

Sliding-mode position control of medium-stroke voice coil motor based on system identification observer

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ISSN 1751-8660

Received on 10th December 2014

Revised on 9th June 2015

Accepted on 1st July 2015

doi: 10.1049/iet-epa.2014.0486

www.ietdl.org

Abstract: This study presents the performance improvement in the position control of a medium-stroke voice coil motor (VCM) using a sliding-mode controller (SMC) with a system identification observer (SIO). The proposed VCM is developed with a full stroke of 24 mm, and its non-linear electro-magneto-mechanical characteristics are analysed by the three-dimensional finite element method. A least-squares-based SIO is introduced into the VCM control system prior to the position regulation of the SMC in order to achieve a shorter rise time of 29 ms and a smaller steady-state error of $<\pm 2$ μm under a square-wave excitation of 20 mm amplitude and 0.5 Hz frequency. An experimental verification between the SMC and a traditional proportion–integral–differential controller is carried out. The results demonstrate improved dynamic and static tracking responses in the SMC under load-free, frequency-varying operations.

1 Introduction

The rapid development of high-precision manipulation, manufacturing, and testing equipment and facilities such as those for the semiconductor industry in recent years has put a high demand for direct-drive linear electric machines with full strokes ranging from 1 to 30 mm [1]. Voice coil motors (VCMs), because of their relatively small inertia, fast response, compact size, light weight, and low cost, have received much attention for short-stroke (0.1–1 mm) applications. Examples include high-density data systems [2], direct-drive valve systems [3, 4], auto-focusing mechanisms for digital cameras [5] etc. However, the short-stroke nature of VCMs often limits their widespread use even though they could be integrated with some other longer stroke machines such as linear synchronous permanent-magnet motors (LSPMMs) to increase the resulting strokes at the expense of deteriorating inertia, response, size, weight, and cost [6, 7]. Moreover, the non-linear current-flux linkage-position characteristics of both VCMs and LSPMMs often cause difficulty in establishing precise mathematical models so that advanced control strategies are generally required to achieve desired position control performance [8].

To evaluate the high-frequency response and application of VCMs, a high-frequency direct-drive valve was developed based on a VCM having a full stroke of 1 mm and a non-linear proportion–integral–differential (PID) controller [3]. A high-frequency VCM-based direct-drive servo valve was also realised using a state-space disturbance observer-based hybrid controller [4]. To overcome the problems of dynamically unknown models in VCM control systems, an articulation control system based on an adaptive cerebellar model and a wavelet fuzzy compensator was proposed for VCMs, and maximum tracking errors of 1.562 and 1.418% were achieved under sinusoidal and periodic step commands, respectively [9]. To obtain a favourable chattering-free trajectory tracking performance in VCMs, a cerebellar model-based articulation controller combined with an adaptive dynamic sliding-mode fuzzy compensator was established to demonstrate an accurate trajectory tracking with reduced transient tracking error and chattering [10]. A sliding-mode friction compensator for tiny VCMs with a full stroke of 0.35 mm was demonstrated to have an absolute steady-state error of 4 μm in a compact camera module [11]. A VCM-driven optical image

stabilising system equipped with a fuzzy sliding-mode controller (SMC) was studied to correct the deviation in optical path caused by hand vibrations, and the results showed an improved performance compared with unit-feedback or PID controllers under step position command of 1 mm amplitude [12]. A VCM-actuated three-axis servo gantry system with an internal model-based controller was found to have good tracking performance with a root-mean-square error of about 2 μm under periodic reference signals [13].

Up till now, there does not appear to be any solid works disclosing the design, modelling, and position control of VCMs having a medium full stroke of 1–30 mm. Nonetheless, the following researches on linear oscillatory machines (LOMs) could provide good references for developing medium-stroke VCMs [14]. A small PMLOM and its test sequence were presented [15]. A thrust force optimisation was performed on a flux-switching, yokeless translator-type LOM to exhibit an output force of 56% higher than a traditional linear LSPMM [16]. A non-linear state-space model suitable for describing the transient states of LOMs was established and studied with good agreement with the experimental results [17]. A sensorless closed-loop position control strategy for LOMs was experimentally evaluated to demonstrate a reduced dynamic position error of <0.05 mm [18]. A super-twisting high-order sliding-mode direct torque control scheme for LOMs was inspected and found to have zero steady-state speed chattering with robust control behaviour [19]. The scheme was extended to direct torque and flux control showing a speed chattering-free operation and an excellent robustness [20].

On the side of SMC, a robust non-linear controller based on a second-order sliding-mode technique combined with block-control linearisation and super-twisting algorithm was reported in a doubly fed induction generator [21]. An adaptive discrete-time tracking controller based on block-control and sliding-mode techniques was investigated [22]. An adaptive second-order SMC strategy for maximising the energy production of a wind energy conversion system was reported [23]. The general criterion for designing multi-input–multi-output homogeneous sliding modes for uncertain dynamic systems was examined, and the ultimate asymptotic accuracy was found to be preservative in both multi-input–multi-output and single-input–single-output systems [24].

Comparing with the reported works on VCMs, LOMs, and SMC, we have achieved three aspects of innovation in our current work. First, a medium-stroke VCM with a full stroke of 24 mm is constructed and modelled. Second, finite element method (FEM) is used to analyse the non-linear electro-magneto-mechanical characteristics of the VCM and to study the effect of stroke on non-linearity, especially for that near the edges of PMs. Third, an SMC with a least-squares-based system identification observer (SIO) is proposed to overcome the non-linear electro-magneto-mechanical characteristics of the VCM and to improve both the dynamic and static position control responses. The ultimate goal of the position control is to minimise the rise time and the steady-state error. Hence, an SIO based on least squares is introduced into the VCM control system before position-regulating the SMC.

The organisation of this paper is as follows. The construction and modelling of the medium-stroke VCM are described in Section 2. The investigation based on FEM is presented in Section 3. The parameter identification and SMC design are given in Section 4. The implementation results and conclusions are delivered in Sections 5 and 6, respectively.

2 Construction and modelling of medium-stroke VCM

2.1 Construction

Fig. 1 shows the structure of the proposed medium-stroke VCM. The VCM mainly consists of a stator with PMs and a mover. The base and inner core of the stator are made of aluminium alloy and inner core, respectively. The mover (winding and holder) is restricted to the axial motion between the air gap of the three arched PMs bonded in the base and the inner core. The winding holder is made of plastic. The major specification data are listed in Table 1.

2.2 Modelling

From the electrical side, the voltage balancing equation can be expressed as

$$u_{in} = R \cdot i + L \cdot \frac{di}{dt} + e_{\sigma} \quad (1)$$

where u_{in} , R , i , L , and e_{σ} are the terminal voltage, winding resistance, current, inductance, and inductive electromotive force, respectively. In normal operations, e_{σ} can be written as [25]

$$e_{\sigma} = B(x) \cdot l \cdot v, \quad (2)$$

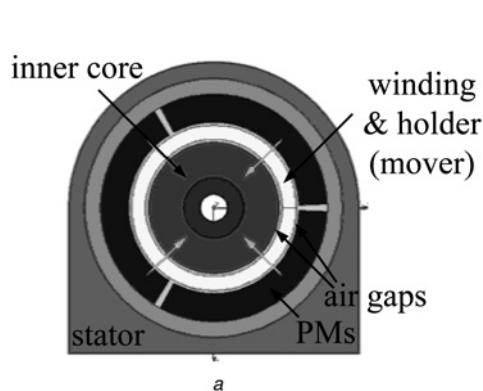


Table 1 Major specification data

Parameter	Value
mass of stator	1 kg
mass of mover	0.2 kg
air gap length	0.2 mm
number of turns	1000
PM type	NdFeB
stator diameter	66.8 mm
stator length	83.94 mm

where $B(x)$, l , and v are the mover displacement-dependent magnet flux density in the air gap, the length of the winding, and the speed of the mover, respectively. As B is a function of x and is not uniform in the whole stroke range, e_{σ} can further be expressed as

$$F(x, t) = K_1 \cdot B(x) \cdot l \cdot i(t), \quad (3)$$

where K_1 is the electromagnetic force coefficient.

From the mechanical side, the equation that governs the dynamic behaviour of machines can be presented as

$$m\ddot{x} + K_v\dot{x} + F_L = F(x, t) = K_f(x) \cdot i(t), \quad (4)$$

$$K_f(x) = K_1 \cdot B(x) \cdot l \cdot i(t), \quad (5)$$

where m is the mass of the mover, K_v is the damping coefficient, and F_L is the load force. The second-order continuous model with the consideration of stochastic noise $\varepsilon(t)$ can be written in discrete-time form as [26]

$$A(z^{-1}) \cdot x(t) = B(z^{-1}) \cdot F(t) + \varepsilon(t), \quad (6)$$

with

$$\begin{cases} A(z^{-1}) = 1 + a_1 \cdot z^{-1} + a_2 \cdot z^{-2}, \\ B(z^{-1}) = b_0 + b_1 \cdot z^{-1}, \end{cases}$$

where a_1 , a_2 and b_0 , b_1 depict the behaviour of the VCM.

3 Investigation based on FEM

To investigate the non-linear electro-magneto-mechanical characteristics of the VCM, a three-dimensional (3D) FEM model is constructed. Using the 3D time-stepping calculation method, the magnetic flux distribution contour at the fully overlapped position from the mover to the stator under a current excitation of 1 A is showed in Fig. 2a. It is clear that magnetic flux lines distribute

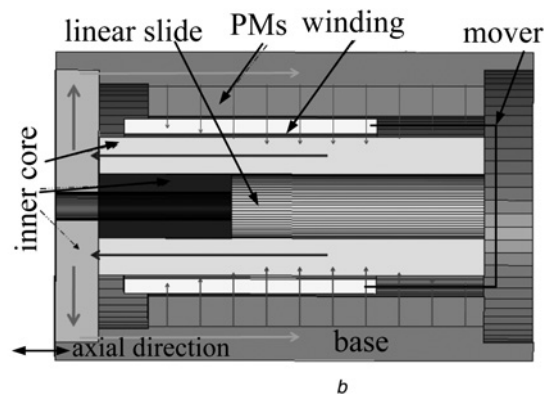


Fig. 1 Structure of the proposed medium-stroke VCM

a Front

b Cross-section views of the medium-stroke VCM

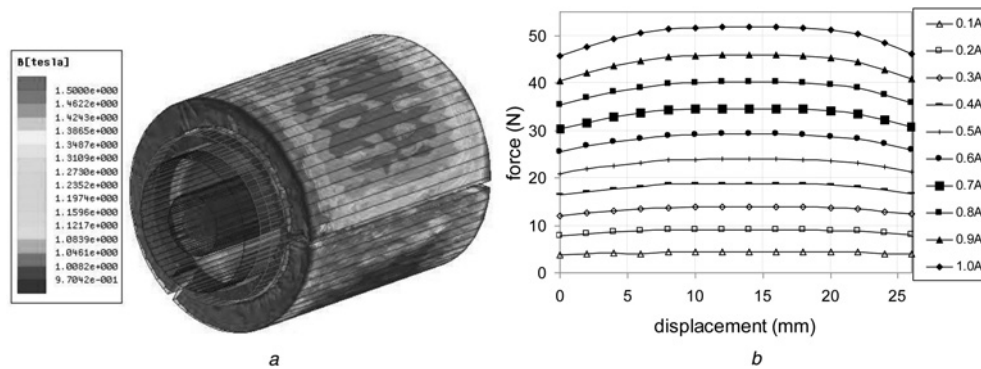


Fig. 2 FEM result of
 a Magnetic flux distribution
 b Force against current at different displacements

unevenly over the entire magnetic path and tend to saturation at the edges of the PMs because of the domination of magnetic flux circulation by end effect.

The propulsion force against displacement at different current levels is plotted in Fig. 2b, where 0 mm stands for the fully overlapped position from the mover to the stator. Non-linear characteristics are observed in the VCM. As the mover enters or leaves the stator base, the end effect becomes more significant at elevated current levels. The occurrence of maximum force at 14 mm for all currents suggests the existence of a linear relationship between the maximum force and the current. Thus, the electromagnetic force coefficient K_1 in (5) can be regarded as a function of displacement x .

4 Parameter identification and SMC design

4.1 Online parameters identification with forgetting factor

For position control applications, (4) gives a physical meaning that the system input and output can be treated as force command F and displacement x , respectively. As denoted in (6), a_1, a_2 and b_0, b_1 are parameters to be estimated. Disturbances may influence the control system in any form. For the N th estimation, the disturbances can be considered as stochastic errors, and the control system can be expressed by least-squares form as [26]

$$X_N = \phi_N \theta + e_N, \quad (7)$$

where $\theta = [a_1, a_2, b_0, b_1]$, $\phi_N = [-X_{N-1}, -X_{N-2}]$, and e are the residuals. ϕ_N includes the position information of the $N-1$ th and $N-2$ th experiments.

For the $N+1$ th experiment, θ can be estimated by the recursive least-squares algorithm as [27]

$$\bar{\theta}_{N+1} = \bar{\theta}_N + G_N [X_{N+1} - (\phi_{N+1})^T \bar{\theta}_N], \quad (8)$$

$$G_{N+1} = \frac{P_N \phi_{N+1}}{\rho + (\phi_{N+1})^T P_N \phi_{N+1}}, \quad (9)$$

$$P_{N+1} = \frac{1}{\rho} [I - G_{N+1} (\phi_{N+1})^T] P_N, \quad (10)$$

where P is the covariance matrix, G is the gain matrix, and ρ is the forgetting factor with 0.99. For initial values, $P = \sigma I$ as $\sigma = 30$ and I is a 4×4 unit matrix. The initial values of the parameters to be estimated from a_1 to b_1 are set to be zero.

The estimation termination criterion for the recursive calculation can be set as follows

$$\left| \frac{\theta_{n+1} - \theta_n}{\theta_n} \right| < e_r. \quad (11)$$

If the maximum proportion of error from the last to the present estimated value is small compared with a positive number e_r , the estimation process will stop.

4.2 Force-to-current conversion

As depicted in Fig. 2b, the force–displacement relationship at different current levels exhibits non-linearity. To precisely derive current command for the current amplifier in the VCM control system, the measured output force in response to the current command is obtained as shown in Fig. 3. The data are stored in the 1D look-up table for the linearisation of current command to output force [28]. The position control block diagram is illustrated in Fig. 4.

4.3 SMC design

For position controller, the relatively simple and effective PID controller can be employed and presented as

$$C(s) = K_p + K_i \cdot \frac{1}{s} + K_d \cdot s, \quad (12)$$

where K_p, K_i , and K_d are the PID gains, respectively.

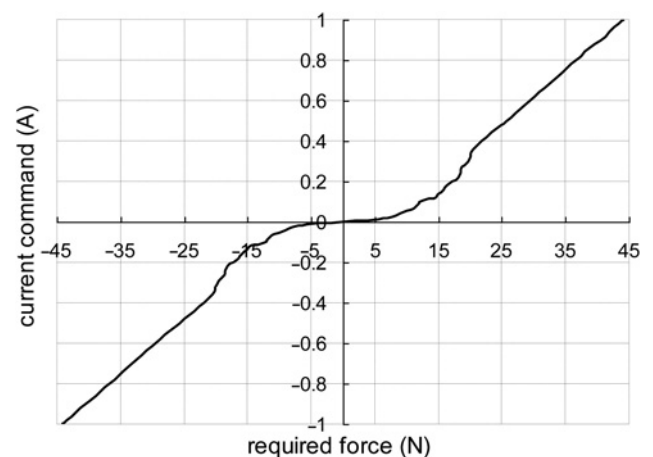


Fig. 3 Relationship of current command to output force

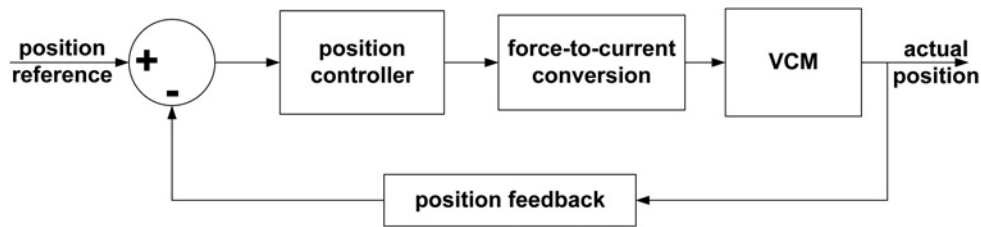


Fig. 4 Position control block diagram

According to the above analysis, the control plant can also be derived as a state-space model as

$$\begin{cases} \dot{x} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \cdot x + \begin{bmatrix} bb_1 \\ bb_2 \end{bmatrix} \cdot u, \\ y = \begin{bmatrix} c_1 & c_2 \end{bmatrix} \cdot x \end{cases} \quad (13)$$

where a_{11} , a_{12} , a_{21} , a_{22} , bb_1 , bb_2 , c_1 , c_2 are the parameters of the VCM control system in state-space form, while $x = \begin{bmatrix} x(1) \\ x(2) \end{bmatrix}$, u , and y are the state variables, system input, and system output, respectively. Then, we have

$$\dot{x}(2) = a_{21} \cdot x(1) + a_{22} \cdot x(2) + bb_2 \cdot u. \quad (14)$$

Assuming the reference command as r , the error and its derivative can be written as [29]

$$E = \begin{bmatrix} e \\ \dot{e} \end{bmatrix} = \begin{bmatrix} r - x(1) \\ \dot{r} - \dot{x}(2) \end{bmatrix}. \quad (15)$$

If we set the gains of errors as $C = [c \ 1]$, the switch function becomes

$$\begin{cases} s = CE \\ \dot{s} = c(\dot{r} - \dot{x}(1)) + \ddot{r} - \dot{x}(2) = \text{slaw} \end{cases} \quad (16)$$

where *slaw* is the trending law. To reduce the trending time and to make the speed approach to the switch sliding surface, the exponential trending law is selected as [30]

$$\dot{s} = -\varepsilon \operatorname{sgn}(s) - ks(\varepsilon > 0, k > 0), \quad (17)$$

where ε denotes the approaching speed to the switch sliding surface and k is the gain that demonstrates local reaching condition to the switch sliding surface. Substituting (14) into (16), the control output can be expressed as

$$u = \frac{1}{bb_2} (c(\dot{r} - \dot{x}(2)) + \ddot{r} - a_{21}x(1) - a_{22}x(2) - \text{slaw}). \quad (18)$$

Stabilisation proof: For the closed-loop system depicted in (17), considering the Lyapunov function and the global stability condition in the following forms

$$\begin{cases} V = \frac{1}{2}s^2(t) \\ \dot{V} = \dot{s}(t) \cdot s(t) < 0 \end{cases} \quad (19)$$

along with the trajectory of the solution for the closed-loop system, we obtain

$$\dot{s} \cdot s = -\varepsilon \cdot s \cdot \operatorname{sgn}(s) - k \cdot s^2 \quad (20)$$

$s \operatorname{sgn}(s) > 0$, $\varepsilon > 0$, and $k > 0$ guarantees that $\dot{s} \cdot s < 0$. This completes the proof. \square

Fig. 5 shows the position control flowchart. As the SIO requires a closed-loop operation of the control system, and since the SMC strategy depends on the SIO information after all the identification parameters are settled, PID position regulation is first implemented. After the configuration of P, I, and D gains from the PID position regulator, the processes of parameter initialisation and sampling of force command and position output start. The control effort output is the force command of the VCM [31]. The force-to-current conversion module calculates the required current command for the current amplifier and then outputs the actual current to the VCM in a closed-loop current regulation manner.

5 Implementation results

5.1 Simulation results

5.1.1 Parameter regulation: The position command is set as a square-wave signal with an amplitude of 20 mm and a frequency

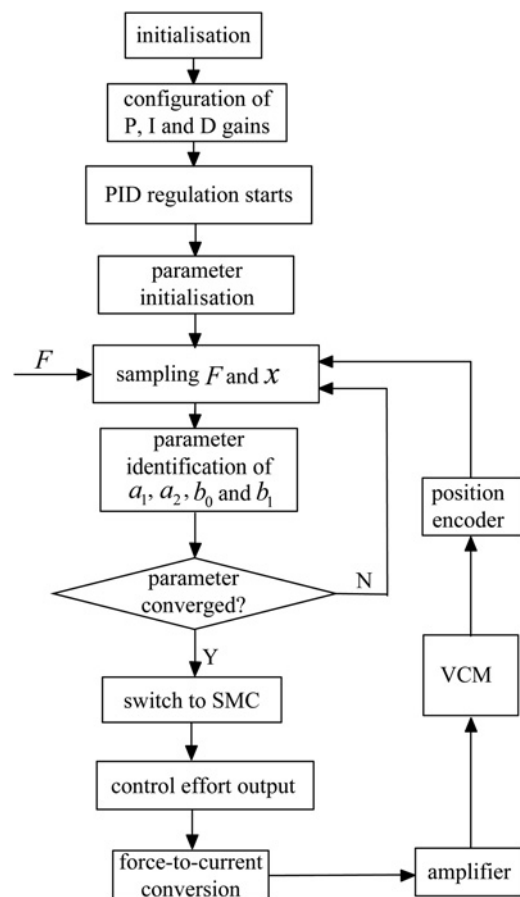


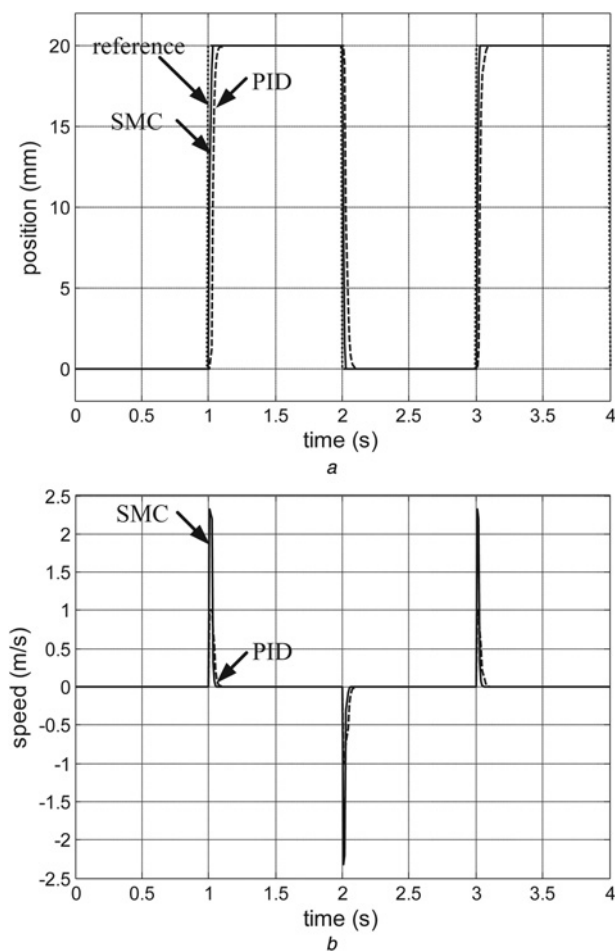
Fig. 5 Position control flowchart

Table 2 Control gains

SMC parameter	Value
P	1.03
I	0.01
D	0.012
C	250
K	150.7
E	2

of 0.5 Hz for a load-free operation. The regulation of P , I , and D gains from the PID position controller is based on the tradeoff between fast rise time and small steady-state error from positive or negative transitions to enjoy an overshoot-free position response. The control parameters can be regulated based on trial and error with PID gains listed in Table 2. After the parameter identification process is completed, the PID control method is switched to the SMC. The control parameters of the SMC include C , k , and ε . Generally, bigger C and k values result in a faster response of the system performance [29]. ε is responsible for perturbation suppression. It is often selected as a tradeoff between the ability of disturbance rejection and system chattering, which is perceived as the oscillating motion about the sliding manifold [29]. For the VCM, the SMC parameters are regulated based on a chattering-free performance and the parameters are tabulated as shown in Table 2.

Figs. 6*a* and *b* demonstrate the position tracking and speed profiles of the SMC and PID. It is observed that all position tracking profiles enjoy an overshoot-free, zero steady-state performance. The rise time

**Fig. 6** Simulation results of

a Position
b Speed responses

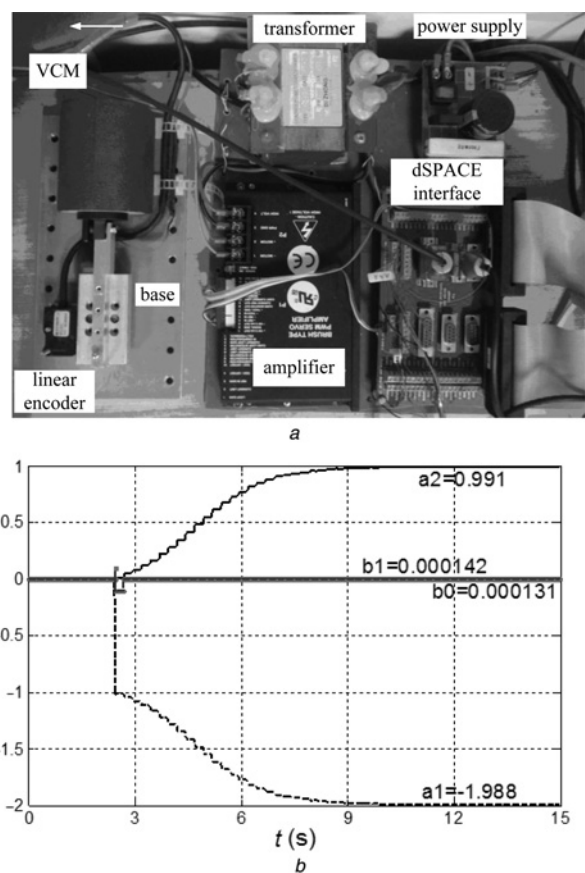
of the SMC is smaller than the PID regulator. It can also be deduced from the speed response waveforms that the dwell time is smaller for the SMC in either positive or negative transition.

5.2 Experimental results

5.2.1 Experimental setup: Fig. 7*a* shows the experimental setup for evaluating the VCM and the SMC with SIO. The position control of the VCM was conducted in real time based on a dSPACE DS1104 controller card [32]. The sampling frequency of the position control loop was set at 1 kHz. The current amplifier was a commercial driver capable of providing an inner current regulation based on a PI algorithm with a sampling rate of 10 kHz. A linear magnetic encoder was mounted on the linear slide with a resolution of 1 μm . The control programme was developed under MATLAB/SIMULINK which was directly downloaded to the digital signal processor (DSP) of the control board. The control parameters, reference profile, and response profiles were modified and supervised online.

5.2.2 Parameter identification: Fig. 7*b* shows the converging profiles for the system parameters. In the initial parameter identification process, it takes about 7–9 s for all parameters to get settled from zero. After the control system enters the stable operation state, any tiny change in the parameters can be quickly identified and observed. Therefore, the speed of the SIO is fast enough for the position control regulation [28].

5.2.3 Control performance of PID controller: Fig. 8*a* shows the dynamic position response of the PID control. The PID and SMC gains remain the same as listed in Table 2. It is seen that the dynamic transitions of the positive and negative cycles are different since the mechanical characteristics such as uneven

**Fig. 7** Experimental setup for evaluating the VCM and the SMC with SIO

a Experiment setup
b Parameter converging profiles

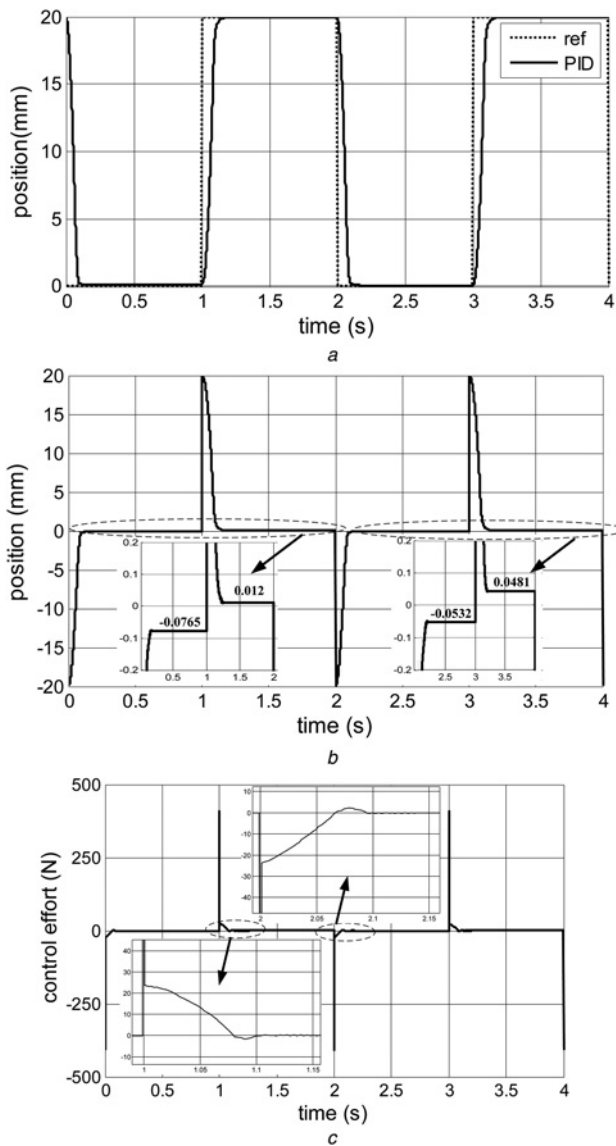


Fig. 8 Position control performance of PID

- a Dynamic response
- b Dynamic error response
- c Control effort output

friction or air gap lengths etc., from each direction of motion are not uniform. From the dynamic error response in Fig. 8b, the tracking precisions of the rise and fall parts for the first half cycle are 12 and $-76.5 \mu\text{m}$, respectively. They change to 0.0481 and -0.0532 mm for the second half cycle. From the control effort output waveform in Fig. 8c, the control effort output jumps sharply at 1 s, decreases gradually, but cannot conform to the reference signal at the stable state. The waveforms from different transitions are not symmetric as well. This can also be verified from the control effort output waveform in Fig. 8c; in that there is a dominant regulation if sharp change in the reference signal occurs. It takes about 0.1 s for the response waveform to dwell and approach to the steady-state value.

5.2.4 Control performance of SMC: With the same operation position reference, Fig. 9 shows the position control performance of the SMC. From the dynamic position response in Fig. 9a, a fast rise time and the symmetric behaviour of the response are notable. From the dynamic error response in Fig. 9b, the motion control system enters the steady state after a shorter duration compared with the PID controller. The absolute steady-state error is

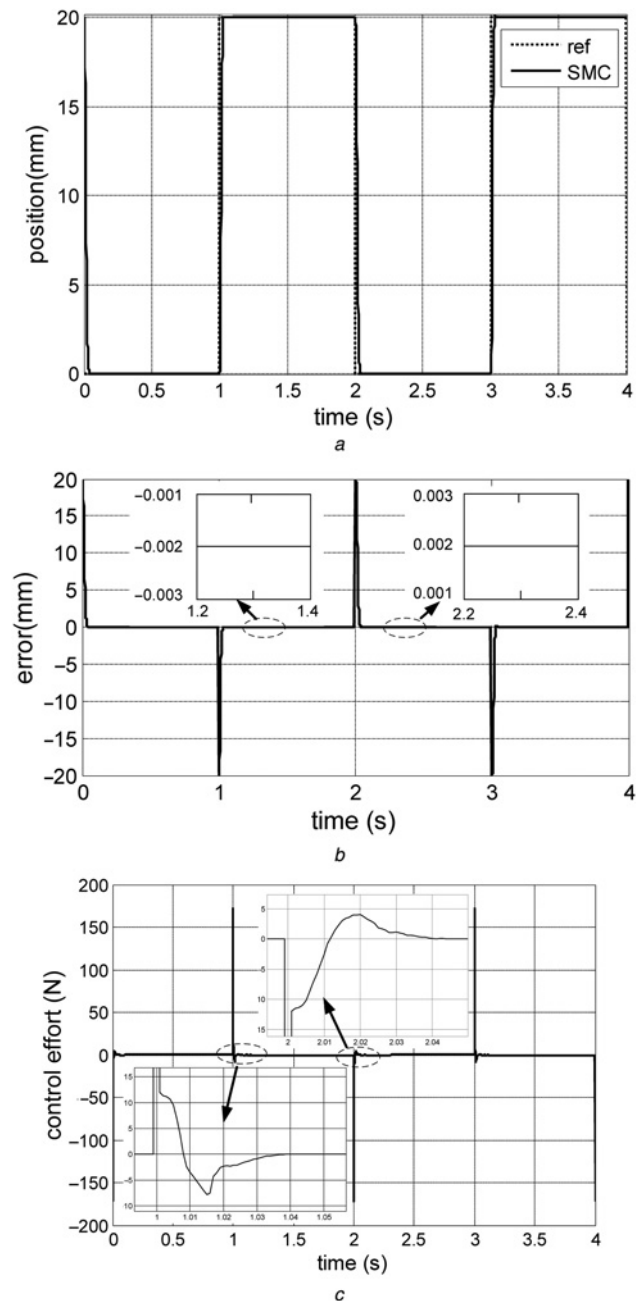


Fig. 9 Position control performance of SMC

- a Dynamic response
- b Dynamic error response
- c Control effort output

uniformly $2 \mu\text{m}$, either for the positive or negative transition. From the control effort output waveform in Fig. 9c, it can be verified that the regulation time is about 40 times shorter than the PID controller.

Owing to mechanical imperfections and unbalanced behaviours of the VCM, the control performance of the positive and negative transitions is not uniform for the PID controller. However, the SMC regulator is capable of providing a uniform tracking performance based on the online parameter identification observer. Table 3 tabulates the key control performance indices of the two position regulators. It can be concluded that the control performance is improved in the SMC regulator. The rise time is 13% shorter than the PID controller. In addition, the tuning time of 2% bandwidth is about 20% compared with the PID controller. The control performance of the SMC with the

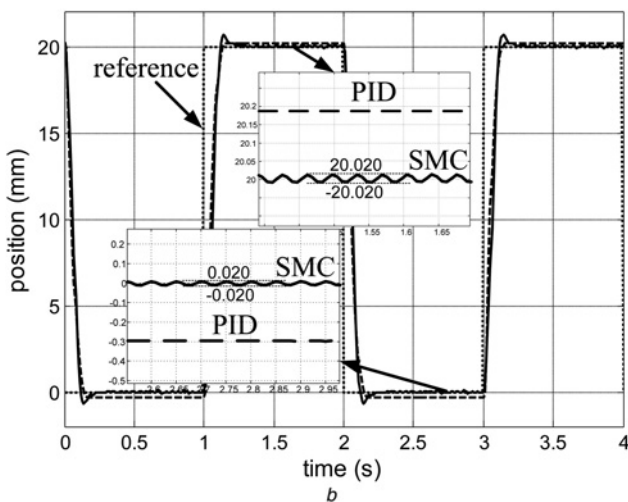
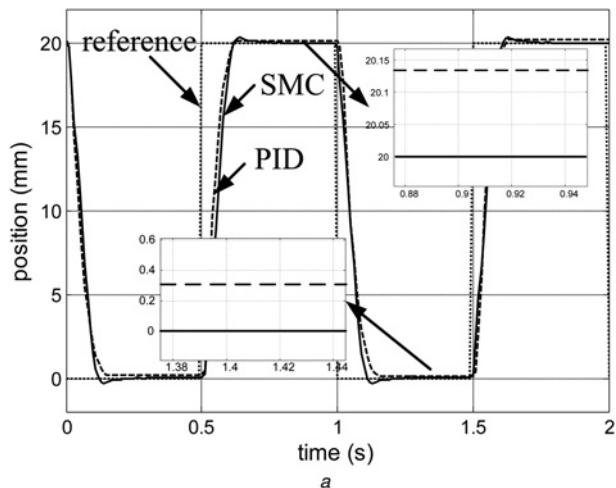
Table 3 Performance comparison between PID and SMC

Controller	Rise time, s	Tuning time (2%), s	Steady-state error (+ transition), μm	Steady-state error (- transition), μm	Steady-state error to full stroke, %
PID	0.229	0.121	12	76	$\geq 0.6\%$
SMC	0.029	0.025	2	2	0.1%

observer ensures a uniform steady-state performance under load-free operation.

5.2.5 Control performance at 1 Hz reference: As illustrated in Table 2, with the control gains for the SMC and PID controller unchanged, the position reference signal is set as square wave of 20 mm amplitude and 1 Hz frequency. From the dynamic tracking profiles in Fig. 10a, although the rise time of the positive transition is faster for the PID controller, the control behaviour is not uniform for both the positive and negative transitions. The SMC is still able to give a uniform control performance with the absolute steady-state error within 2 μm .

5.2.6 Control performance at 50% load: At 0.5 Hz frequency and 500 g mass load, the load translates together with the moving platform, and the position tracking profiles can be found in Fig. 10b. For the SMC, there exists considerable chattering in steady-state in the limit of $\pm 20 \mu\text{m}$. For the PID controller, the behaviour of each transition is still not uniform and the steady-state errors are 0.18 and -0.3 mm .

**Fig. 10** Dynamic tracking profiles

a Position control performance at 1 Hz reference
b Position control performance at 50% load

6 Conclusion and discussion

A medium-stroke VCM with a full stroke of 24 mm has been physically constructed, theoretically modelled, and computationally analysed. An SMC with a least-squares-based SIO has been proposed to overcome the non-linear current-flux linkage-position characteristics of the VCM and to improve the position control performance by minimising the rise time and the steady-state error. The control effectiveness of the SMC on the VCM has been experimentally verified and compared with a traditional PID controller. It has been found that the SMC possesses improved dynamic and static tracking responses under load-free, frequency-varying operations. Specifically, it demonstrates a shorter rise time of 29 ms and a smaller steady-state error of $\leq 2 \mu\text{m}$ at a square-wave excitation of 20 mm amplitude and 0.5 Hz frequency. Comparing with short-stroke VCM-actuated motion systems, a small value of 0.001 has been achieved in the ratio of steady-state error to full stroke at the condition of load free with the frequency variation to 1 Hz.

It has been reported that the super-twisting sliding-mode (STSM) control strategy possesses the features of a conventional SMC combined with the proportional integral algorithm to enjoy a steady-state chattering-free and robust behaviour [19]. It is suitable for rotary PM or induction motors with direct torque regulations [19, 20]. Since the STSM has the ability to correct machine coupling and non-linearity, the authors suggest evaluating the performance of the STSM on eliminating chattering and achieving a more robust behaviour of the medium-stroke VCM under external load disturbances. A simple and straightforward STSM algorithm can be expected for easy implementation of digital VCM control systems based on single digital processing chips.

7 Acknowledgments

This work was supported by the Research Grants Council of the HKSAR Government (PolyU 5288/13E), the National Natural Science Foundation of China (51477103), and the Guangdong Natural Science Foundation (S2014A030313564). The authors would also like to thank for the support of the Shenzhen Government and The Hong Kong Polytechnic University under codes JCYJ20130329144017199 and G-YK63.

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