

Design concept development of a variable magnetization motor with improved efficiency and controllable stiffness for robotic applications

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A variable magnetization (VM) motor by incorporating magnets that can be flexibly configured with variable magnetization process is proposed to meet the emerging requirements on motor efficiency and actuator compliance in robotic applications. A generalized spin torque model is established which provides a relationship between the motor torque and two different types of motor inputs, the current inputs and the magnet magnetizations. A variable magnetization process is proposed based on the study of the hysteresis properties of the magnetic materials and the design criteria for implementing the variable magnetization process with current pulses are established. The feasibility of the variable magnetization is validated with experimental data and the motor functions and performances are numerically demonstrated and evaluated. The results show that the VM motor can maintain high efficiency by switching between two actuation modes. Controllable stiffness at different equilibria can be also achieved with the VM motor with instantaneous magnetizing current pulses.

compliant actuators, direct-drive motors, variable stiffness motors, variable magnetization motors

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1 Introduction

Actuators are key enabling components for robots. Although the applications of robots are no longer limited in industrial workcells and robots have been endowed with unprecedented mobility, maneuverability and capability to interact with human/environment [1,2], the actuator systems in robots still borrow ideas from industrial machines where conventional electric motors and gears are the most common configurations. The conventional actuator systems have hindered the development of robots with capabilities comparable to humans in two major aspects: (1) Lack of compliance. Conventional motors are usually featured with high stiffness in order to maintain high position accuracy in pre-

sentence of disturbances. However, recent applications such as assistive [3] and rehabilitative [4] robots require certain compliance of the actuator systems when interacting with human/environment in order to ensure safe and friendly operations. (2) Low efficiency. Conventional electric motors such as DC or PM motors can provide high efficiency at high speed but have extremely low efficiency at low-speed or static state (with loading). In robotic applications, a large portion of manipulations perform at low-speed, which leads to motor operations in low-efficiency zone. Therefore, in order to fully explore the capability of intelligent robots, it is essential to design and develop motors with adjustable compliance and improved efficiency (in a wider motion range).

Existing solutions to achieve compliance in actuators is to implement force/impedance control based on the feedback

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from expensive force/torque sensors in robots. This usually leads to high cost systems which also suffer from instability issues because of the low bandwidth as well as the noises of the force/torque sensors [5]. To solve this problem, new actuators such as serial elastic actuators (SEAs) and variable stiffness actuators (VSA) [6–8] have been extensively studied to provide intrinsic compliance in actuators. These actuators usually consist of motors and compliant components/mechanisms in series to achieve spring-like behavior of the end-effectors. In order to adapt to sophisticated control objectives, these actuators usually consists of complicated structures and usually more than one motor in order to adjust the equilibrium as well as stiffness in a joint.

On the other hand, gearboxes are commonly used in robotic applications as a solution to work-around the low efficiency at low speed. By changing the ratio of speed from motor shaft to end-effector, gearboxes allow the motor to operate at a higher speed with higher efficiency. However, gearboxes can result in issues such as backlash, large weight/inertia and non-backdriveability [9]. Also, the gearboxes restrict the bandwidth and performance of force/impedance control in robotic joints.

One of the major reason for the low efficiency of electric motors is that current inputs must be constantly supplied to the electro-magnets (EMs) in order to provide motor torque even at static state. Recently, there are proposed approaches which use permanent magnets (where the magnetization can be changed with pulse currents) to generate passive and active torque. In ref. [10], “Electropermanent magnet” (EPM) was proposed which can be switched on and off with pulse currents to function as a programmable module [11] and a valve in a soft robot [12]. In ref. [13], a “programmable permanent magnet” (PPM) actuator was proposed where the magnetizations of permanent magnets (PMs) can be continuously adjusted via pulses of current in a solenoid to provide torque when the rotor spins. The test results showed that the proposed motor (with relative low speed limit) can provide high efficiency motion for low-speed high-torque applications. As the magnetic forces between magnets do not consuming electrical energy and are featured with spring-like repulsions/attractions, it is a promising solution to achieve compliance and improve efficiency in motors. In this paper, a variable magnetization (VM) motor combining both electromagnetic actuation and permanent magnet force actuation with additional layer of VM magnets (the magnetizations can be reconfigured to any values in real-time with magnetizing current pulses) is proposed. With derivations of precise torque models for two different actuation modes, the proposed motor can provide controllable equilibrium and stiffness and maintain high-efficiency in both low and high speeds, which are expected to contribute in various applications such as robotic graspers, legged robots and assistive exoskeletons.

2 Design concept of a VM motor

Figure 1 illustrates the conceptual design of a variable magnetization (VM) motor. As shown in Figure 1(a), the proposed VM motor consists of a stator and a rotor. The rotor is embedded with PMs located circumferentially at radius r_p with alternating magnetizations (see Figure 1(b)); and the stator consists of two layers which include a layer of electromagnets (EMs at radius r_E) and a layer of VM magnets at r_V . While the EMs can apply Lorentz forces on the rotor PMs to provide spin torque when supplied with currents (same as conventional PM motors), the VM magnets composed of magnetic cores (made of hard magnetic material) wrapped with magnetizing coils (see Figure 1(a)) can be magnetized to any magnetization strength by applying appropriate magnetizing current pulses in the magnetizing coils. Unlike the EMs, once the magnetic cores of the VM magnets are magnetized (usually within nano-seconds), there will be remanence (similar to PMs) which can provide torque on the rotor PMs without consuming any electrical power. As will be illustrated later, the VM magnets in the stator can be reconfigured in real-time during the rotor spinning to generate torque (in addition to the electromagnetic torque generated between the EMs and the PMs) to adjust the compliance and to improve motor efficiency at low speed or static state. The key models for designing the VM motor are presented in the following subsections.

2.1 Spin torque models

Figure 1(b) illustrates the coordinate systems where XY and xy represent the stator and rotor frames respectively; the angular displacement of the rotor is defined by θ ; $\mathbf{r}_i$ represents the unit vector of i th PM position in xy frame with ϕ_i denoting the position angle; $\mathbf{s}_j$ and $\mathbf{t}_l$ represent the unit vec-

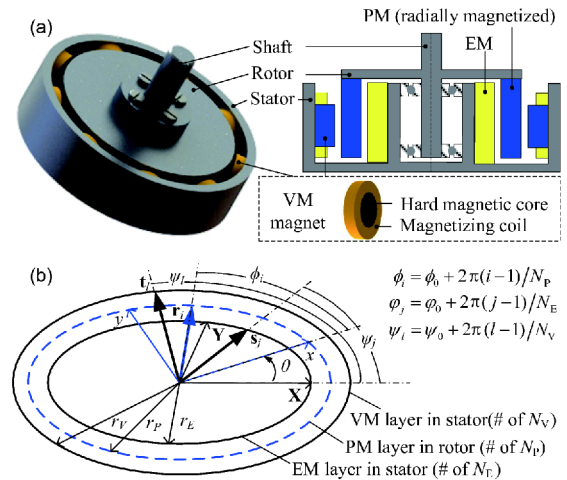


Figure 1 (Color online) Illustration of VM motor. (a) CAD model and illustrative schematic (the rotor PMs are radially magnetized with alternating magnetizations); (b) coordinate systems and pole configurations.

tors of the positions of the j th EM and l th VM magnet in XY frame with φ_j and ψ_l denoting their position angles. The total spin torque applied on the rotor can be computed as a superimpose of the interactions applied on the rotor PMs by the EMs and VM magnets in the stator respectively, which has the form:

$$\tau = \mathbf{a}^T \mathbf{p}, \quad (1a)$$

$$\mathbf{a} = [k_1 \dots k_j \dots k_{NE} \ p_1 \dots p_l \dots p_{NV}]^T, \quad (1b)$$

$$\mathbf{p} = [u_1 \dots u_j \dots u_{NE} \ \lambda_1 \dots \lambda_l \dots \lambda_{NV}]^T, \quad (1c)$$

where k_j and u_j are the torque coefficient and current input of the j th EM (EM _{j}); p_l and λ_l are the torque coefficient and the normalized magnetization strength (with respect to the vacuum permeability $1/\mu_0$) of the l th VM magnets (VM _{l}); k_j and p_l can be computed using eq. (2a) and (2b) in terms of the PM-EM and PM-VM separation angles as expressed in eq. (2c) and (2d):

$$k_j = \sum_{i=1}^{N_p} f(\sigma_{i,j}), \quad (2a)$$

$$p_l = \sum_{i=1}^{N_p} g(\gamma_{i,l}), \quad (2b)$$

$$\sigma_{i,j} = \theta + \phi_i - \varphi_j, \quad (2c)$$

$$\gamma_{i,l} = \theta + \phi_i - \psi_l, \quad (2d)$$

where f is a kernel function describing the variation of flux linkage [5] in an EM-PM pair of the motor with respect to the separation angle $\sigma_{i,j}$ (between EM _{j} and PM _{i}). The kernel function can be computed with eq. (a1) in the Appendix. g is a kernel function describing the normalized magnetic torque (with respect to the VM magnetization λ) in an PM-VM pair as a function of the separation angle $\gamma_{i,l}$ (between PM _{i} and VM _{l}), which can be computed with eq. (a4) in the Appendix.

Based on eq. (1), an optimal input $\mathbf{p}$ minimizing the total input energy for a desired torque τ_d can be determined in the form of pseudo inverse using

$$\mathbf{p} = \mathbf{k}^T (\mathbf{k} \mathbf{k}^T)^{-1} \tau_d. \quad (3)$$

Eqs. (1) and (3) are referred to here as the forward and inverse torque models of the VM motor. When a desired input is determined using eq. (3), while the desired currents in the EMs can be supplied with electrical current amplifiers, it is essential to continuously set the VM magnets to the desired magnetization values utilizing the variable magnetization process introduced in the following subsection.

2.2 Variable magnetization analysis and design

For the magnetic cores in the VM magnets, the relationship between the magnetization M and the applied external magnetic field strength H is governed by a dynamic process which can be expressed with the Jiles-Atherton (J-A) model

as eq. (4a) based on the domain wall motion [14]:

$$\frac{dM}{dH} = \frac{1}{1+c} \frac{1}{k\delta - \alpha(M_{an} - M)} (M_{an} - M) + \frac{c}{1+c} \frac{dM_{an}}{dH}, \quad (4a)$$

where

$$M_{an} = M_s [\coth(H_c/a) - H_c/a], \quad (4b)$$

and

$$H_c = H + \alpha M, \quad (4c)$$

where δ takes the value +1 for $dH/dt > 0$ and -1 for $dH/dt < 0$; c is a coefficient representing the reversible motion of domain wall; a is the shape parameter determining the distribution of the magnetic domains; α is a mean field parameter representing inter-domain coupling; k determines the hysteresis loss [15]; M_s is the saturation magnetization.

A typical hysteresis loop which can be calculated using eq. (4a) is presented in Figure 2 where the key parameters are introduced in the figure. The M - H relationship is history dependent and the change of M - H state from one point to another follows the directions denoted by the arrows in the hysteresis loop as shown in Figure 2. As an illustration, the process for magnetizing a VM magnet at three different magnetization values as denoted by c_1 , c_2 and c_3 on the y -axis of the hysteresis loop is described as follows.

(1) At initial state O , the magnetic core is not magnetized. When the applied external field H increases, the M - H state will change following the initial magnetization curve (IMC) until the saturation point $s_+(+M_m, +H_m)$ is reached. When the external field H vanishes, the M - H state will follow the major loop curve $C1$ and a remanence M_r will remain in the VM magnet (like a PM) at $H = 0$. Then, if H starts to increase in the opposite direction, the M - H state will change following $C1$ until a_1 . At this point, if H decreases to zero, the state will follow the recoil line (with slope being recoil permeability μ_{re}) and stop at c_1 which leads to a remanence at c_1 in the magnet. The whole process can be achieved in nano-seconds in the material.

(2) To get to c_2 from c_1 , the magnet will be first magnetized to the saturation point s_+ and the same process can be repeated to get to c_2 (following the curve $s_+a_2c_2$).

(3) If magnetization with opposite sign is desired (such as c_3), $-H_m$ will be applied first to reach the saturation point s_- in the third quadrant (symmetric to s_+) and the similar process can be repeated to lead the M - H state to get to c_3 following the curve $s_-a_3c_3$.

The applied magnetic field H is supplied by the magnetizing coil wrapped around the magnetic core (see Figure 1). The current pulses for magnetization is characterized with a charge-discharge process realized with a circuit as shown in Figure 3. The magnetic field strength can be approximately computed by

$$H = \frac{N i_d}{\sqrt{l^2 + d^2}}, \quad (5)$$

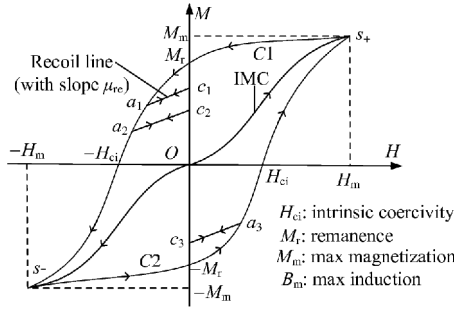


Figure 2 Typical material hysteresis loop and illustration of variable magnetization process.

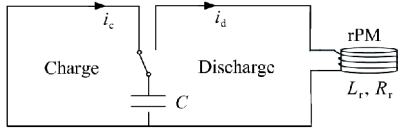


Figure 3 Schematic of magnetizing circuit.

where N is the number of turns of the magnetizing coil and i_d is the magnitude of the pulse current generated in the discharge phase; l and d are the thickness and diameter of the coil. The charging phase can be characterized with a constant-current process and the charge time can be derived as

$$t_c = CU / i_c, \quad (6)$$

where C is the capacitance, U_c is the desired charge voltage and i_c is the charging current. Referring to Figure 3, the discharge phase can be characterized with a state-space representation eq. (7a) with initial condition given in eq. (7c):

$$\dot{\mathbf{x}} = \begin{bmatrix} -R_r / L_r & -1 / L_r \\ 1 / C & 0 \end{bmatrix} \mathbf{x}, \quad (7a)$$

$$\mathbf{x} = [i_d, u_d], \quad (7b)$$

$$\mathbf{x}(0) = [0, U_c], \quad (7c)$$

where i_d is the current in the circuit at the discharge phase and u_d is the voltage across the capacitor. For a desired magnetization as illustrated in Figure 2, the applied field can be determined from the hysteresis loop in Figure 3 and the magnitude of the pulse current (i_d) to be applied in the magnetizing coil can be computed using eq. (5), which can be supplied with the magnetizing circuit by adjusting the charge voltage U_c .

2.3 Motor efficiency

In order to evaluate the performance of the proposed VM motor, the motor efficiency is formulated for PM-VM and PM-EM driving mode. The latter also provides a basis for comparing the efficiency of the VM motor with that of conventional PM motors.

Efficiency of PM-VM actuation

When the motor is driven by the torque contributed by the interactions between PM layer and the VM layer, the motor efficiency can be computed as

$$\eta = \frac{2\pi\tau}{N_{\text{pulse}}E_{\text{pulse}}}, \quad (8a)$$

$$E_{\text{pulse}} = \frac{1}{2}CU_c^2, \quad (8b)$$

where N_{pulse} is the number of magnetizing pulses needed for a single rotation; E_{pulse} is the energy for generating each pulse. As the VM magnets are not constantly energized during the rotation, eq. (8b) provides an average efficiency per rotation.

Efficiency of PM-EM actuation

When the motor is driven by the torque contributed by the interactions between PM layer and the EM layer, the voltage across EM_j can be expressed as [16,17]

$$V_j = R_j u_j + L_j \dot{u}_j + k_f \omega, \quad (9)$$

where R_j , L_j are the resistance and self-inductance of EM_j . The efficiency when the EMs are energized can be computed as eq. (10) with ω denoting the motor speed:

$$\eta = \frac{\tau\omega}{\sum_{j=1}^{N_E} V_j \cdot u_j}. \quad (10)$$

When both EM layer and VM layer are energized to provide the spin torque, the efficiency can be computed as eq. (11) based on eq. (8b) and

$$\eta = \frac{\tau\omega}{\sum_{j=1}^{N_E} V_j \cdot u_j + \frac{\omega}{2\pi} N_{\text{pulse}} E_{\text{pulse}}}. \quad (11)$$

3 Results and discussion

In this section, numerical and experimental results are presented to illustrate and validate the design concept of the VM motor for high-efficiency actuation and to demonstrate the VM motor functions. The numerical simulations are based on the CAD model as shown in Figure 1 where the design parameters are schematically illustrated in Figure 4. The motor consists of 16 PMs, 12 EMs and 9 VM magnets circumferentially spaced in three layers at $r_p = 46.5$ mm, $r_E = 40$ mm and $r_v = 56$ mm respectively. The wedge-shaped PMs are radially magnetized (N52 grade) and have alternating magnetizations. The EMs have air cores and the VMs have magnetic cores. For comparison, three different magnetic materials are considered for the VM magnet cores and the material properties are listed in Table 1.

3.1 VM hysteresis and recoil tests

Based on the J-A model (4), the hysteresis loops were simulated using the parameters for three different kinds of VM

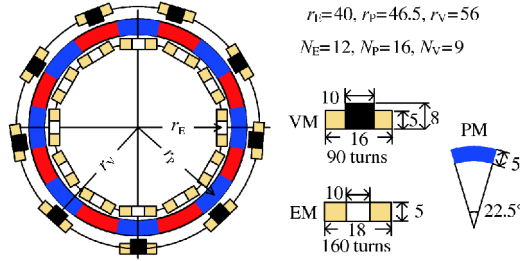


Figure 4 (Color online) Schematic of VM motor parameters (dimensions are in mm otherwise denoted).

Table 1 Magnetic core properties of the VM

Mag. core	NdFeB(N35)	SmCo#1 ¹⁾	SmCo#2 [13]
H_{cj} (A/m)	1.01×10^6	1.009×10^6	0.395×10^6
B_r (T)	1.2	1.05	0.723
M_r (A/m)	9.549×10^5	8.356×10^5	5.754×10^5
$(BH)_{max}$ (J/m ³)	0.286	0.199	0.073
J-A model parameters			
H_{max} (A/m)	5.1×10^6	5.0×10^6	2.0×10^6
M_{max} (A/m)	9.892×10^5	8.414×10^5	7.035×10^5
M_s (A/m)	1.03×10^6	0.88×10^6	0.87×10^6
a (A/m)	0.095×10^6	0.08×10^6	0.39×10^6
α	1.125	1.27	1.45
c	0.001	0.1	0.3
k (A/m)	1.47×10^6	1.48×10^6	0.4×10^6
μ_{re} (dM/dH)	0.0233	0.0205	0.33
μ_{re} (dB/dH)	1.0233	1.0205	1.33
Magnetizing circuit parameters ($L_r=97 \mu\text{H}$, $R_r=0.78 \Omega$)			
C (μF)	21	20	2.4
i_{dmax} (A)	763	748	299
U_{cmax} (V)	2119	2116	2086
Charge time t_c (ms)	17.8	16.9	2.0
Discharge current peak time t_p (ms)	0.07	0.069	0.023

magnetic cores listed in Table 1 and the simulation results are shown in Figure 5(a). As the variable magnetization process (Figure 2) primarily depends on the demagnetization curves (the second quadrant section of the hysteresis loop), the simulation results of the demagnetization curves are compared with experimental results¹⁾ for three magnetic cores in Figure 5(b) to (c) respectively, which show good agreements and provide a good basis for the design and analysis of the variable magnetization process.

Based on the illustration of variable magnetization process and the simulation results, the relationship between the magnetizing field H and the desired magnetization M can be obtained which leads to a variable magnetization curve as

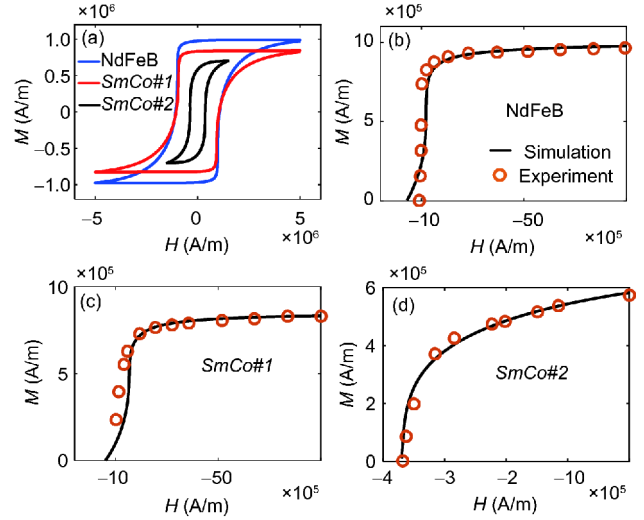


Figure 5 (Color online) Hysteresis loops (a) and demagnetization curves of different materials for VM cores; (b) NdFeB; (c) SmCo #1; (d) SmCo #2.

shown in Figure 6(a). As can be seen in the figure, for a desired magnetization value, the magnitude of the magnetizing current pulse can be determined which can be realized by setting the charge voltage U_c in the magnetizing circuit as illustrated in Figure 3. Table 1 lists the parameters for characterizing magnetizing current pulses in the variable magnetization process. It can be seen that due to the difference in the intrinsic coercivities of the magnetic cores, the magnetizing energy (maximum current and voltage) as well as the magnetizing duration (summation of t_c and t_p) are different. Based on the analysis, SmCo#2 in Table 1 is selected for the following simulations.

As an illustration, the variable magnetization process for the magnetic core (SmCo#2) is simulated and the results are presented in Figure 6(b)–(d). As shown in Figure 6(b), the magnetic core was first magnetized to the saturation point s_+ following the initial magnetization curve (IMC) where the magnitude of the current pulse was determined using the curve in Figure 6(a). The responses of the voltage and current of the capacitor for both charge and discharge phases are plotted in Figure 6(c) with t_p and t_c representing the charge time and the peak time of the discharge current. The simulated responses of from s_+ to a are shown in Figure 6(d) and the magnetization will get the desired point c (0.5 T or 400 kA/m) following the recoil line when the magnetizing current and the external magnetic field decay to zero.

3.2 Effects of VM process on the PMs and EMs

In order to validate the VM motor design, the effects of the VM process on the PMs and EMs were simulated using FE analysis software (Comsol) based on CAD model in Figure 1

1) "Dura magnetics website." Available online: <http://www.duramag.com>.

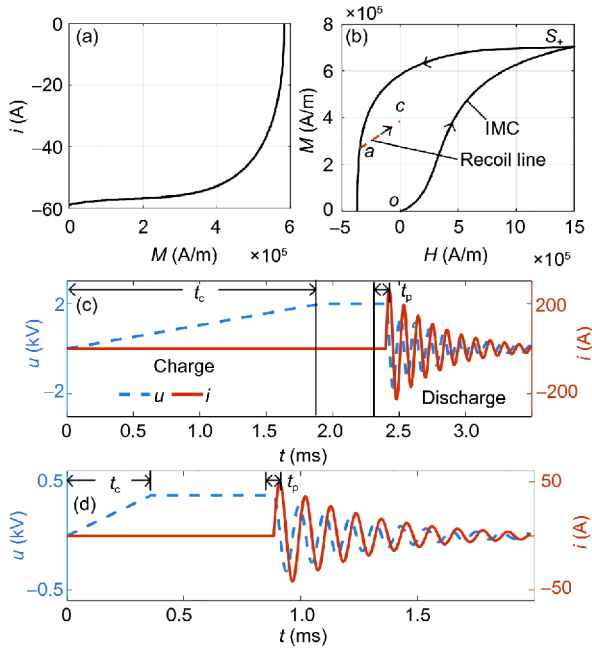


Figure 6 (Color online) Illustration of magnetizing field and current pulses. (a) M vs i_d ; (b) demagnetization curve; (c) current pulses to $s+$; (d) current pulses to a .

and the parameters in Figure 4. The simulation results are presented in Figure 7 which are discussed in the following subsections. Due to symmetry, only one sector of the VM motor including 3 PMs, 1 EM and 1 VM are shown in Figure 7.

Effects on the PM

Figure 7(a) and (b) shows the magnetizations of the PMs and the VM when the VM are magnetized at $M=6 \times 10^5$ A/m and $M=-6 \times 10^5$ A/m respectively. As the intrinsic coercivity of the PM (NdFeB) is much larger than that of the VM (SmCo, see Figure 5(a) for comparison), the magnetization of the VM has negligible effects on the PM. This can be also validated with the results in Figure 7(c) where the time variations of the magnetizations at the centers of the PM and VM are plotted.

Effects on the EM

Figure 7(d) presents the magnetic flux density distributions when the magnetizing current is at the peak value. It can be seen that most of the magnetic flux generated by the VM during the magnetization process is coupled with the PMs. To have a quantitative evaluation, the induced current in the EM was simulated during the magnetizing process of the VM and the result is plotted in Figure 7(e) as a function of time. Although the induced current is much smaller than the magnetizing current pulse (with a magnitude of 300 A as shown in Figure 6(c)), the induced current will still lead to disturbance torque on the motor. To solve this problem, two methods are proposed for control:

(1) As the duration of the magnetizing current pulse is very small (less than 0.1 ms), the EMs can be cut off in the control

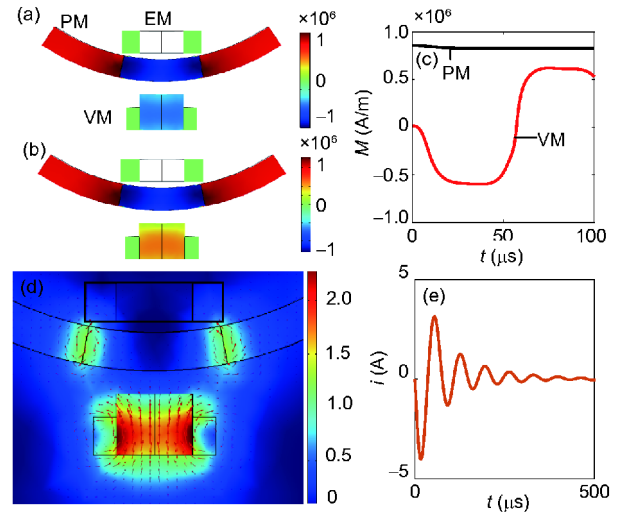


Figure 7 (Color online) Effects of VM process on the PMs and EMs. The PM magnetizations when the VM are magnetized at (a) $M=6 \times 10^5$ A/m and (b) $M=-6 \times 10^5$ A/m; (c) the magnetization variations at the centres of the PM and the VM when the VM are magnetized in opposite directions; (d) magnetic flux densities at the peak value of the magnetizing current pulse as shown in Figure 6(c); (e) induced current in the EM.

circuit and resumed in actuation after the magnetization of the VMs.

(2) As the oscillation frequency of induced current in the EM is around 10 kHz, which is much larger than the frequency of the actuation current (less than 1 kHz), a low pass filter can be added in the EM driver circuit in order to eliminate the effects of the VM process on the EM actuation.

3.3 VM motor demonstrative simulations

Based on the proposed motor torque model and the analysis of the variable magnetization process, the concept feasibility of the proposed VM motor is investigated. Figure 8 shows the kernel functions eq. (2a) and (2b) computed using eqs. (a1) and (a4) in the appendix which provides a basis for computing the forward torque model (1) and the inverse model (3) of the motor. The capability of the proposed VM motor with improved efficiency and compliance were demonstrated with numerical simulations.

Motor efficiency evaluation

As an illustration, the motor inputs (magnetizations of the 9 VM magnets at VM actuation mode or current inputs of the 12 EMs at EM actuation mode) were computed using the inverse model (3) for the VM motor to generate a spin torque $\tau=1$ Nm at different rotor positions. Figure 9(a) and (b) shows the simulated results. Due to periodicity, the results were plotted in the range from 0 to 45°. The motor efficiencies at two actuation modes were computed using eqs. (8a) and (10) where the results are shown in Figure 9(c). To investigate the effects of the magnetizing frequency on the motor performance, the motor efficiencies and the torque

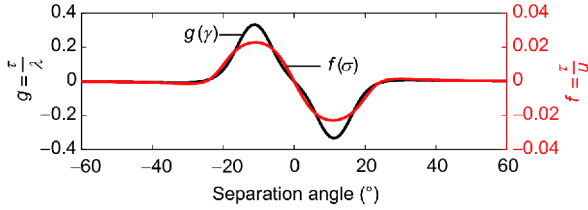


Figure 8 (Color online) Illustration of kernel functions.

ripples were compared in Figure 9(c) and (d) for three cases where the VM magnets were magnetized at different rotor incremental angles ($\Delta\theta = 1^\circ, 3^\circ, 5^\circ$). As a comparison, the efficiency curve of an industrial DC motor [13] is plotted in Figure 9(c).

Some observations can be drawn based on the results.

(1) Due to the periodic placements of the EMs and PMs, the current patterns (Figure 9(b)) are periodic and similar to a three-phase motor at EM actuation mode.

(2) At EM actuation mode, the efficiency is approximately proportional to the motor speed and close to zero at low speed (which is the same case for the industrial motor). At VM actuation mode, the efficiency is constant. Therefore, the motor can maintain at high efficiency by switching between EM mode and VM mode for different motor speeds.

(3) At VM mode, the efficiency is higher when the VM magnets are magnetized less frequently (see Figure 9(c)) but at an expense of larger ripples in the motor spin torque (see Figure 9(d)).

Demonstration of adjustable stiffness and equilibrium

By reconfiguring the VM magnets at different rotor positions, the motor can output a spring-like angle-to-torque relationship. For a desired stiffness at desired equilibrium, the VM magnetizations can be computed using the inverse model (3) by specifying the desired angle-to-torque relationship. Figure 10(a) and (b) demonstrates the relationship between rotor displacement and the motor torque at two different equilibria with different stiffnesses with the color-bars representing the magnetizations of the VM magnets for each configuration. Note that each configuration can be achieved with one magnetization operation. Unlike the compliance achieved through control on conventional motors, once the VM magnets are magnetized as desired, the spring-like feature maintains without the need to supply any electrical energy.

4 Conclusions

A VM motor combining two different actuation modes for improving the motor efficiency at low speed and providing actuator compliance is presented. By analysing the hysteresis properties of the magnetic cores of the VM magnets, the concept of variable magnetization process is proposed and

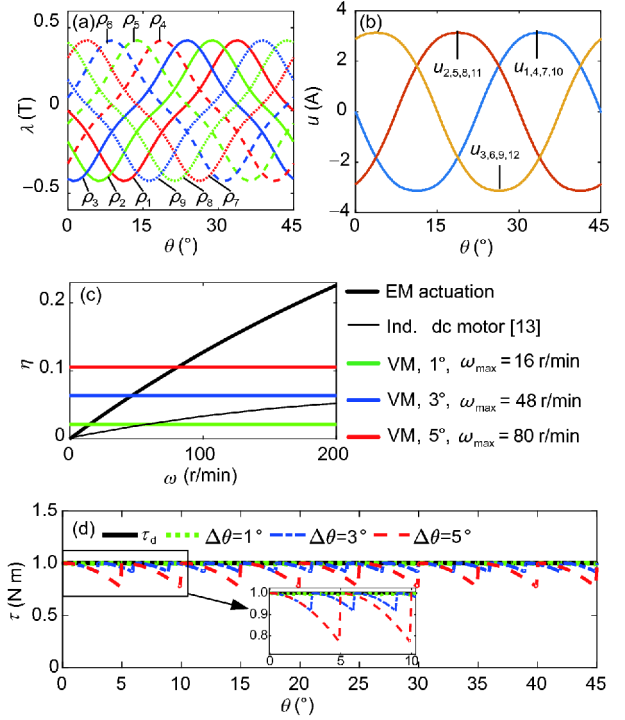


Figure 9 (Color online) Motor performances (a) variable magnetizations at VM actuation mode and (b) current inputs at EM actuation for generating motor torque $\tau = 1$ N m; comparison of (c) motor efficiencies and (d) torque ripples for different configurations.

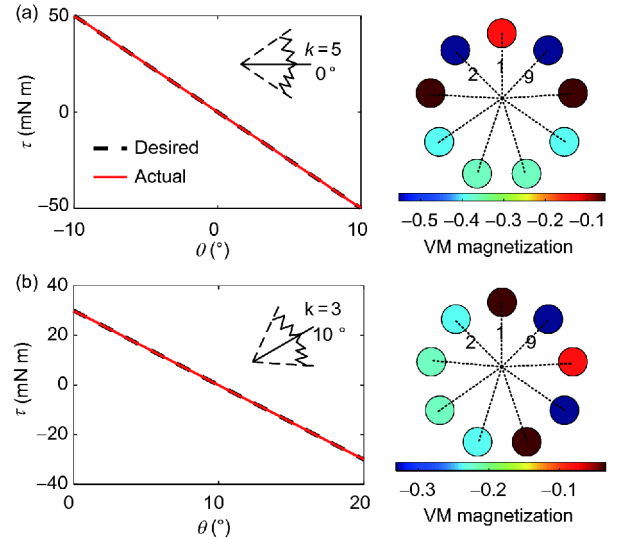


Figure 10 (Color online) Adjustable stiffness and equilibrium of motor at different VM configurations. (a) Equilibrium at 0° , stiffness $k = 5$ N mm/deg; (b) equilibrium at 10° , stiffness $k = 3$ N mm/deg.

the feasibility of the variable magnetization has been validated with experimental data for three different hard magnetic materials. The parameters of the electrical systems for delivering the magnetizing current pulses have also been investigated accordingly. By deriving the spin torque models of the VM motor for two different actuation modes, the speed regulation and motor compliance can be achieved. The re-

sults demonstrate that the proposed VM motor can maintain high efficiency at both low and high speeds and the stiffness and equilibrium can be controlled by manipulating the magnetizations in the VM layer in a passive manner without constantly consuming energy.

Appendix

The total magnetic flux linkage (MFL) through the EM can be obtained as

$$\Lambda = \frac{1}{a} \int_V (\mathbf{A}_p \cdot \mathbf{l}) dV, \quad (\text{a1})$$

where $\mathbf{A}_p$ is the magnetic vector potential of a PM. The magnetic vector potential and the magnetic flux density at point $\mathbf{R}$ can be computed using [18]

$$\mathbf{A}_p = \frac{\mu_0}{4\pi} \int_V \frac{(\nabla \times \mathbf{M})}{|\mathbf{R} - \mathbf{R}'|} dV + \frac{\mu_0}{4\pi} \int_S \frac{(\mathbf{M} \times \mathbf{n})}{|\mathbf{R} - \mathbf{R}'|} dS, \quad (\text{a2})$$

$$\mathbf{B}_{PM} = \frac{\mu_0}{4\pi} \int_V \frac{-(\nabla \cdot \mathbf{M})(\mathbf{R} - \mathbf{R}')}{|\mathbf{R} - \mathbf{R}'|^3} dV + \frac{\mu_0}{4\pi} \int_S \frac{(\mathbf{M} \cdot \mathbf{n})(\mathbf{R} - \mathbf{R}')}{|\mathbf{R} - \mathbf{R}'|^3} dS, \quad (\text{a3})$$

where $\mathbf{R}'$ represent variable point; $\mathbf{M}$ is the magnetization of the PM; $\mathbf{n}$ is the surface normal. The magnetic torque between the PM and the VM magnets can be computed using Maxwell Stress Tensor [18]:

$$\boldsymbol{\tau} = \oint_S (\mathbf{r} \times \mathbf{T}) dS,$$

where

$$\mathbf{T} = \frac{1}{\mu_0} \left(\mathbf{B}(\mathbf{B} \cdot \mathbf{n}) - \frac{1}{2} |\mathbf{B}|^2 \mathbf{n} \right), \quad (\text{a4})$$

where S is an arbitrary boundary enclosing the body of interest; and $\mathbf{n}$ is the normal of the boundary interface; $\mathbf{B}$ is the total magnetic flux density contributed by both the PM and VM magnet on S which can be computed using eq. (a3); $\mathbf{r}$ is the moment arm at the computation point.

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