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(SPMPM)

(Induction-Planar)

(Sawyer)

SPMPM

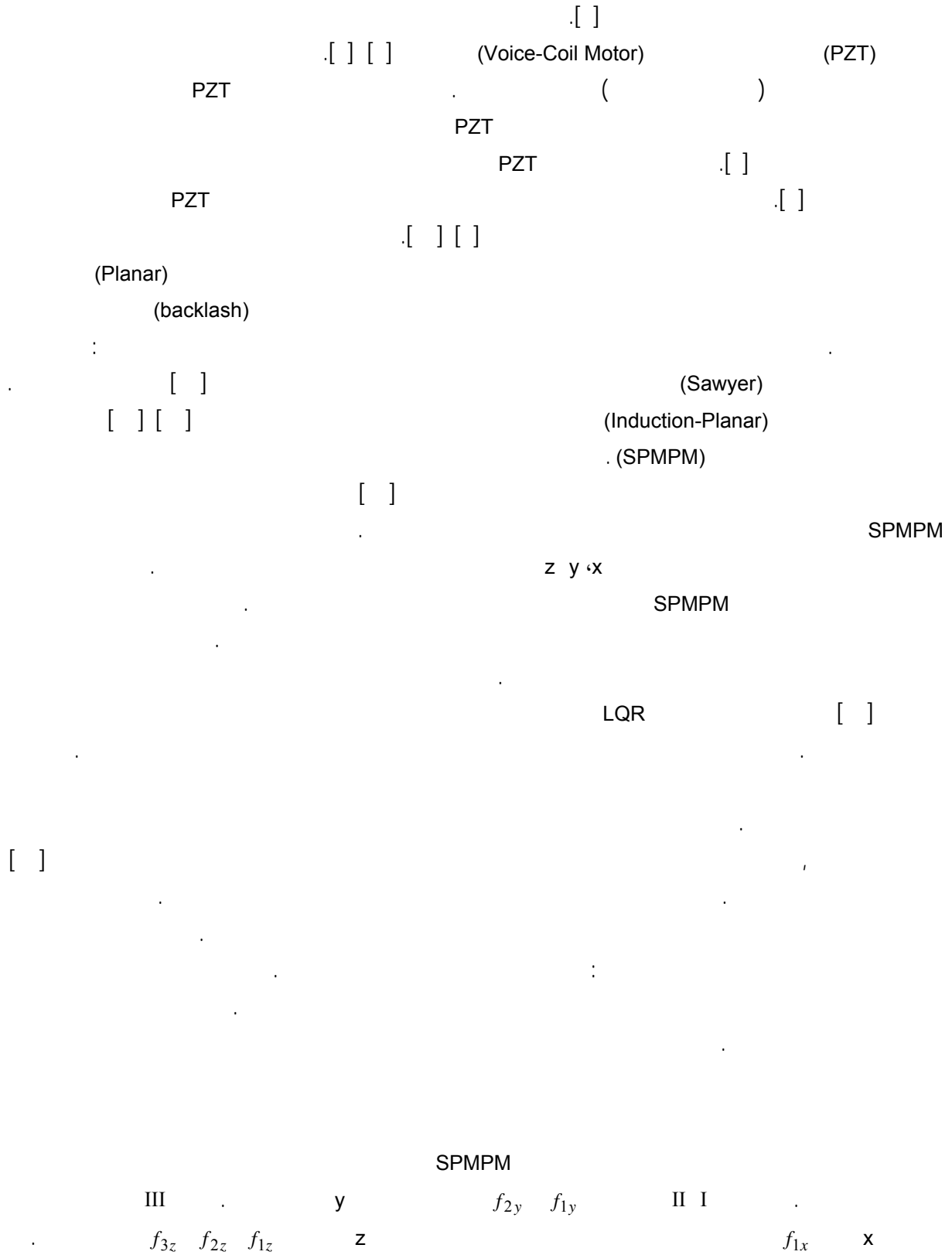
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z y x

II I

$$\begin{bmatrix} f_y \\ f_z \end{bmatrix} = \frac{1}{2} \mu_0 M_0 \eta_0 N_m G e^{-\gamma_1 z_0} \times \begin{bmatrix} \cos \gamma_1 y & \sin \gamma_1 y \\ -\sin \gamma_1 y & \cos \gamma_1 y \end{bmatrix} \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & \frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad ()$$

i_C i_B i_A z y f_z f_y

y x m³ () G

II I

$$G = \frac{\sqrt{2} w l^2}{\pi^2} (1 - e^{-\gamma_1 \Gamma}) (1 - e^{-\gamma_1 \Delta}) \quad ()$$

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Magnet remanence	$\mu_0 M_0 = 0.71T$
Effective spatial period	$N_m = 2$
Pitch	$l = 50.98mm$
Absolute value of the fundamental wave number	$\gamma_1 = \frac{2\pi}{l} = 123.25m^{-1}$
Nominal motor air gap	$z_0 = 2.32$
Magnet array thickness	$\Delta = \frac{l}{4} = 12.7mm$
Winding thickness	$\Gamma = \frac{l}{5} = 10.16mm$

II I

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z x

III

z y

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DQ

$$\begin{bmatrix} i_Q \\ i_D \end{bmatrix} = \begin{bmatrix} \cos \gamma_1 y & \sin \gamma_1 y \\ -\sin \gamma_1 y & \cos \gamma_1 y \end{bmatrix} \times \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & \frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad ()$$

z y

() ()

$$\begin{bmatrix} f_y \\ f_z \end{bmatrix} = \frac{1}{2} \mu_0 M_0 \eta_0 N_m G e^{-\gamma_1 z_0} \begin{bmatrix} i_Q \\ i_D \end{bmatrix} \quad ()$$



μm z

()

z_0 , mm

$i_D f_z$ $i_Q f_y$

:

$$m \frac{d^2 x}{dt^2} = f_x \quad ()$$

$$m \frac{d^2 y}{dt^2} = f_y \quad ()$$

$$m \frac{d^2 \varphi}{dt^2} = \tau \quad ()$$

$f_y f_x$, kg

()

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\varphi} \\ \dot{h} \\ \dot{u} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ \varphi \\ h \\ u \\ v \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{c}{m} \\ \frac{c}{m} & \frac{c}{m} & 0 \\ -\frac{c}{I_{zz}} l_{1y} & \frac{c}{I_{zz}} l_{2y} & 0 \end{bmatrix} \begin{bmatrix} i_{1q} \\ i_{2q} \\ i_{3q} \end{bmatrix} \quad ()$$

φ y x
III II I

y x
 $i_{3q} i_{2q} i_{1q}$ z

kgm²
mm

I_{zz}
II I

$l_{2y} l_{1y}$
mm

:

$$\dot{x} = Ax + Bu + f(x,t) \quad ()$$

$f(x,t)$ $u \in R^m$ $B \in R^{n \times m}$ $A \in R^{n \times n}$ $x \in R^n$

$f(x,t)$ () :

$$\text{rank}[B | f(x,t)] = \text{rank}[B] \quad ()$$



$$\Delta Ax$$

$$M \in R^{n \times n}$$

$$Bd(t)$$

$$f(x,t) = \Delta Ax + Bd(t)$$

$$d(t)$$

$$(\Delta A)(\Delta A)^T \leq MM^T$$

$$\dot{x} = Ax + \Delta Ax + B(u + d(t))$$

()

$$u \in R^m$$

$$A \in R^{n \times m}$$

$$A \in R^{n \times n}$$

$$x \in R^n$$

$$: [\quad]$$

$$(\quad)$$

$$C$$

$$A - BK_1$$

$$K_1 (\quad)$$

:

CB

$$u = -K_1 x - K_0 (CB)^{-1} \text{sgn}(S)$$

$$S = Cx - \int_0^t C(A - BK_1)x dt$$

()

$$K_0 = \hat{D}$$

$$\dot{\hat{D}} = -\gamma_1 \hat{D} + \gamma_2 \|S\|$$

$$\gamma_2 \quad \gamma_1$$

S

()

()

$$A - BK_1$$

$$K_1$$

lqr(.)

$$K_1$$

$$K_1$$

(A, B)

:

MATLAB

$$K_1^T = \begin{bmatrix} 0 & 0 & 3.1623 \\ 2.2905 & 2.1803 & 0 \\ -2.1803 & 2.2905 & 0 \\ 0 & 0 & 3.4431 \\ 2.4367 & 2.3183 & 0 \\ -2.2063 & 2.3165 & 0 \end{bmatrix}$$

()

$$x(0) = [0.5 \quad 0.3 \quad -0.5 \quad 2 \quad 1 \quad 2]^T$$

C

$$C = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

()

:

CB



$$\Delta A = \begin{bmatrix} 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \end{bmatrix}$$

()

$$d(t) = 0.2 \sin(t)$$

$$\gamma_2 = 80 \quad \gamma_1 = 1$$

$$\tan^{-1}(S/0.001) \quad \text{sgn}(S)$$

$$(\Delta A)(\Delta A)^T \leq MM^T \quad \Delta A$$

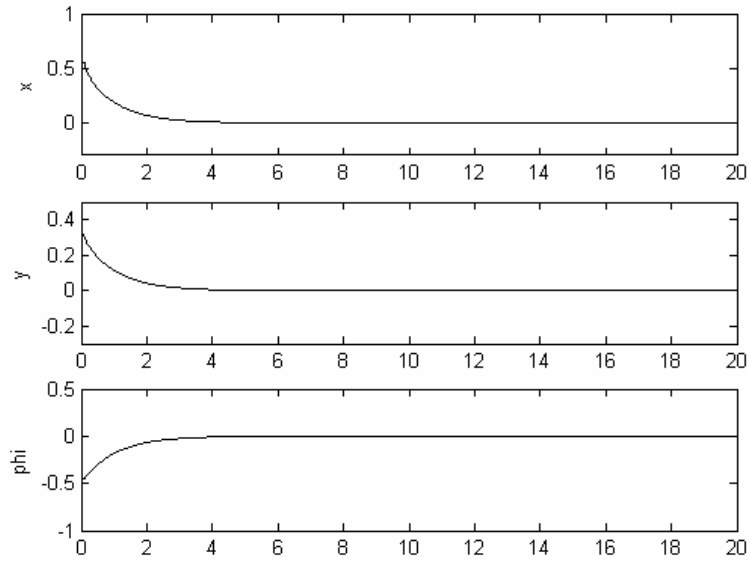
(Chattering)

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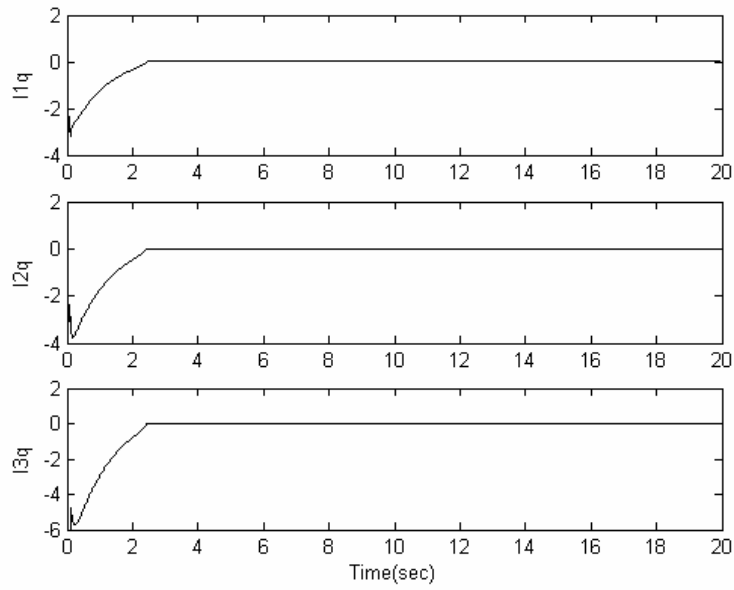
() $d(t)$ ΔA

i_{3q} i_{2q} i_{1q}

φ y x



() φ y x

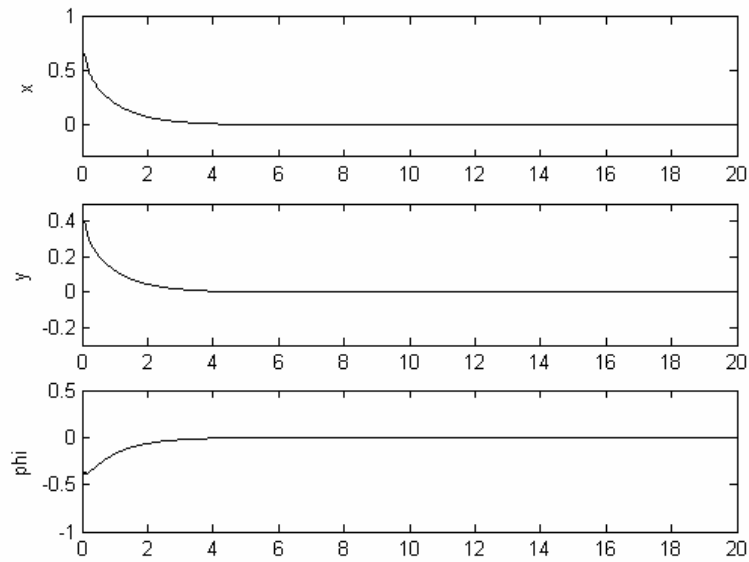


() i_{3q} i_{2q} i_{1q}

()

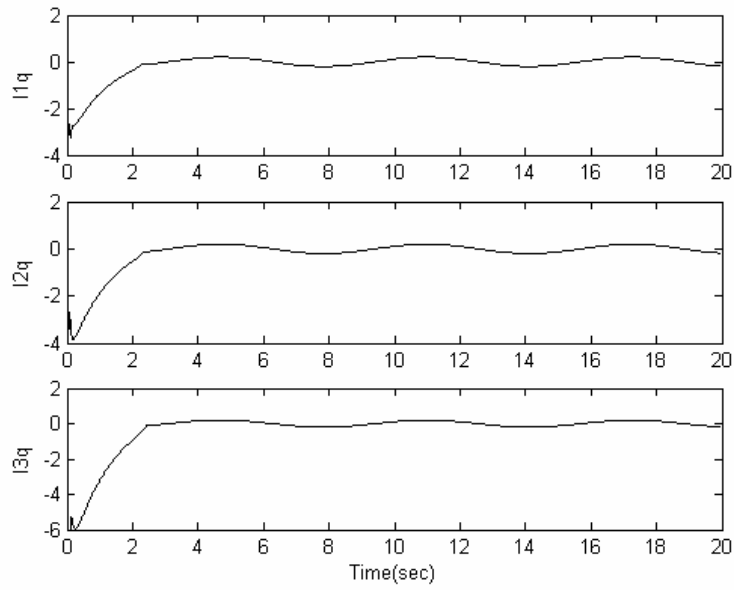
i_{3q} i_{2q} i_{1q}

φ y x



() φ y x

()



() i_{3q} i_{2q} i_{1q}

:

	()	()
e_x	, ×	, ×
e_y	, ×	,
e_φ	, ×	, ×

()

()

SPMPM

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