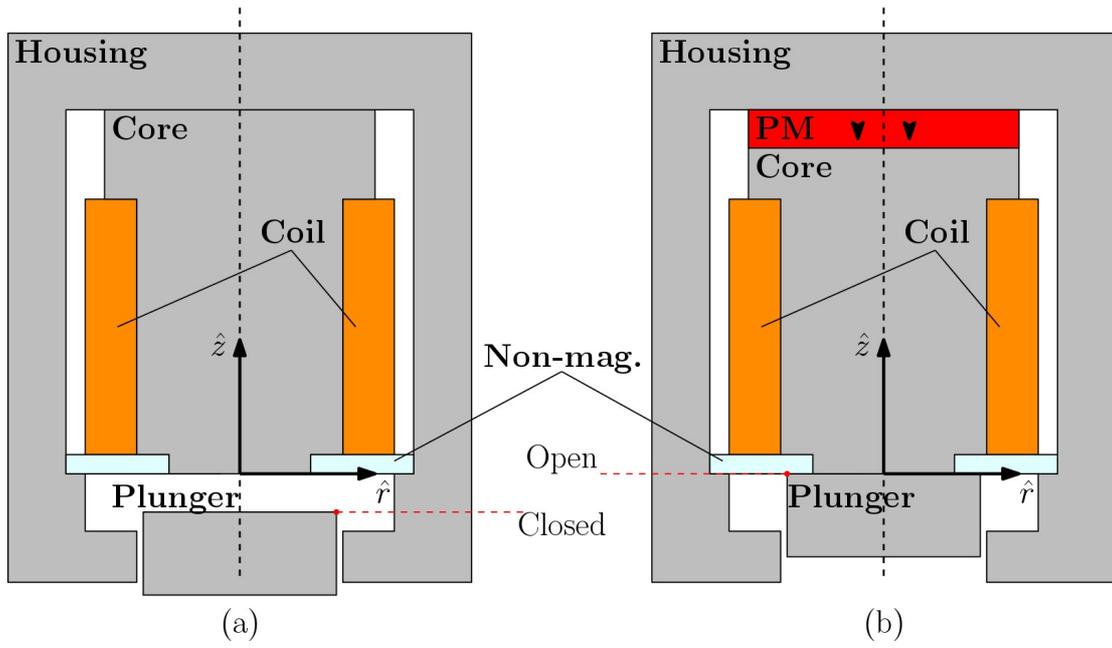
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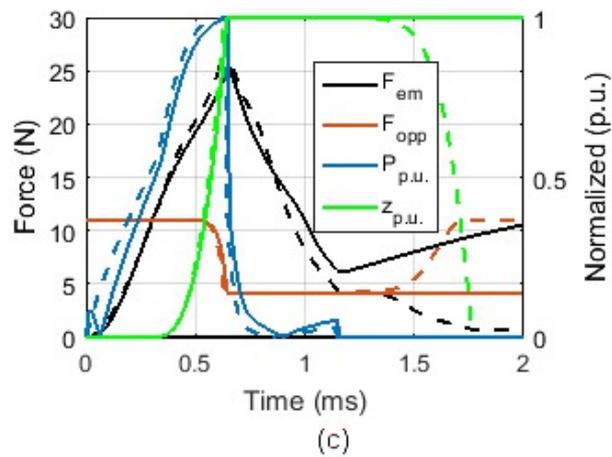
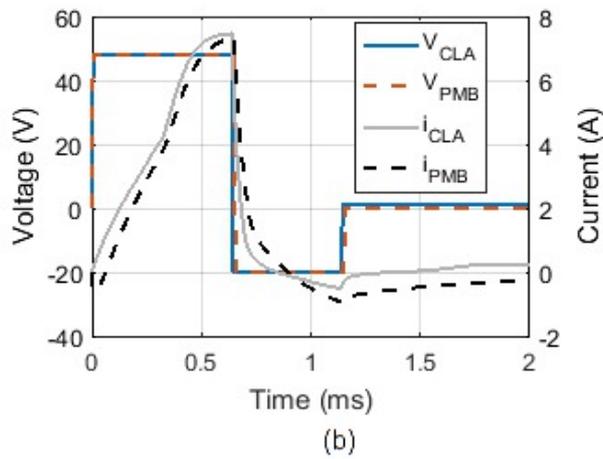
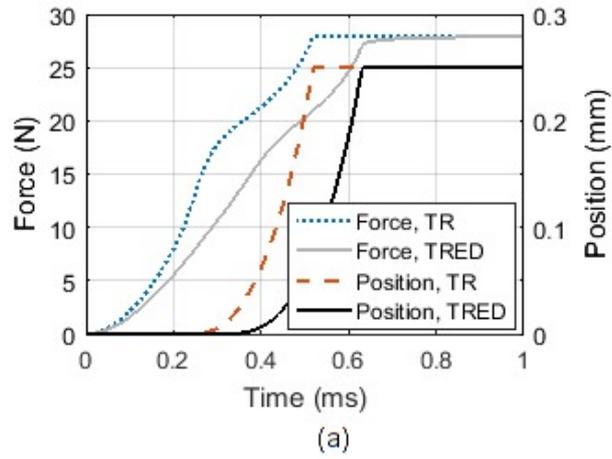
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**KEYWORDS:** Actuators, Control, Design, Eddy current.



(a) Classical reluctance actuator (CLA), and (b) permanent magnet-biased reluctance actuator (PMB).



Open-loop transient simulation results for predefined voltage profiles and equal maximal current to achieve closed-to-open plunger movement, with (a) force levels and plunger positions without (TR) and with (TRED) eddy currents for CLA, (b) predefined voltages and resulting current levels in TRED, and (c) electromagnetic and opposing force (left axis), input power and plunger position (right axis) in TRED, for CLA (- -) and PMB (---).

**IMAGE CAPTION:** (a) Classical reluctance actuator (CLA), and (b) permanent magnet-biased reluctance actuator (PMB). Open-loop transient simulation results for predefined voltage profiles and equal maximal current to achieve closed-to-open plunger movement, with (a) force levels and plunger positions without (TR) and with (TRED) eddy currents for CLA, (b) predefined voltages and resulting current levels in TRED, and (c) electromagnetic and opposing force (left axis), input power and plunger position (right axis) in TRED, for CLA (- -) and PMB (---).

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