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Adaptive Control Approach for Speed Motion-Sensorless of Linear Induction Motor Unknown Resistance and Payload

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Abstract: In this paper, we will propose a nonlinear adaptive controller for a linear induction motor to achieve speed tracking. A nonlinear transformation is proposed to facilitate controller design. In this controller, only the primary currents are assumed to be measured. The secondary flux and speed observers are designed to relax the need of flux and speed measurement. Besides, the very unique end effect of the linear induction motor is also considered and is well taken care of in our controller design. Stability analysis based on Lyapunov theory is also performed to guarantee that the controller design here is stable. Also, the computer simulations and experiments are done to demonstrate the performance of our various controller design.

Nomenclature

$V_{qs}(V_{ds})$	q-(d-) axis input stator voltage	$i_q(i_d)$	q-(d-) axis input stator current
$R_s(R_r)$	Primary (secondary) resistance	$L_s(L_r)$	Primary (secondary) inductance
$\lambda_{qr}(\lambda_{dr})$	q-(d-) axis rotor flux	v_r	Linear speed of the primary
p_r	Position of the primary	M_m	Primary mass
B	Viscous friction coefficient	F_e	Electromagnetic force
P	Mechanical load force	L_m	Mutual inductance
K_f	Force constant$(=3PL_m\pi/2\tau L_r)$	$a_2=\beta R_r/L_r, a_3=L_mR_r/L_r, a_4=R_r/L_r$	
$D=L_sL_r-L_m^2, p=P\dfrac{\pi}{\tau}, \beta=L_m/D, c=L_r/D, a_1=(R_sL_r)/D+\beta L_mR_r/L_r$			

1. INTRODUCTION

Sensorless control of rotary induction motor (RIM) or linear induction motor (LIM) drives is now receiving wide attention. The main reason is that the speed sensor spoils the ruggedness and simplicity of induction motors (IM). In a hostile environment, speed sensors cannot even be mounted. However, due to the high order and nonlinearity of the dynamics of an IM, estimate the states of speed and rotor flux without measurement becomes a challenging problem [23]. There are many works concerning the sensorless control problem, in which the vector control technique is utilized, but the research results there on sensorless vector control, e.g. [18-19], base their analysis mainly on the steady-state behavior and only supply approximate proofs. In [20], the speed observer is designed and analyzed based on the Lyapunov stability theory. Both observer and controller apply the direct adaptive control scheme to cope with the unknown rotor resistance. In [21-22], an indirect adaptive scheme instead is proposed.

Nowadays, LIMs are now widely used in many industrial applications including transportation, conveyor systems, actuators, material handling, pumping of liquid metal, and sliding door closers, etc., with satisfactory performance. The most obvious advantage of linear motor is that it has no gears and requires no mechanical rotary-to-linear converters. The linear electric motors can be classified into the following: D.C. motors, induction motors, synchronous motors and stepping motors, etc. Among these, the LIM has many advantages such as simple structure replacement of the gear between motor and motion devices, reduction of mechanical losses and the size of motion devices, silence, high starting thrust force, and easy maintenance, repairing and replacement.

In the early works, Yamamura has first discovered a particular phenomenon of the end effect on LIM [1]. A control method, decoupling the control of thrust and the attractive force of a LIM using a space vector control inverter, was presented in [2], i.e. by selecting voltage vectors of PWM inverters appropriately.

Although the parameters of the simplified equivalent circuit model of an LIM can be measured by conventional methods (no-load and locked secondary tests), due to limited length of the machine the realization of the no-load test is almost impossible. Thus, the applicability of conventional methods for calculating the parameters of the equivalent model is limited. In order to measure the parameters, application of the finite element (FE) method for determining the parameters of a two-axis model of a three-phase linear induction motor has been proposed in [3]. Another method is proposed by removing the secondary [4].

To resolve the unique end effect problem, speed dependent scaling factors are introduced to the magnetizing inductance and series resistance in the d-axis equivalent circuit of the rotary induction motor [5] to correct the deviation caused by the "end effect". On the other hand, there is a thrust correction coefficient introduced by [6,7] to calculate an actual thrust to compensate for the end effect. A related method to deal with the problem is that an external force corresponding to the end effect is introduced into the RIM model to provide a more accurate modeling of an LIM under consideration of end effect as shown in [8]. In another work [9], extra compensating-winding was proposed to compensate such problem.

Although the end effect is an important issue of the LIM control, but there are still many works in the literature without considering it, such as [10-16]. In this paper, we will take this as an important issue which can not be ignored.

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2. PROBLEM FORMULATION

To formulate the dynamic model of a LIM as shown in Fig 2.1, we consider the following assumptions to simplify the analysis:

(A.1) Three phases are balanced;
(A.2) The magnetic circuit is unsaturated;
(A.3) It is without end effect (we will relax this assumption later in controller design);
(A.4) All parameters of the induction motor are known, except the secondary resistance R_r *;*
(A.5) Among all states, only the stator currents are measurable,

then the dynamics of the entire system can be rearranged into the following more compact form

$$\begin{aligned}
\dot{i}_q &= -a_1 i_q + a_2\lambda_q - \beta p v_r \lambda_d + cV_{qs} \\
\dot{i}_d &= -a_1 i_d + \beta p v_r \lambda_q + a_2\lambda_d + cV_{ds} \\
\dot{\lambda}_q &= a_3 i_q - a_4\lambda_q + p v_r \lambda_d \\
\dot{\lambda}_d &= a_3 i_d - a_4\lambda_d - p v_r \lambda_q \\
M_m \dot{v}_r &= K_f(\lambda_d i_q - \lambda_q i_d) - F_L' \qquad (1)
\end{aligned}$$

In this paper, we try to design the speed and position controller for the LIM. All the parameters are assumed known except the payload. The only information about the payload is its structure, and we use a second-order equation to represent it, i.e., the payload is expressed in terms of

$$F_L' = M_L \dot{v}_r + b_{L0} + b_{L1} v_r + b_{L2} v_r^2 . \qquad (2)$$

3. OBSERVER DESIGN

3.1 Analysis of mechanical load and end effect

The fundamental difference between a rotary induction motor and a LIM is the finite length of the magnetic and electric circuit of the LIM along the direction of the travelling field. The open magnetic circuit causes an initiation of the so-called longitudinal end effects.

In a LIM, as the primary moves, the secondary is continuously replaced by a new material. This new material will tend to resist a sudden increase in flux penetration and only allow a gradual build up of the flux density in the air gap. As the primary coil set of the LIM moves, a new field penetrates into the reaction rail in the entry area, whereas the existing filed disappears at the exit area of the primary core as shown below:

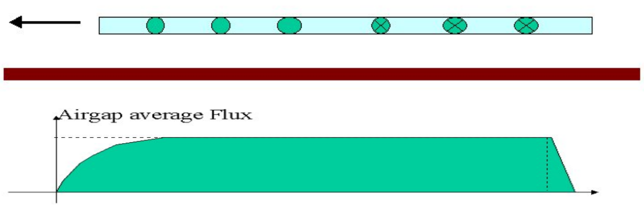

Fig 3.1:Airgap average flux distribution due to end effect [5]

We should note that when the speed is higher, the air-gap flux is more unbalanced. Because the mutual flux between the primary and the secondary is reduced by the end effect, we can see that the equivalence of the end effect is a reduction force, which is a function of speed. As we know that most functions can be described in Taylor series reasonably, we hence can assume that the end effect can be regarded as an external force which may be expressed as $\sum_{n=0}^{\infty} b_n' v_r^n + M_e \dot{v}_r$. In the paper, we will truncate the series into the first three terms.

For a LIM, the end effect with the load force can be represented as a function of the speed v_r , which can be normally simplified into the form

$$\begin{aligned}
F_L &= \sum_{n=0}^{2} b_n' v_r^n + M_e \dot{v}_r + F_L' \\
&= M_e \dot{v}_r + b_0 + b_1 v_r + b_2 v_r^2 + M_L' \dot{v}_r + b_{L0} + b_{L1} v_r + b_{L2} v_r^2 \\
&= M_L \dot{v}_r + b_o + b_1 v_r + b_2 v_r^2
\end{aligned}$$

In this paper, the mechanical load with end effect is assumed in the aforementioned form as $F_L = \Theta V_r^T$ with the unknown constant parameters $\Theta = \begin{bmatrix} M_L & b_0 & b_1 & b_2 \end{bmatrix}$, and a known function vector $V_r^T = \begin{bmatrix} \dot{v}_r & v_r^0 & v_r^1 & v_r^2 \end{bmatrix}$. The joint mass $M = M_m + M_L$ is therefore also unknown, which leads to the total mechanical load with motor itself as $F = \Theta^T V_r$, where $\Theta^T = [M \ b_0 \ b_1 \ b_2]$.

To proceed further, we introduce some more assumption as shown below:

(A.6) $x_2 = \lambda_q^2 + \lambda_d^2 > 0$*,*

(A.7) The desired speed should be a bounded smooth function with known first and second order time derivatives,

and then further simplify the dynamics shown in (1) by introducing a nonlinear coordinate transformation given as follows:

$$\begin{aligned}
x_1 &= i_q^2 + i_d^2 \\
x_2 &= \lambda_q^2 + \lambda_d^2 \\
x_3 &= i_q\lambda_q + i_d\lambda_d \\
x_4 &= i_q\lambda_d - i_d\lambda_q \\
x_5 &= v_r
\end{aligned}$$

Initially, we adopt the stator voltage inputs as $cV_{ds} = -(\lambda_q / \sqrt{\lambda_d^2 + \lambda_q^2})V, cV_{qs} = (\lambda_d / \sqrt{\lambda_d^2 + \lambda_q^2})V$ [17], with such transformation, then the dynamical equations shown in (1) can thus be transformed into the following dynamic model:

$$\begin{aligned}
\dot{x}_1 &= -2a_1 x_1 + 2a_2 x_3 + (2x_4 / \sqrt{x_2})V \\
\dot{x}_2 &= -2a_4 x_2 + 2a_3 x_3 \\
\dot{x}_3 &= a_3 x_1 + a_2 x_2 - (a_1 + a_4)x_3 + p x_5 x_4 \\
\dot{x}_4 &= -p x_5 x_3 - \beta p x_5 x_2 - (a_1 + a_4)x_4 + \sqrt{x_2}V \\
M\dot{x}_5 &= K_f x_4 - \sum_{n=0}^{2} b_n x_5^n \qquad (3)
\end{aligned}$$

To control the system (3) we develop the position controller to achieve the goal $p_r \to p_d$ as introduced in the following section.

3.2 Observer Design and Analysis

To facilitate observer design to be easy, the dynamics of a linear induction motor can be expressed as

$$\begin{aligned}
L_o \dot{i}_q &= -L_m R_r i_q - \alpha_1 i_q - \alpha_2 v_r \lambda_d + R_r \lambda_q + \alpha_3 V_{qs} \\
L_o \dot{i}_d &= -L_m R_r i_d - \alpha_1 i_d + R_r \lambda_d + \alpha_2 v_r \lambda_q + \alpha_3 V_{ds} \\
L_r \dot{\lambda}_q &= -R_r \lambda_q + L_m R_r i_q + \alpha_2 v_r \lambda_d \\
L_r \dot{\lambda}_d &= -R_r \lambda_d + L_m R_r i_d - \alpha_2 v_r \lambda_q \qquad (4)
\end{aligned}$$

where the meanings of all the variables are listed in the Nomenclature.

As has been mentioned earlier, the secondary resistance R_r is assumed unknown due to its fluctuation with temperature and the primary speed v_r is not measurable since no speed sensor is mounted. To cope with this, we first rewrite R_r and v_r as

$$R_r = R_{rn} + \theta_r \text{ and } v_r = v_{rd} + \theta_v$$

where R_{rn} is the nominal value of secondary resistance and v_{rd} is the desired primary speed. Apparently, θ_r and θ_v stand for the discrepancies from what we know about R_r and v_r . For subsequent simplicity of the problem, we will assume θ_r is a constant and θ_v, although it is not a constant, will be slowly varying, i.e., $\dot{\theta}_v$ is small enough. According to the structure of the dynamics in (4), the observers are proposed as follows:

$$\begin{aligned}
L_o\dot{\hat{i}}_q &= k_0\tilde{i}_q - L_m\hat{R}_r i_q - \alpha_1 i_q - \alpha_2\hat{v}_r\hat{\lambda}_d + \hat{R}_r\hat{\lambda}_q + \alpha_3 V_{qs} + u_1 + u_5\\
L_o\dot{\hat{i}}_d &= k_0\tilde{i}_d - L_m\hat{R}_r i_d - \alpha_1 i_d + \hat{R}_r\hat{\lambda}_d + \alpha_2\hat{v}_r\hat{\lambda}_q + \alpha_3 V_{ds} + u_2 + u_6\\
L_r\dot{\hat{\lambda}}_q &= -\hat{R}_r\hat{\lambda}_q + L_m\hat{R}_r i_q + \alpha_2\hat{v}_r\hat{\lambda}_d + u_3\\
L_r\dot{\hat{\lambda}}_d &= -\hat{R}_r\hat{\lambda}_d + L_m\hat{R}_r i_d - \alpha_2\hat{v}_r\hat{\lambda}_q + u_4
\end{aligned} \tag{5}$$

where $\hat{R}_r = R_{rn} + \hat{\theta}_r$, $\hat{v}_r = v_{rd} + \hat{\theta}_v$, $k_0 > 0$ and $u_1 \sim u_6$ are the auxiliary control signals to be designed later. Note that the symbol ^ above indicates an observed value, whereas the symbol ~ denotes the associated observation error. The design of observers can be detailed as in *Theorem 1* shown below.

Theorem 1: Consider the linear induction motor whose dynamics are governed by (4) under the assumptions (A1)–(A7). If the stator current observers and the secondary flux observers are designed as in (5), where

$$\dot{\hat{\theta}}_r = -k_R(\hat{\varphi}_{11}\tilde{i}_q + \hat{\varphi}_{21}\tilde{i}_d)$$

$$\dot{\hat{\theta}}_v = -k_v(\hat{\varphi}_{12}\tilde{i}_q + \hat{\varphi}_{22}\tilde{i}_d),$$

then the observed speed and flux of the secondary will be driven to the actual speed and flux and the estimate of secondary resistance will also converge to the actual one subject to the control signals designed as follows:

$$\begin{aligned}
u_1 &= \tfrac{\hat{R}_r}{L_y}(L_0\tilde{i}_q - r_q) + \tfrac{\alpha_2\hat{v}_r}{L_r}(L_0\tilde{i}_d - \gamma_d)\\
u_2 &= \tfrac{\hat{R}_r}{L_y}(L_0\tilde{i}_d - r_d) + \tfrac{\alpha_2\hat{v}_r}{L_r}(L_0\tilde{i}_q - \gamma_q)\\
u_3 &= -k_0\tilde{i}_q + \tfrac{L_0}{L_r}(\hat{R}_r\tilde{i}_q - \alpha_2\tilde{v}_r\tilde{i}_d)\\
u_4 &= -k_0\tilde{i}_d + \tfrac{L_0}{L_r}(\hat{R}_r\tilde{i}_d - \alpha_2\tilde{v}_r\tilde{i}_q)\\
u_5 &= \tfrac{1}{L_r}\operatorname{sgn}(\tilde{i}_q)\left[F_1(t) + \alpha_2 F_2(t)\right]\\
u_6 &= \tfrac{1}{L_r}\operatorname{sgn}(\tilde{i}_d)\left[F_3(t) + \alpha_2 F_4(t)\right],
\end{aligned}$$

where the auxiliary signals (γ_q, γ_d) are designed as follows:

$$\begin{aligned}
\gamma_q &= \dot{\hat{\chi}}_q + K_\psi(\tfrac{\hat{R}_r}{L_r}\tilde{i}_q + \tfrac{\alpha_2\hat{v}_r}{L_r}\tilde{i}_d)\\
\gamma_d &= \dot{\hat{\chi}}_d + K_\psi(\tfrac{\hat{R}_r}{L_r}\tilde{i}_d - \tfrac{\alpha_2\hat{v}_r}{L_r}\tilde{i}_q)\\
\dot{\hat{\chi}}_q &= -k_o\tilde{i}_q - u_1 - u_3 - u_5\\
\dot{\hat{\chi}}_d &= -k_o\tilde{i}_d - u_2 - u_4 - u_6
\end{aligned}$$

for some constant $k_R, k_v, k_o, k_\psi > 0$.

***Proof*:** The proof can be referred to in [22]. □

Lemma 1*: The upper bound on $(\tilde{\psi}_q, \tilde{\psi}_d)$ can be explicitly derived by proper design of $(\hat{\psi}_q, \hat{\psi}_d)$ as some positive constants δ_q and δ_d .*

Proof*:* The proof can be referred to in [20]. □

Since the upper bound (δ_q, δ_d) is acquired from *Lemma 1*, we can design the additional functions $F_1(t) \ge \delta_q\left|\tilde{R}_r\right|$, $F_2(t) \ge \delta_d\left|\tilde{v}_r\right|$, $F_3(t) \ge \delta_d\left|\tilde{R}_r\right|$ and $F_4(t) \ge \delta_q\left|\tilde{v}_r\right|$ and devise the control signals as follows:

$$u_5 = \tfrac{1}{L_r}\operatorname{sgn}(\tilde{i}_q)[F_1(t) + \alpha_2 F_2(t)]$$

$$u_6 = \tfrac{1}{L_r}\operatorname{sgn}(\tilde{i}_d)[F_3(t) + \alpha_2 F_4(t)]$$

where

$$\operatorname{sgn}(x) = \begin{cases} 1, & \text{if } x \ge 0 \\ -1, & \text{if } x < 0 \end{cases}, \quad \forall x \in R.$$

Seemingly, u_5 and u_6 may not be realizable due to lack of knowledge of $\left|\tilde{R}_r\right|$ and $\left|\tilde{v}_r\right|$. However, in reality, one can always choose higher gains $F_i(t), i = 1...4$, initially to establish close observations first, i.e., $\tilde{R}_r$ and $\tilde{v}_r$ tend to small residual values and then gradually reduce the gains. As the result of the above designs, $\dot{V}_o$ becomes

$$\dot{V}_o = -k_o\tilde{i}_q^2 - k_o\tilde{i}_d^2. \tag{6}$$

it immediately follows that

$$(\tilde{i}_q, \tilde{i}_d, \psi_q, \psi_d, \tilde{v}_r, \tilde{R}_r) \text{ is bounded and } (\tilde{i}_q, \tilde{i}_d) \in L_2. \tag{7}$$

In order to confirm the above claim on the proper design of u_5 and u_6, we soon show that $\tilde{R}_r$ and $\tilde{v}_r$ will converge to zero under appropriate conditions besides the high gain condition in the following. Before that, we first present the following working lemmas.

Lemma 2*: The states (λ_q, λ_d) are bounded provided (i_q, i_d) are bounded in finite time.*

Proof*:* The proof can be referred to in [20]. □

Now, we need to establish another result, which guarantees boundedness of v_r presuming boundedness of (λ_q, λ_d) in *Lemma 3.3* as follows.

Lemma 3*: The primary speed v_r is bounded if (i_q, i_d) is bounded.*

Proof*:* The proof can be referred to in [20]. □

Since $\tilde{R}_r$ is bounded from the previous argument, it follows that $\hat{R}_r$ is also bounded. That will lead to the following *Lemma 4* to guarantee the boundedness of the estimated rotor flux.

Lemma 4: *The error dynamics of the secondary flux in (5) are rearranged in vector form as*

$$L_r\begin{bmatrix}\dot{\tilde{\lambda}}_q\\ \dot{\tilde{\lambda}}_d\end{bmatrix}=\begin{bmatrix}-\hat{R}_r & \alpha_2\hat{v}_r\\ -\alpha_2\hat{v}_r & -\hat{R}_r\end{bmatrix}\begin{bmatrix}\tilde{\lambda}_q\\ \tilde{\lambda}_d\end{bmatrix}+\begin{bmatrix}L_m\hat{R}_r & 0\\ 0 & L_m\hat{R}_r\end{bmatrix}\begin{bmatrix}\hat{i}_q\\ \hat{i}_d\end{bmatrix}+\begin{bmatrix}u_3\\ u_4\end{bmatrix}. \quad (8)$$

Thus, if the estimate of the secondary resistance, $\hat{R}_r$, is kept positive and bounded away from the origin, then $(\hat{\lambda}_q,\hat{\lambda}_d)$ will be bounded provided (i_q,i_d) are bounded.

Proof: The proof can be referred to in [20]. □

From *Lemma 3.4*, $(\tilde{\lambda}_q,\tilde{\lambda}_d)$ are bounded, which together with the boundedness of $\tilde{i}_q$ and $\tilde{i}_d$ from (7) readily implies that $(\tilde{\chi}_q,\tilde{\chi}_d)$ are also bounded. Then, that (γ_q,γ_d) are bounded. Now, $(\dot{\tilde{i}}_q,\dot{\tilde{i}}_d)$ are proved bounded as well since signals on the RHS are all bounded, which together with the property that is revealed in (7) implies

$$\lim_{t\to\infty}\tilde{i}_q(t)=0 \text{ and } \lim_{t\to\infty}\tilde{i}_d(t)=0$$

via Barbalat's Lemma. Now, we have proved the convergence of the observation errors of the stator currents under the premises of *Lemma 3.4*. The next problem is to prove if the estimation errors of the secondary resistance and the primary speed have the same convergence property.

To solve this problem, we first make the following definitions:

$$\tilde{I}=\begin{bmatrix}\tilde{i}_q & \tilde{i}_d\end{bmatrix}^T$$

$$X=\begin{bmatrix}\tilde{R}_r & \tilde{v}_r & \psi_q & \psi_d\end{bmatrix}^T$$

$$\Lambda=diag\begin{bmatrix}L_ok_R & L_ok_v & L_ok_\psi & L_ok_\psi\end{bmatrix}$$

and rearrange the error dynamics equations

$$\dot{\tilde{I}}=A\tilde{I}+W^T(t)X+B(t)$$
$$\dot{X}=-\Lambda W(t)\tilde{I}+\Lambda C\tilde{I} \quad (9)$$

where

$$A=\begin{bmatrix}-\frac{k_o}{L_o} & 0\\ 0 & -\frac{k_o}{L_o}\end{bmatrix}, W^T(t)=\begin{bmatrix}\frac{\varphi_{11}}{L_o} & \frac{\varphi_{12}}{L_o} & \frac{\hat{R}_r}{L_oL_r} & -\frac{\alpha_2\hat{v}_r}{L_oL_r}\\ \frac{\varphi_{21}}{L_o} & \frac{\varphi_{22}}{L_o} & \frac{\alpha_2\hat{v}_r}{L_oL_r} & \frac{\hat{R}_r}{L_oL_r}\end{bmatrix},$$

$$B(t)=\begin{bmatrix}\frac{u_5}{L_o}\\ \frac{u_6}{L_o}\end{bmatrix}, C=\begin{bmatrix}\frac{\psi_q}{L_oL_r} & \frac{\alpha_2\psi_d}{L_oL_r} & 0 & 0\\ \frac{\psi_d}{L_oL_r} & \frac{\alpha_2\psi_q}{L_oL_r} & 0 & 0\end{bmatrix}^T.$$

Now, to prove X tends to zero asymptotically, we have to use the conclusion stated in *Lemma 3.5* given below.

Lemma 3.5: *The system with the form*

$$\dot{\tilde{I}}=A\tilde{I}+W^T(t)X$$
$$\dot{X}=-\Lambda W(t)\tilde{I} \quad (10)$$

is exponentially stable if and only if $W(t)$ is persistently exciting (PE), i.e., there exist two positive constant and such that

$$\int_t^{t+T}W(\tau)W^T(\tau)d\tau\ge\varepsilon I>0 \quad \forall t\ge 0.$$

Proof: The proof can be referred to in [20]. □

By *Lemma 5*, we conclude that the system (10) is exponentially stable provided $W(t)$ is PE. However, from (9) the asymptotic convergence property of X and $\tilde{I}$ may no longer hold due to the forcing term added to the homogeneous system (10). To cope with this, we first note that the forcing term in (9) with respect to the homogeneous part in (10) will be ultimately in the order of the magnitude of $|B(t)|$ under the premises of *Lemma 3.4*, since $(\tilde{i}_q,\tilde{i}_d)$ will then tend to zero. Thus, in our observer design, we gradually decrease the values of the control signals (u_5,u_6) to zero as $\tilde{I}$ tends to zero. Under such design, the equilibrium point $(\tilde{I}=0, X=0)$ of (9) remains asymptotically stable so that $(\tilde{R}_r,\tilde{v}_r,\psi_q,\psi_d)$ tends to zero asymptotically. In turn, this will confirm the hypothesis where the rotor resistance estimate $\hat{R}_r$ is kept positive and bounded away from the origin in *Lemma 3*.4. Finally, the fact that $\tilde{R}_r$ and $\tilde{v}_r$ tend to zero asymptotically and that the control signals u_3 and u_4 converge to zero, $\tilde{\lambda}_q$ and $\tilde{\lambda}_d$ will also tend to zero asymptotically. Up to now, we can conclude the satisfactory convergence property provided PE condition holds and (i_q,i_d) are bounded.

4. ADAPTIVE CONTROLLER DESIGN

The controller can overcome the unknown payload of the LIM under the reasonable assumptions. In subsection 4.1, we will propose a speed controller to achieve the objective of speed tracking. A nonlinear adaptive speed controller is proposed to deal with parameters understanding of the mutual inductance and in the uncertain inductance is also considered in our controller design subsection 4.2.

4.1 Non-adaptive speed controller design

Theorem 2 Consider a linear induction motor whose dynamics are governed by system (3) under the assumptions (A.1~A.7). Given Flux and Speed Observers (5) and a smooth desired speed trajectory v_d with $v_d,\dot{v}_d$and $\ddot{v}_d$ being all bounded, then the following controller can achieve the control objective $v_r\to v_d$ (i.e., $x_5=v_r$ will follow v_d asymptotically) with the control input

$$V_{qs}=\frac{\lambda_d}{\sqrt{\lambda_q^2+\lambda_d^2}}\frac{V}{c},\ V_{ds}=\frac{-\lambda_q}{\sqrt{\lambda_q^2+\lambda_d^2}}\frac{V}{c},$$

and

$$V=\frac{1}{\sqrt{x_2}}[(a_1+a_4)x_4+px_3x_5+\dot{x}_{4d}-\rho_2e_4],$$

where

$$x_{4d}=\frac{1}{K_f}(b_0+b_1x_5+b_2x_5^2+M\dot{v}_d-\rho_1e_5)$$

with $\rho_1,\rho_2>0$, and $e_5=x_5-v_d$, $e_4=x_4-x_{4d}$, while all the internal signals are kept bounded.

Proof:

In order to show the boundedness the tracking errors e_4, e_5, we choose a Lyapunov like function V_e as shown below:

$$V_e=\frac{1}{2}[Me_5^2+e_4^2], \quad (11)$$

whose time derivative is obtained as follows

$$\dot{V}_e = K_f e_5 x_4 - e_5(b_0 + b_1 x_5 + b_2 x_5^2) - M e_5 v_d + e_4(\dot{x}_4 - \dot{x}_{4d}).$$

If one design the auxiliary signal x_{4d} as

$$x_{4d} = \frac{1}{K_f}(b_0 + b_1 x_5 + b_2 x_5^2 + M\dot{v}_d - \rho_1 e_5),$$

then the time derivative of the function V_e becomes

$$\dot{V}_e = -\rho_1 e_5^2 + e_4[-(a_1 + a_4)x_4 - \beta p x_5 x_2 - p x_5 x_3 + \sqrt{x_2}V - \dot{x}_{4d}].$$

Now, design the actual input

$$V = \frac{1}{\sqrt{x_2}}[(a_1 + a_4)x_4 + \beta p x_5 x_2 + p x_5 x_3 + \dot{x}_{4d} - \rho_2 e_4],$$

then it will lead to the result that

$$\dot{V}_e = -\rho_1 e_5^2 - \rho_2 e_4^2 \le 0 \text{ with } \rho_1, \rho_2 > 0. \quad (12)$$

Since $\dot{V}_e$ in (12) is nonpositive, we conclude all the error signals in V_e and, in particular, x_5 and x_{4d} are bounded, which in turn implies that x_4 and hence $\dot{x}_5$ (from system (3)) are both bounded. By Lemma 2, we thus conclude that all the internal signals are kept bounded. Now, since I_s is bounded, then Lemma 2 guarantees that of all signals $x_i, i = 1,..,5.$, are hence bounded.

By the power formula, $P_s = a_5\ x_4\ x_5 = 3\ V_s I_s$, which can be shown bounded from the above. We now show that I_s will be bounded via argument of contradiction. Say, I_s eventually grows unbounded, then V_s and, hence, V will diminish eventually. However, if I_s does grow unbound, then it implies that V will tend to $p x_5 x_3 / \sqrt{x_2}$ eventually. However, from the dynamics of x_2 in (3), we have x_2 and x_3 grow at the same rate, which readily says that V will also grow unbounded. This obviously leads to a contradiction and therefore I_s is bounded.

Furthermore, we can show that $\dot{x}_{4d}$ is bounded, and hence $\dot{e}_4$ and $\dot{e}_5$ are also bounded, which implies the convergence of e_4 and e_5 due to Barbalat's Lemma. Therefore, the control scheme with the properly designed input V will drive the output v_r to the desired v_d asymptotically. □

Actually, the parameters M, b_0, b_1 and b_2 in the system (3) are unknown, and therefore the adaptive speed controller design will be proposed in the following subsection.

4.2 Nonlinear adaptive speed controller design

From the previous LIM dynamics, the parameters a_1, β, c and K_f depend on the mutual inductance, but as we know the mutual inductance is hard to identify due to its intricate structure and undesirable end effect. In particular,

$$a_1 = \frac{R_s L_r + R_r L_m^2 / L_r}{L_s L_r - L_m^2} = a_{10} + \alpha,$$

$$c = \frac{L_r}{L_s L_r - L_m^2} = c_0 + \sigma$$

where α and σ are uncertainty terms of a_1 and c, respectively. We rewrite the dynamic equations (3) as follows:

$$\dot{x}_1 = -2a_1 x_1 + 2a_2 x_3 + \frac{2(c_0+\sigma)x_4}{\sqrt{x_2}}V$$

$$\dot{x}_2 = -2a_4 x_2 + 2a_3 x_3$$

$$\dot{x}_3 = a_3 x_1 + a_2 x_2 - (a_{10} + \alpha + a_4)x_3 + p x_5 x_4$$

$$\dot{x}_4 = -p x_5 x_3 - \beta p x_5 x_2 - (a_{10} + \alpha + a_4)x_4 + (c_0+\sigma)\sqrt{x_2}V$$

$$\frac{M}{K_f}\dot{x}_5 = x_4 - \sum_{n=0}^{2}\frac{b_n}{K_f}x_5^n \quad (26)$$

and design the control input

$$V_{qs} = \frac{\lambda_d}{\sqrt{\lambda_q^2 + \lambda_d^2}}\frac{V}{c},\ V_{ds} = \frac{-\lambda_q}{\sqrt{\lambda_q^2 + \lambda_d^2}}\frac{V}{c}$$

To facilitate subsequent investigation, we define several variables as follows:

$$\tilde{\alpha} = \alpha - \hat{\alpha},\ \tilde{\beta} = \beta - \hat{\beta},\ d_n = \frac{b_n}{K_f} \text{ and } H = \frac{M}{K_f}$$

where $\hat{\alpha}$ is the estimate of α, $\hat{\beta}$ is the estimate of β.

In order to show the boundedness of all the parameter estimates and the tracking errors e_4, e_5, we choose a Lyapunov like function V_e as shown below:

$$V_e = \frac{1}{2}[He_5^2 + e_4^2 + \tilde{d}_0^2 + \tilde{d}_1^2 + \tilde{d}_2^2 + \tilde{H}^2 + \tilde{\alpha}^2 + \tilde{\beta}^2] \quad (27)$$

whose time derivative can be evaluated as follows.

If we design the parameter adaptive laws as

$$\dot{\hat{d}}_0 = -e_5,\quad \dot{\hat{d}}_1 = -e_5 x_5,\quad \dot{\hat{d}}_2 = -e_5 x_5^2,\quad \dot{\hat{H}} = -e_5 \dot{v}_d,$$
$$\dot{\hat{\alpha}} = -e_4 x_4,\ \dot{\hat{\beta}} = -e_4 p x_5 x_2$$

together with the proper design of x_{4d} as

$$x_{4d} = [\sum_{n=0}^{2}\hat{d}_n x_5^n + \hat{H}\dot{v}_d - \rho_1 e_5],$$

then the time derivative of the Lyapunov-like function V_e becomes

$$\dot{V}_e = -\rho_1 e_5^2 + e_4[g(x) + (c_0+\sigma)\sqrt{x_2}V]$$

where $g(x) = -p x_5 x_3 - \beta p x_5 x_2 - (a_{10} + \alpha + a_4)x_4 - \dot{x}_{4d}$. After we substitute the properly designed input V as:

$$V = \frac{1}{c_0\sqrt{x_2}}\{-g(x) - \eta\,\text{sgn}(e_4)\}$$

where $\text{sgn}(\cdot)$ is the sign function, then the time derivative $\dot{V}_e$ can be re-expressed as

$$\dot{V}_e = -\rho_1 - (\frac{c_0+\sigma}{c_0})e_4[\eta\,\text{sgn}(e_4) + (\frac{c_0}{c_0+\sigma})g(x)\}$$
$$\le -\rho_1 e_5^2 - (\frac{c_0+\sigma}{c_0})[\eta - (\frac{c_0}{c_0+\sigma})|g(x)|\}|e_4|$$

Now, if η is chosen to satisfy $\eta \ge |g(x)| + k$ for some k>0, then we have

$$\dot{V}_e \le -\rho_1 e_5^2 - \rho_2 |e_4|$$

for some ρ_2 >0, which again implies boundedness of all internal signals and convergence of the speed tracking error by the argument similar to that in subsection 4.2. □

5. EXPERIMENTAL RESULTS

Table 5.1: Specification and parameter of the motor

Specification	Parameters normal value
3 Phase (Y-connected)	$R_s = 13.2\Omega$
Rated Power 1HP	$R_r = 11.78\Omega$
Rated Air gap 0.125in	$L_s = 0.42H$
Rated Current 5A	$L_r = 0.42H$
Rated Voltage 240V	$L_m = 0.4H$
Rated Poles 4	M = 4.775 Kg
Pitch 46.5mm	B = 53Kg/sec
Secondary length 82cm	

The experiment are done with a 4-ploe, 3-phase LIM with a Y-connected primary, and is manufactured by NORMAG Co.. Detailed parameters and specification will be found in Table 5.1. The power stage of the motor driver uses a IGBT module, and the PWM drive signals are generated by a 10 KHz SPWM with a 2.5 μs dead-time protection circuit.

For the exponential desired speed trajectory in Figure 5.1, the speed error is nearly limited within ±10% of the command magnitude. In Figure 5.2, we adopt external disturbance, a 1.6Kg book, at about 4sec and remove it at 8sec, we see that the performance is also good.

7. CONCLUSIONS

In this paper, we have proposed an adaptive speed sensorless controller for the LIM. In addition, to cope with situation where some states, such as flux and primary speed, are not available and the uncertainty part of the LIM, i.e., secondary resistance, end effect, payload, and inductance, we first construct the state observers and the secondary resistance estimator to provide the asymptotic accurate value of the states and the parameters. Then, we design our controller based on an appropriate nonlinear transformation. Stability analysis based on Lyapunov theory is performed to guarantee the controller design is stable. Finally, the experimental results confirm the effectiveness of our control design.

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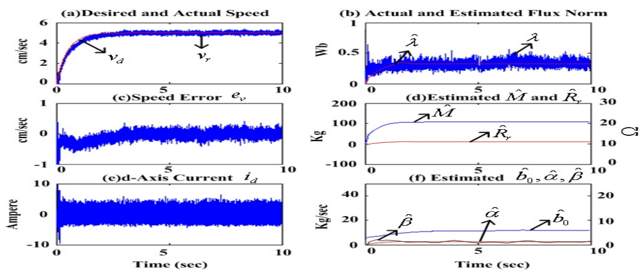

Fig 6.1: $v_d = 5(1-e^{-2t})$ cm/s

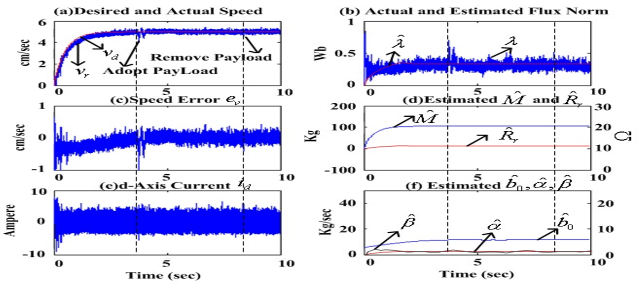

Fig 6.2: $v_d = 5(1-e^{-2t})$ cm/s with disturbance