Flatness Based Control Structure for Polysolenoid Permanent Stimulation Linear Motors

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Abstract:
Nowadays, linear motions are almost indirectly realized by rotational motors which cause several inherent weaknesses. Using motors able to create directly linear movements is capable of removing the above limitations. This paper presents a control solution for Polysolenoid permanent-stimulation linear motors according to flatness based structure. The system allows output parameters reach reference trajectories and all of currents are mobilized to make the propulsion force of the linear motors even when there is lack of model parameters or effects of disturbances. The fundamental of the mentioned control solution is the model of the object and the flatness based method. Simulation results generated by MATLAB – Simulink re-emphasize performance of the proposed control structure.

Keyword: *Flatness control, Polysolenoid linear motors, SVM, two-phase inverter , uncertain compensation, parameter estimation.*

Nomenclature

Symbol	Unit	Meaning
L_{sd}, L_{sq}	H	d-axis and q-axis inductance
m	Kg	mass of the primary part
$\underline{u}_s$, $\underline{i}_s$	V, A	voltage and current vector
R_s	Ω	stator resistance
v , v_e	m/s	Mechanical and electrical speed
F_m , F_c	N	repulsion force, resisting force
i_{sd}, i_{sq}	A	d-axis and q-axis current
u_{sd}, u_{sq}	V	d-axis and q-axis voltage
τ	Mm	Meaning Pole pitch
p		number of pole
ψ_p	Wb	pole flux
w_e, θ	Rad/s; Rad	Electric angular velocity and position
x_p	Mm	Motor position

Abbreviation

PMSLM	Permanent-Magnetic Synchronous Linear Motor
SVM	Space Vector Modulation

I. INTRODUCTION

Although using linear motors in a drive system enables to eliminate intermediate mechanical elements, it makes the system sensitive to factors such as friction force, end effect, load changes, non-sinusoidal flux distribution and so on. These sensitivities badly affect control quality. There have been several studies on how to avoid mentioned destructive impacts. [1] has proposed a speed controller according to self-tuning PI and estimation algorithms at low speed in order to achieve sufficient performance in the operating range. However, a variation of load such as mass will lead friction force and resisting forces to changing. Consequently, the PI controller loses its efficiency so a model-tracking adaptive control method associated with Lyapunov has been applied in [2].

In addition, the back-stepping measure has been undertaken to address effects of friction and a Lugrie friction model-estimating controller has been demonstrated in [3]. However, friction is a factor depending on work conditions (temperature, pressure and so on); therefore, friction-estimating models remain some errors when being applied in reality. An application of the adaptive neuron network will tackle this problem as shown in [4].

This method allows controller's parameters to be tuned according to assumptions and adaptive laws in order to guarantee convergence of outputs. Adaptive fuzzy has been introduced to minimize friction drawbacks in [5]. It is shown that these above controllers require robust microprocessors because of its enormous number of calculations. Sliding controllers in [6] lead real outputs to tracking reference inputs rapidly. Nevertheless, the method as shown in [6] faces difficulty of determining sliding surface and fluctuation phenomena around sliding orbit. [7] has proposed a solution to address the variation problem with upgraded sliding mode controllers. Additionally, end effect will be executed as shown in [8]. Another means of fluctuation cancellation is to use H_∞ controllers [9]. For permanent stimulation synchronous motors, a control method that applies fatness principle has been shown in [9]. However, [9] has not mentioned remedies when necessary voltage is out of range of an inverter's outcomes and flatness characteristics of the motor model will be defined after flatness variables are determined. The paper will illustrate solutions to eliminate the above drawbacks.

Permanent stimulation motor Polysolenoid is constructed according to electromagnetic induction as shown in [10-12]. [13] has mentioned application of flatness based method to control permanent-stimulation synchronous motor but solutions to handle parameters' errors, noises and saturated primary part voltage. This study will discuss these problems and solutions.

II. FLATNESS-BASED APPROACH

According to [13-14], the flatness-based hierarchical control was introduced in 1992 as described as follows: Given a non-linear system: $\frac{dx}{dt} = f(x,u)$ where $x \in R^n$ is a state variable, $u \in R^m$ is an input variable.

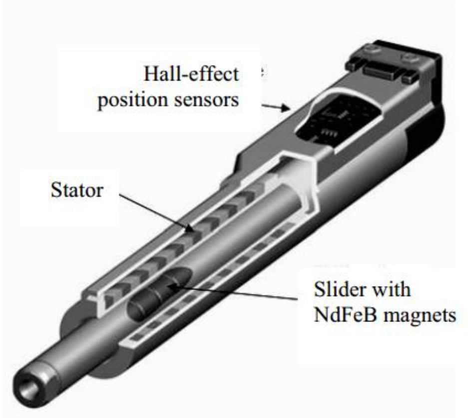


Fig 1. Composition of PMSLM Polysolenoid

The system is flat if only if $y = (y_1, y_2, ..., y_m)$ satisfies:

- Existing F function with $y = F\left(x, u, \frac{du}{dt}, ..., \frac{d^q u}{dt^q}\right), q \in N$ big enough. (1)
- Existing P, Q with $x = P\left(y, \frac{dy}{dt}, ..., \frac{d^r u}{dt^r}\right), r \in N$ finite

and $$u = Q\left(y, \frac{dy}{dt}, ..., \frac{d^r y}{dt^r}\right) \quad (2)$$

Variable $y = (y_1, y_2, ..., y_m)$ is differentially independent that means there is no function H satisfy $H\left(y, \frac{dy}{dt}, ..., \frac{d^k y}{dt^k}\right) = 0$ where k is finite and big enough (3)

If the system meets all 3 above criteria, it will be a flat system and $(y_1, y_2, ..., y_m)$ is called flat outputs of the system. [11, 12] introduced equations (4) demonstrating relationships among PMSLM parameters in the dq coordinate system.

$$\begin{cases} \frac{di_{sd}}{dt} = -\frac{R_s}{L_{sd}} i_{sd} + \left(\frac{2\pi}{\tau} v\right) \frac{L_{sq}}{L_{sd}} i_{sq} + \frac{U_{sd}}{L_{sd}} \\ \frac{di_{sq}}{dt} = -\frac{i_{sq}}{L_{sq}} - \left(\frac{2\pi}{\tau} v\right) \frac{L_{sd}}{L_{sq}} i_{sd} - \left(\frac{2\pi}{\tau} v\right) \frac{\psi_p}{L_{sq}} + \frac{U_{sq}}{L_{sq}} \\ F = \frac{2\pi p}{\tau} \left(\psi_p + (L_{sd} - L_{sq}) i_{sd}\right) i_{sq} \\ F - F_c = m\frac{dv}{dt} = \frac{m\tau}{\pi} \frac{d^2\theta}{dt^2} \end{cases} \quad (4)$$

That is the function illustrating a non-linear system:

$$\frac{dx}{dt} = f(x,u) \quad (5)$$

where $x = [i_{sd}, i_{sq}, \theta]^T, u = [u_{sd}, u_{sq}, v]^T$

Choose $y = (\theta, i_{sd}, F_c)$ and prove that y is a flat variable of 2-phase PMSLM through the following steps:

- Condition (1) is satisfied by

$$\begin{cases} \theta = \theta; i_{sd} = i_{sd} \\ F_c = \frac{2\pi p}{\tau} \left(\psi_p + (L_{sd} - L_{sq}) i_{sd}\right) i_{sq} - \left(\frac{m\tau}{\pi}\right) \frac{d^2\theta}{dt^2} \end{cases} \quad (6)$$

- Condition (2) is satisfied by

$$\begin{cases} i_{sd} = i_{sd} = g_1(y_2) \\ i_{sq} = \dfrac{\left(\dfrac{m\tau}{\pi}\right)\dfrac{d^2\theta}{dt^2} + F_c}{\dfrac{2\pi p}{\tau}\left(\psi_p + \left(L_{sd} - L_{sq}\right)i_{sd}\right)} = g_2(y_1, y_3, \ddot{y}_2) \\ \theta = \theta = g_3(y_1) \\ u_{sd} = L_{sd}\left(\dfrac{di_{sd}}{dt} + \dfrac{i_{sd}}{T_{sd}} - \dfrac{2\pi v}{\tau}\dfrac{L_{sq}}{L_{sd}} i_{sq}\right) \\ \quad = g_4\left(i_{sd}, i_{sq}, v\right) = g_4\left(y_2, g_2(y_1, y_3, \ddot{y}_2), \dot{y}_1\right) \\ v = \dfrac{\tau}{\pi}\dfrac{d\theta}{dt} = g_5(\dot{y}_1) \\ u_{sq} = R_s i_{sq} + \dfrac{2\pi v}{\tau}\psi_p + \dfrac{2\pi v}{\tau} L_{sd} i_{sd} + L_{sq}\dfrac{di_{sq}}{dt} \\ \quad = R_s g_2(y_1, y_3, \ddot{y}_2) + \dfrac{2\pi}{\tau}\psi_p g_5(\dot{y}_1) + \\ \dfrac{2\pi v}{\tau} L_{sd} g_1(y_2) + g_6\left(y_2, \dfrac{d^3\theta}{dt^3}, \dfrac{d^2\theta}{dt^2}, \dfrac{dy_2}{dt}, F_c, \dfrac{dF_c}{dt}\right) \end{cases} \quad (7)$$

For the resisting force F_c depends on ambient conditions and operating modes, only motor's parameters (i_{sd}, F_c) could not be used to express F_c. Therefore, (θ, i_{sd}, F_c) are linearly independent (3). It can be seen that complicated calculations of input variables from flat output variables in equations (7) cause difficulties in designing the control structure. In order to reduce these difficulties, the control structure could be designed by separating PMSLM model into 3 subsystems (4.1 → 4.3) that all satisfy flat system characteristics. Proof of flatness of these subsystems is similar to that of the entire system in equations (4).

$$\begin{cases} \dfrac{di_{sd}}{dt} = -\dfrac{R_s}{L_{sd}} i_{sd} + \left(\dfrac{2\pi}{\tau}v\right)\dfrac{L_{sq}}{L_{sd}} i_{sq} + \dfrac{U_{sd}}{L_{sd}} \\ \dfrac{di_{sq}}{dt} = -\dfrac{i_{sq}}{L_{sq}} - \left(\dfrac{2\pi}{\tau}v\right)\dfrac{L_{sd}}{L_{sq}} i_{sd} - \left(\dfrac{2\pi}{\tau}v\right)\dfrac{\psi_p}{L_{sq}} + \dfrac{U_{sq}}{L_{sq}} \end{cases} \quad (4.1)$$

$$\frac{dv}{dt} = \frac{\dfrac{2\pi p}{\tau}\left(\psi_p + \left(L_{sd} - L_{sq}\right)i_{sd}\right)i_{sq} - F_c}{m} \quad (4.2)$$

$$\frac{dx_p}{dt} = v \quad (4.3)$$

- i is shown in (4.1) where $x = \left[i_{sd}, i_{sq}\right]^T, u = \left[u_{sd}, u_{sq}\right]^T$, v is input disturbances. Flat variable is $\left(i_{sd}, i_{sq}\right)$.
- v is shown in (4.2) where $x = [v], u = \left[i_{sd}, i_{sq}\right]^T$. Flat variable is $\left(F_c, i_{sd}, v\right)$.
- x_p is shown in (4.3) where $x = x_p, u = v$. Flat variable is $\left(x_p\right)$.

From above assumption, a specific control scheme is shown in Fig. 2 with 3 control loops for current, velocity and position.

A. Current control loop design

- Calculating $\left(u_{sd}^*, u_{sq}^*\right)$ from reference currents $\left(i_{sd}^*, i_{sq}^*\right)$ that are outputs of speed control loop.

$$\begin{cases} \dfrac{di_{sd}^{**}}{dt} = -\dfrac{R_s}{L_{sd}} i_{sd} + \left(\dfrac{2\pi}{\tau}v\right)\dfrac{L_{sq}}{L_{sd}} i_{sq} + \dfrac{U_{sd}^*}{L_{sd}} \\ \dfrac{di_{sq}^{**}}{dt} = -\dfrac{i_{sq}}{L_{sq}} - \left(\dfrac{2\pi}{\tau}v\right)\dfrac{L_{sd}}{L_{sq}} i_{sd} - \left(\dfrac{2\pi}{\tau}v\right)\dfrac{\psi_p}{L_{sq}} + \dfrac{U_{sq}^*}{L_{sq}} \end{cases} \quad (8)$$

- However, if only $\left(u_{sd}^*, u_{sq}^*\right)$ affects the motor, a difference between $\left(i_{sd}, i_{sq}\right)$ of the motor and reference values from the speed control loop will arise. The reason would be the errors in estimated parameters in the controllers such as ($R_s, L_{sd}, L_{sq}, \ldots$). Thus, a current error cancelation needs to be added to the system as demonstrated in Fig. 2. Real voltages supplied to the motor will be $\left(u_{sd}^{**}, u_{sq}^{**}\right)$ where $u_{sd}^{**} = u_{sd}^* + \Delta u_{sd}$, $u_{sq}^{**} = u_{sq}^* + \Delta u_{sq}$. Then, the motor will generate currents $\left(i_{sd}, i_{sq}\right)$:

$$\begin{cases} \dfrac{di_{sd}}{dt} = -\dfrac{R_s}{L_{sd}} i_{sd} + \left(\dfrac{2\pi}{\tau}v\right)\dfrac{L_{sq}}{L_{sd}} i_{sq} + \dfrac{U_{sd}^{**}}{L_{sd}} \\ \dfrac{di_{sq}}{dt} = -\dfrac{i_{sq}}{L_{sq}} - \left(\dfrac{2\pi}{\tau}v\right)\dfrac{L_{sd}}{L_{sq}} i_{sd} - \left(\dfrac{2\pi}{\tau}v\right)\dfrac{\psi_p}{L_{sq}} + \dfrac{U_{sq}^{**}}{L_{sq}} \end{cases} \quad (9)$$

According to (8), we have:

$$\begin{cases} \dfrac{di_{sd}}{dt} = \dfrac{di_{sd}^{**}}{dt} + \Delta u_{sd} \\ \dfrac{di_{sq}}{dt} = \dfrac{di_{sq}^{**}}{dt} + \Delta u_{sq} \end{cases} \quad (10)$$

$$\text{where } \begin{cases} \Delta u_{sd} = K_1(i_{sd}^{**} - i_{sd}) \\ \Delta u_{sq} = K_2(i_{sq}^{**} - i_{sq}) \end{cases} \quad (11)$$

(10) can be rewritten as follows:

$$\begin{cases} \frac{d}{dt}(i_{sd}^{**} - i_{sd}) + K_1(i_{sd}^{**} - i_{sd}) = 0 \\ \frac{d}{dt}(i_{sq}^{**} - i_{sq}) + K_2(i_{sq}^{**} - i_{sq}) = 0 \end{cases}$$

It can be seen that $(i_{sd}^{**} - i_{sd})$ and $(i_{sq}^{**} - i_{sq})$ are going to be zero.

- Design an uncertain compensator in case (L_{sd}, L_{sq}, R_s) are unknown. Effects of gaps inside the motor may lead parameters (L_{sd}, L_{sq}, R_s) to being inaccurate. In order to solve uncertainties, we consider $(\hat{L}_{sd}, \hat{L}_{sq}, \hat{R}_s)$ as estimated parameters:

$$\begin{cases} \frac{di_{sd}^{**}}{dt} = -\frac{\hat{R}_s}{\hat{L}_{sd}} i_{sd} + \left(\frac{2\pi}{\tau} v\right) \frac{\hat{L}_{sq}}{L_{sd}} i_{sq} + \frac{U_{sd}^*}{L_{sd}} \\ \frac{di_{sq}^{**}}{dt} = -\frac{i_{sq}}{\hat{L}_{sq}} - \left(\frac{2\pi}{\tau} v\right) \frac{\hat{L}_{sd}}{\hat{L}_{sq}} i_{sd} - \left(\frac{2\pi}{\tau} v\right) \frac{\psi_p}{\hat{L}_{sq}} + \frac{U_{sq}^*}{\hat{L}_{sq}} \end{cases} \quad (12)$$

Substitute (12) to the motor model then we have:

$$\begin{cases} \frac{di_{sd}}{dt} = -\frac{R_s}{L_{sd}} i_{sd} + \left(\frac{2\pi}{\tau} v\right) \frac{L_{sq}}{L_{sd}} i_{sq} + \frac{U_{sd}}{L_{sd}} \\ \frac{di_{sq}}{dt} = -\frac{i_{sq}}{T_{sq}} - \left(\frac{2\pi}{\tau} v\right) \frac{L_{sd}}{L_{sq}} i_{sd} - \left(\frac{2\pi}{\tau} v\right) \frac{\psi_p}{L_{sq}} + \frac{U_{sq}}{L_{sq}} \end{cases}$$

$$\Leftrightarrow \begin{cases} \frac{di_{sd}}{dt} = -\frac{\hat{R}_s}{\hat{L}_{sd}} i_{sd} + \left(\frac{2\pi}{\tau} v\right) \frac{\hat{L}_{sq}}{L_{sd}} i_{sq} + \frac{U_{sd}}{L_{sd}} + f_{sd} \\ \frac{di_{sq}}{dt} = -\frac{i_{sq}}{\hat{L}_{sq}} - \left(\frac{2\pi}{\tau} v\right) \frac{\hat{L}_{sd}}{\hat{L}_{sq}} i_{sd} - \left(\frac{2\pi}{\tau} v\right) \frac{\psi_p}{\hat{L}_{sq}} \\ \qquad + \frac{U_{sq}}{\hat{L}_{sq}} + f_{sq} \end{cases} \quad (13)$$

where (f_{sd}, f_{sq}) contains uncertainties as well as $(u_{sd}^{**}, u_{sq}^{**})$. Then (u_{sd}, u_{sq}) can be calculated as follows:

$$\begin{cases} u_{sd} = u_{sd}^* + \Delta u_{sd} - f_{sd} \\ u_{sq} = u_{sq}^* + \Delta u_{sq} - f_{sq} \end{cases}$$

And (f_{sd}, f_{sq}) are determined by:

$$\begin{cases} f_{sd} = \frac{di_{sd}}{dt} + \frac{\hat{R}_s}{\hat{L}_{sd}} i_{sd} - \left(\frac{2\pi}{\tau} v\right) \frac{\hat{L}_{sq}}{L_{sd}} i_{sq} - \frac{U_{sd}}{L_{sd}} \\ f_{sq} = \frac{di_{sq}}{dt} + \frac{i_{sq}}{\hat{L}_{sq}} + \left(\frac{2\pi}{\tau} v\right) \frac{\hat{L}_{sd}}{\hat{L}_{sq}} i_{sd} + \left(\frac{2\pi}{\tau} v\right) \frac{\psi_p}{\hat{L}_{sq}} - \frac{U_{sq}}{\hat{L}_{sq}} \end{cases} \quad (14)$$

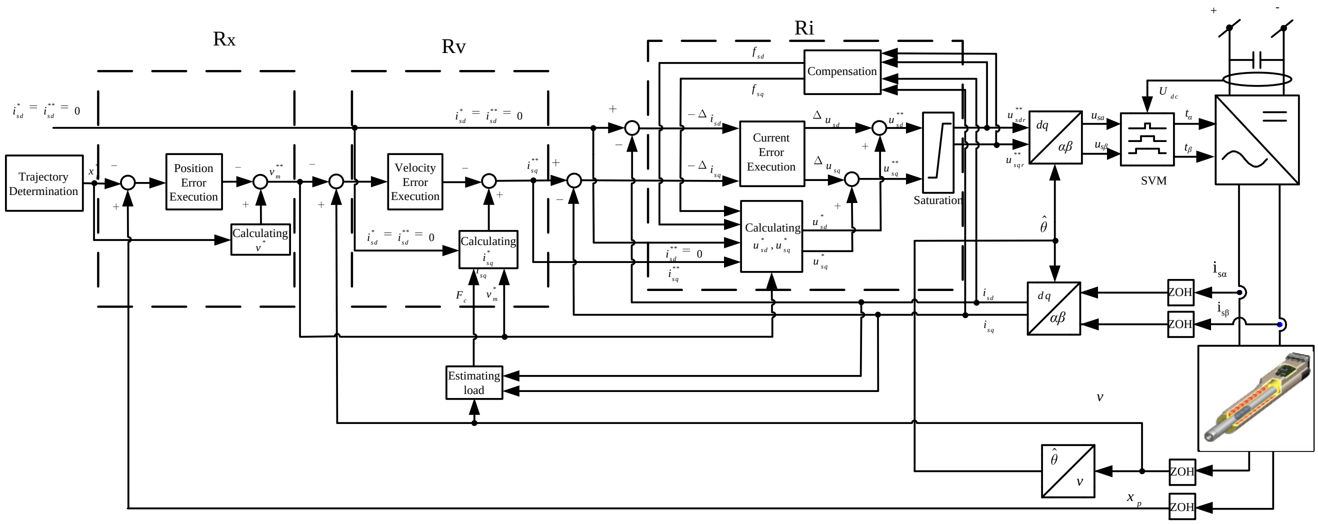


Fig 2. Diagram of control structure of PMSM using flatness method

- Solutions for excess of (u_{sd}, u_{sq}) over the limited area mentioned in [6] are necessary to be applied to the flatness-based control structure. In this case, $(i_{sd}^{**}(k), i_{sq}^{**}(k))$ should be turned into $(i_{sdr}^{**}(k), i_{sqr}^{**}(k))$

in order to stop the function of the saturation. It will result in (12), (13):

$$\begin{cases} \delta i_{sd}(k) = \dfrac{\left(\dfrac{L_{sq}}{T_s}+R_s\right)\delta u_{sd}(k)+\dfrac{2\pi}{\tau}v(k)L_{sq}\delta u_{sq}(k)}{\left(\dfrac{L_{sd}}{T_s}+R_s\right)\left(\dfrac{L_{sq}}{T_s}+R_s\right)+\left(\dfrac{2\pi}{\tau}\right)^2 v^2(k)\left(L_{sd}L_{sq}\right)} \\ \delta i_{sq}(k) = \dfrac{\left(\dfrac{L_{sd}}{T_s}+R_s\right)\delta u_{sq}(k)-\dfrac{2\pi}{\tau}v(k)L_{sd}\delta u_{sd}(k)}{\left(\dfrac{L_{sd}}{T_s}+R_s\right)\left(\dfrac{L_{sq}}{T_s}+R_s\right)+\left(\dfrac{2\pi}{\tau}\right)^2 v^2(k)\left(L_{sd}L_{sq}\right)} \end{cases} \quad (15)$$

$$\begin{cases} u,i_{sdr}(k)=u,i_{sd}(k)-\delta u,i_{sd}(k) \\ u,i_{sqr}(k)=u,i_{sq}(k)-\delta u,i_{sq}(k) \end{cases} \quad (16)$$

b. Design speed control loop

- Calculate: $i_{sq}^* = \dfrac{m\dfrac{dv^*}{dt}+F_c}{\dfrac{2p\pi}{\tau}\left(\psi_p+\left(L_{sd}-L_{sq}\right)i_{sd}^*\right)}$ (17)
- Speed Error Execution is implemented by PI controllers as described in (15), (16):

$$K_v\left(1+\frac{1}{T_v s}\right) \quad (18)$$

$$\begin{cases} T_v = 4T_{sq} \\ K_v = \dfrac{1}{2T_{sq}\left(\dfrac{3\pi}{\tau m}\right)\left(\psi_p+\left(L_{sd}-L_{sq}\right)i_{sd}^*\right)} \end{cases} \quad (19)$$

- Resisting force F_c is estimated by

$$\hat{F}_c = \frac{2\pi}{\tau}\left(\psi_p+\left(L_{sd}-L_{sq}\right)i_{sd}\right)i_{sq}-m\frac{dv}{dt} \quad (20)$$

c. Constructing the position control loop

Including the following items:

- Calculate $v^* = \dfrac{d\theta^*}{dt}$.
- Proportional function is used to execute position error.

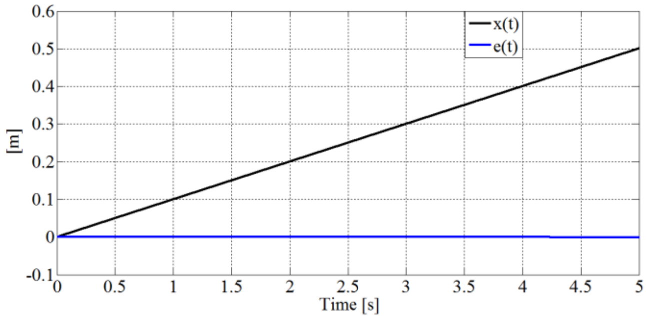
III. SIMULATION

The whole system as shown in Fig. 2 has been designed in MATLAB-Simulink.

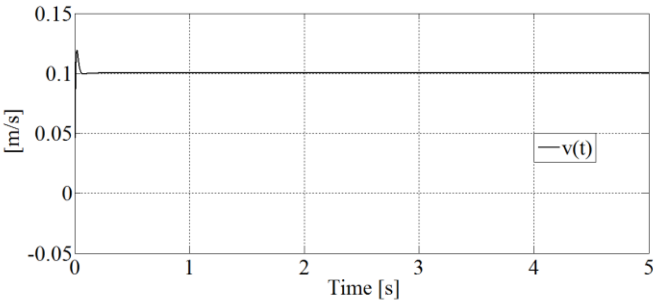
Coefficients of LinMot motor P01_48x240/390x540_C are described in Table 1.

TABLE 1. LINMOT MOTOR PARAMETERS

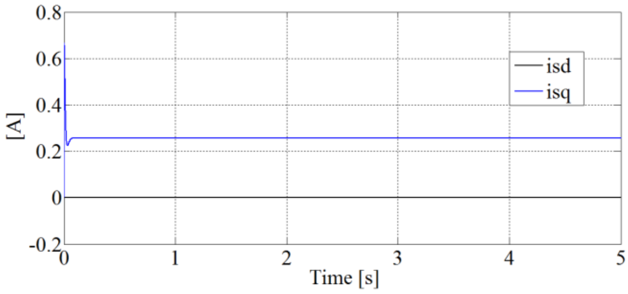
Number of Pole:	4
Pole step:	60mm
Rotor mass	1.5kg
Phase coil Resistance:	3.1 Ω
d-axis inductance	2.182 *mH*
q-axis inductance	2.182 *mH*
Flux	9.31Wb



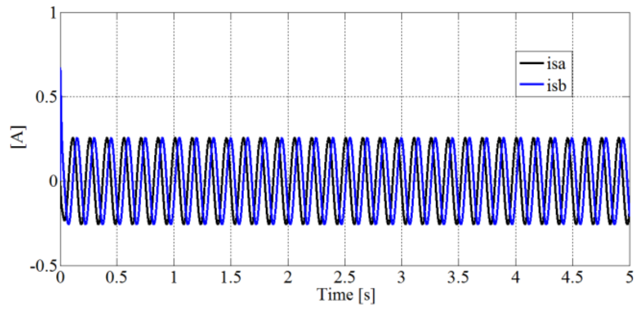
(a). Trajectory and Error



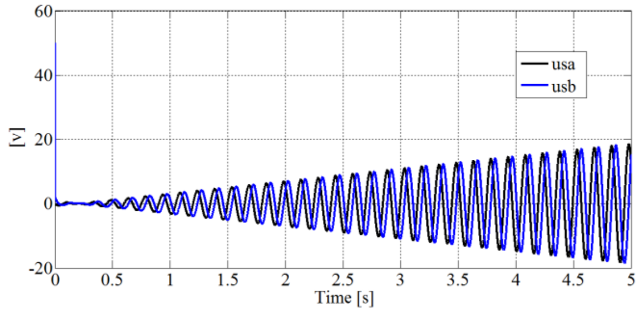
(b). Speed response



(c). Currents i_{sd} i_{sq}

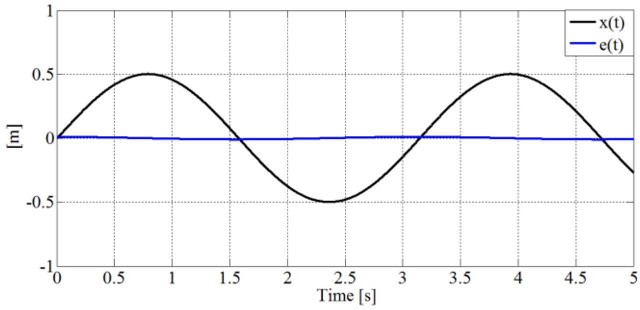


(d). Stator current

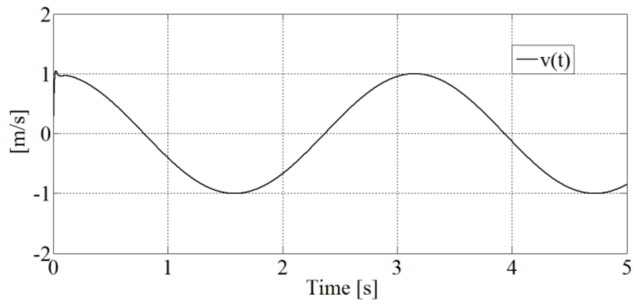


(e). Motor voltage $u_{s\alpha}$ $u_{s\beta}$

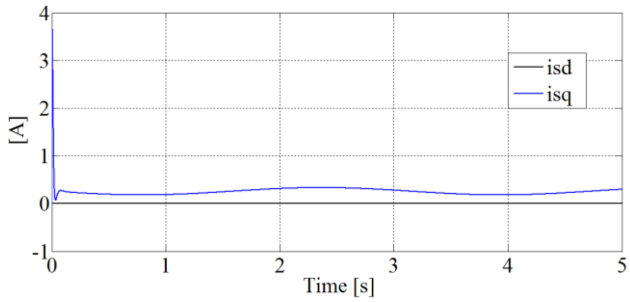
Fig. 3. Responses with reference orbit x(t)=0.1t (including a,b,c,d,e Figures)



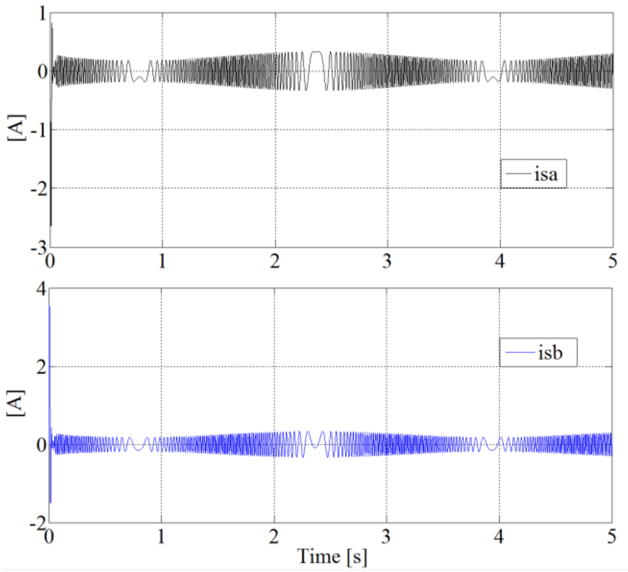
(a). Trajectory and error



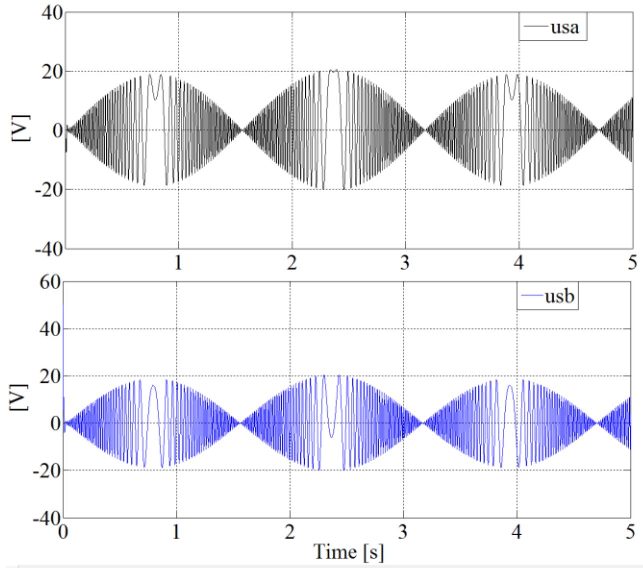
(b). Velocity response



(c). i_{sd} i_{sq} current



(d). Stator current



(e). Motor voltage $u_{s\alpha}$ $u_{s\beta}$

Fig. 4. Simulation results with x(t)=0.5sin(t) (including a, b, c, d, e Figures)

Modes in which positions of the motor are determined by a linear function *x(t)=0.1t* or a sinusoidal function *x(t)=0.5sin(t)* have been demonstrated in Fig. 3 and Fig. 4. It can be seen that motor position and speed converge to desired inputs rapidly even immediately. Voltages of phase a and b (u_{sa} and u_{sb}) are sinusoidal with phase difference of 90^0 and minor overshoots. It is thanks to the controller that the motor obtains its high performance. That means i_{sd} becomes zero and entire vector $\underline{i}_s$ is used to produce movement force.

IV. CONCLUSIONS

Responses of position, speed and motor voltage have re-emphasized work-ability of the proposed structure. Specially, the measured current $i_{sd,q(ZOH)}$ tracks $i^{**}_{sd,q}$ and the real one $i_{sd,q}$ oscillates around $i^{**}_{sd,q}$ due to inverter impacts [12,15]. In future, end effect will be considered in the model of the system. Adaptive features could be applied to deal with end effect according to feedback signals.

VI. ACKOWLEDGMENTS

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