OBSERVER BASED OPTIMAL CONTROL OF SHIP ELECTRIC PROPULSION SYSTEM

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Abstract: This paper describes the synthesis of a linear state observer based optimal control of ship electric propulsion using permanent magnet synchronous motor. The proposed approach is used for the ship speed control by measuring the stator current and the motor speed. This strategy of control is made possible by using a ship speed state observer. A numerical simulation study, applied to the global system, has confirmed the efficiency and the good performances of the proposed control law.

1 INTRODUCTION

The characterization of industrial processes leads, in most cases, to nonlinear models which are generally difficult to control. The study of such processes was generally used by a linearization leading to a linear model on which the linear arsenal of controls can be applied. These different control laws use often a state feedback. However the state vector is not always measurable, so it is necessary to use state observers.

The work presented in this paper concerns the modelisation of a ship electric propulsion system. The obtained global model is strongly nonlinear, coupled and presenting non measurable variables. Indeed, a linearization was firstly elaborated and the synthesis of a control law with state feedback, for the regulation of the stator current and the ship speed of the synchronous motor, was secondly designed.

This control strategy is carried out using a linear state observer allowing the ship speed reconstruction.

This paper is organized as follows: the modeling of the different subsystems of the ship is developed in the section 2. The linearization model of the global system is elaborated in section 3. Section 4 is devoted to the optimal control development based on state observer and in section 5 simulation resultats are reported and discussed. Finally some conclusions ended this work.

2 MODELISATION OF THE ELECTRIC PROPULSION SYSTEM

2.1 Different Parts of the Ship Electric Propulsion System

An electric ship is generally composed by two principal parts (Dallagi and Nejim, 2004).

- a first part ensuring the energy production using several alternators drived either by diesel motors, or by gas turbines. It feeds the board network and the propulsion equipment.
- a second part of electric propulsion composed by one or two electric motors, each one of them driving a fixed blade propeller.

2.2 Modelling of the Permanent Magnet Synchronous Motor

By the Park transformation, the voltage equations of the permanent magnet synchronous motor are written as follows (Grellet and Clerc, 2000):

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$$\begin{cases} v_d = R_s i_d + L_d \dfrac{di_d}{dt} - p\Omega L_q i_q \\ v_q = R_s i_q + L_q \dfrac{di_q}{dt} + p\Omega L_d i_d \end{cases} \quad (1)$$

The motor torque is given by:

$$C_e = p\Phi_f i_q + p(L_d - L_q) i_d i_q \quad (2)$$

The mechanical equation can be written as following:

$$I_m \dot{\Omega} = C_e - Q_{prop} \quad (3)$$

with:
Φ_f : inductor flux,
R_S : stator phase resistance,
v_d : stator voltage longitudinal component,
v_q : stator voltage transverse component,
i_d : stator current longitudinal component,
i_q : stator current transverse component,
L_d : longitudinal inductance,
L_q : transverse inductance,
I_m : shaft inertia,
P : pole pairs numbers,
Ce : electromagnetic torque,
Q_{prop} : propeller torque,
Ω: shaft speed.

2.3 Hull Resistance

During displacement, the ship is confronted to several constraints among them, the sea state, conditioned by the climatic data which is a significant factor influencing the ship behaviour. The sea applies a resistance which is opposed to the ship moving forward. Thus, to study the ship movement, it is necessary, on the one hand, to model its displacement and, on the other hand, to know the constraints which are opposed to its movement as presented in the figure 1 (Dallagi and Nejim, 2006).

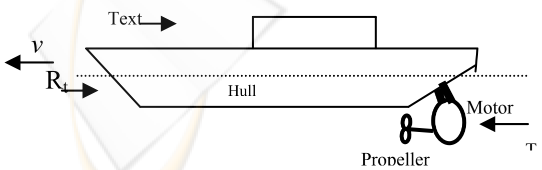

Figure 1: Ship movement.

The advance total resistance to is given by:

$$R_t = R_f + R_w + R_{app} + R_{air} \quad (4)$$

with:

R_t : advance total resistance,
R_f : friction resistance,
R_W : waves resistance,
R_{app} : appendices resistance,
R_{air} : air resistance.

This modeling is based on the resistance tests of the ship. Thus, total resistance to advance can be represented by the sum of four resistances (4). It is obtained by applying different practical pulling tests on the similarity model (Izadi-Zamanabadi and Blank, 2001. Doutreleau and Codier, 2001).
Resistance to advance can be modeled by a function of the following form (Dallagi and Nejim, 2006):

$$R_t = av^2 \quad (5)$$

with:
v: ship speed,
a: constant coefficient of the following curve.

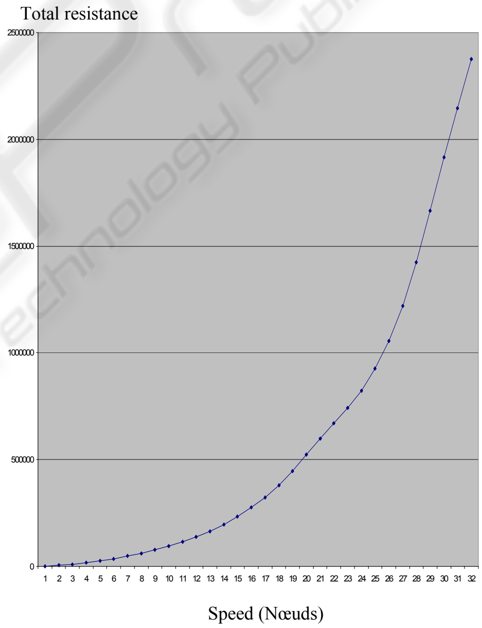

Figure 2: Advance total resistance.

2.4 Equations of the Propeller

The model of propeller thrust can be written as follows (Fosen and Blanke, 2000).(Guo, Zheng, Wang and Shen, 2005):

$$K_T = \frac{T}{\rho N^2 D^4} \quad (6)$$

with T the propeller thrust given by:

$$T = \rho n^2 D^4 K_T \quad (7)$$

The model propeller torque can be written as follows:

$$K_Q = \frac{Q_{prop}}{\rho\, n^2 D^5} \qquad (8)$$

with Q_{prop} the propeller torque given by:

$$Q_{prop} = \rho\, n^2 D^5 K_Q \qquad (9)$$

The coefficients K_T and K_Q given respectively by (6) and (8) depend on the following parameters (Izadi-Zamanabadi and Blank):
v_a : advance speed (m/s), p_a : propeller pitch,
v : ship speed (m/s), J : advance coefficient,
w : wake coefficient , n : propeller speed (tr/s).
Coefficients K_T and K_Q are given from ship practical tests. The advance coefficient is given by (Devauchell, 1986). (Lootsma, Izadi-Zamanabadi and Nijmeijer, 2002):

$$J = \frac{2\Pi\, v_a}{nD} \qquad (10)$$

and the advance speed is written as:

$$v_a = (1-w)v \qquad (11)$$

Coefficients K_T and K_Q can be represented by the affine lines having the following forms:

$$K_T = r_1 + r_2 J \qquad (12)$$

$$K_Q = s_1 + s_2 J \qquad (13)$$

The substitution of equations (10), (11), (12) in (7) gives:

$$T = \rho\, n^2 D^4 \left(r_1 + r_2 \frac{2\Pi(1-w)v}{nD}\right) \qquad (14)$$

by replacing the equations (10), (11) (13) in (9), it yields:

$$Q_{prop} = \rho\, n^2 D^5 \left(s_1 + s_2 \frac{2\Pi(1-w)v}{nD}\right) \qquad (15)$$

The ship motion equation is given by (Fosen and Blanke 2000):

$$m\dot{v} = -R + (1-t)T - T_{ext} \qquad (16)$$

2.5 Global Model of the Ship Electric Propulsion System

The global model of the ship electric propulsion using synchronous motor is represented by the following system.

$$\begin{cases} \dot{x} = f(x) + g(x)u \\ y_s = h(x) \end{cases} \qquad (17)$$

with:

$$f(x) = \begin{pmatrix} (1/2\Pi I_m)[(p(L_d - L_q)i_d i_q + p\Phi_f i_q) \\ \quad -(s_1 \rho n^2 D^5) - (s_2 \rho n D^4 2\Pi(1-w)v)] \\ (1/m)[-av^2 + (1-t)r_1 \rho D^4 n^2 \\ \quad +(1-t)2\Pi(1-w)r_2 \rho D^3\, nv - T_{ext}] \\ \frac{-R_s}{L_d} i_d + \frac{p2\Pi\, nL_q}{L_d} i_q \\ \frac{-p2\Pi\, nL_d}{L_q} i_d - \frac{R_s}{L_q} i_q - \frac{p2\Pi\, n\Phi_f}{L_q} \end{pmatrix}$$

$$g(x) = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix} \text{ and } h(x) = \begin{bmatrix} n \\ id \end{bmatrix}$$

The following figure gives the structure of the ship electric propulsion system and its different subsystems:

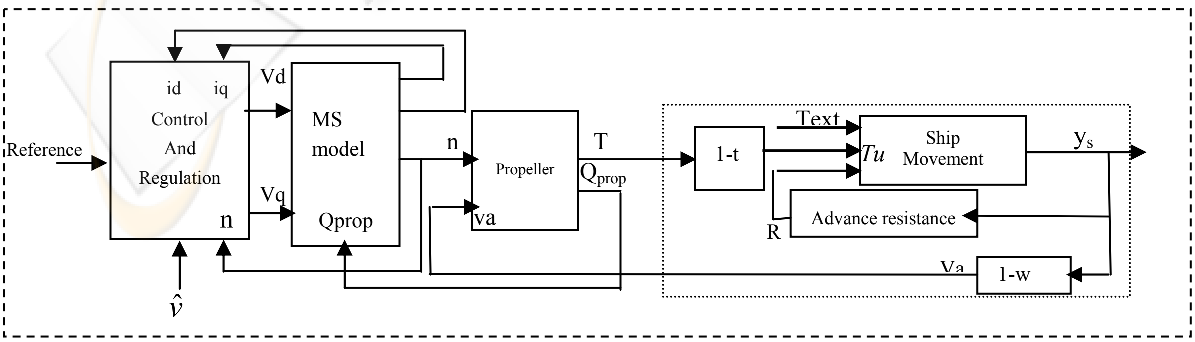

Figure 3: Synoptic of the ship propulsion system.

3 LINEARIZATION OF THE SHIP ELECTRIC PROPULSION SYSTEM

An industrial system is often intended to operate in regulation mode, i.e. the system output has to track an imposed the reference signal despite of the various disturbances. Under these conditions, the use of nonlinear state representation for the purpose of control is not necessary. A linear local state representation is sufficient.

The linearization of (17), around an operating point characterized by (x_0, y_0, u_0), is given by:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \tag{18}$$

with:

$x = [n, v, i_d, i_q]^T$ the state vector

$u = [v_q \quad v_q]^T$ the input vector,

$y_s = [n \quad i_d]^T$ the output vector.

A, B and C are the Jacobien matrices given by:

$A = \frac{\partial f}{\partial x}\Big|_{x=x_0}$; $B = \frac{\partial f}{\partial u}\Big|_{u=u_0}$ and $C = \frac{\partial h}{\partial x}\Big|_{x=x_0}$

$$A = \begin{bmatrix} \frac{a_n}{2\Pi I_m} & \frac{a_v}{2\Pi I_m} & \frac{a_{id}}{2\Pi I_m} & \frac{a_{iq}}{2\Pi I_m} \\ \frac{b_n}{m} & \frac{b_v}{m} & 0 & 0 \\ c_n & 0 & c_{id} & c_{iq} \\ d_n & 0 & d_{id} & d_{iq} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

with:

$$a_{iq} = 2\Pi p \Phi_f + p(L_d - L_q)\, i_{d0}$$

$$a_v = -\rho 2\Pi D^4 s_2 (1 - w_0)\, n_0$$

$$a_{id} = p(L_d - L_q) i_{d0}$$

$$a_n = -2s_1 \rho D^5 n_0 - s_2 \rho 2\Pi D^4 (1 - w_0) v_0 + p(L_d - L_q)\, i_{d0}$$

$$b_n = 2a_1 \rho D^4 (2\Pi)^2 (1 - t_0) n_0 + (1 - t_0) 2\Pi (1 - w_0) a_2 \rho D^3 v_0$$

$$b_v = -2a v_0 + a_2 \rho D^3 (1 - t_0) 2\Pi (1 - w_0) n_0$$

$$c_n = p \frac{L_q}{L_d} i_{q0}, \quad c_{id} = -\frac{R_s}{L_d}, \quad c_{iq} = \frac{2\Pi p n_0 L_q}{L_d}$$

$$d_n = -p \frac{L_d}{L_q} i_{d0} - p 2\Pi \frac{\Phi_f}{L_q}, \quad d_{iq} = -\frac{R_s}{L_q}$$

$$d_{id} = \frac{p 2\Pi n_0 L_d}{L_q}$$

4 OPTIMAL CONTROL OF THE SHIP ELECTRIC PROPULSION

4.1 Principle of the Optimal Control

To obtain an optimal control law for the ship electric propulsion system, we minimize the following criterion (Toscano, 2005). (Rachid and Mehdi, 1997 (Corriou , 1996.):

$$J = \frac{1}{2} \int_0^\infty (u^T R\, u + \varepsilon^T Q\, \varepsilon) dt \tag{19}$$

with:

R a symmetric positive definite matrix,

Q a symmetric non-negative definite matrix,

$\varepsilon(t) = e(t) - y(t)$ is the difference between the reference and the output vector.

The control law is then given by:

$$u(t) = Fe(t) - Kx(t) \tag{20}$$

where:

- $e(t) = [i_{dref} \quad v_{ref}]^T$ is the reference vector.
- K is control gain matrix defined by:

$$K = R^{-1} B^T P \tag{21}$$

- F is reference gain matrix given by:

$$F = R^{-1} B^T (A^T - PBR^{-1} B^T)^{-1} PC^T Q \tag{22}$$

with P the solution of the following Riccati equation:

$$A^T P + PA - PBR^{-1} B^T P + C^T QC = 0 \tag{23}$$

4.2 The Ship Speed State Observer

To design the sate feedback optimal control law, it is necessary to reconstruct the ship speed v in order to be controlled. For this purpose, we propose a linear state observer using the output vector $y_s = [i_d \quad n]$ and the vector $u = [u_d \quad u_q]$.

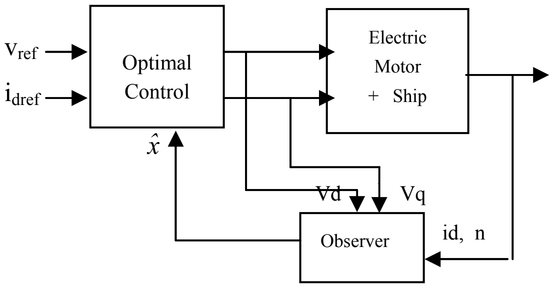

Figure 4: Control with ship speed observer.

The structure a luenberger observer is given by (Stoorvogel , Saberi and Chen 1994). (Mieczarski, 1988):

$$\begin{cases} \dot{\hat{x}} = A\hat{x} + Bu + L(y_s - \hat{y}) \\ \hat{y} = C\hat{x} \end{cases} \quad (24)$$

where:

$\hat{x}$ is the output vector of the state observer
L is the observer gain
This structure can be written in this form:

$$\dot{\hat{x}} = \hat{A}\hat{x} + Bu + Ly_s \quad (25)$$

with : $\hat{A} = A - LC$

To have an asymptotic convergence of the observed state towards the real state, it is necessary to choose the gain L such that the matrix $(A - LC)$ has negative real part eigen values. The control law using the state observer is presented as follows:

$$u(t) = Fe(t) - K\hat{x}(t) \quad (26)$$

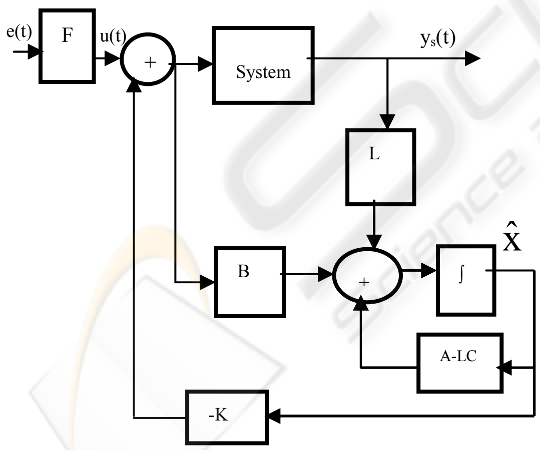

Figure 5: Observed state feedback control.

5 SIMULATION RESULTS SECOND SECTION

A digital simulation of the proposed control law with the designed state observer has been carried out with on the ship electric propulsion system using the following characteristics.

Para.	value		Par.	Value
ρ	1025 Kg/m ^{3}		Q_n	3.1480010 ^{5} Nm
D	5.9 m		T_n	3.82000 10 ^{5} N
m	20690000 kg,		Q_f	0.382 10 ^{5}
t	0.178		$T_{ext.}$	-1.8*0.1*10^5N
w	0.2304		s_1	0.075
a	1.54 10 ^{6}		s_2	0.1375
r2	1.1		r_1	0.5

The resolution of the Riccati equation (23) yields to:

- The optimal control gain:

$$K = \begin{bmatrix} 0.9807 & 0.0520 & 10.3830 & -0.0002 \\ 0.1064 & 0.0467 & 9.7618 & 0.0030 \end{bmatrix}$$

- The observer gain:

$$L = \begin{bmatrix} 3.5 & 1964.8 \\ -10.6 & -339.6 \\ 0.1 & 6.6 \\ 10.3 & 1362.9 \end{bmatrix}$$

The resolution of the equation (22) gives the reference gain:

$$F = \begin{bmatrix} 0.9963 & -3.05078 \\ 0.1064 & 26.3032 \end{bmatrix}$$

For the designed control, we impose i_{dref}=0, so that the electromagnetic torque C_e will be proportional to i_q.

In order to control the ship speed v it is necessary to change the motor speed n through the stator component i_q which modify the electromagnetic torque (Dallagi and Nejim, 2005).

The performances of the proposed strategy control law are depicted in the figures 6, 7, 8 and 9.

The ship speed is needed to reach the reference speed value V_{ref}=8m/s in the interval [0 150s] and V_{ref}=10m/s in the interval [150 300s].

It appears from figure 6, that the proposed control law allows a convergence towards the desired value of the ship speed v.

The figure 7 shows the behavior of the motor speed. It's clear that the ship speed changes where the variation of the propeller speed changes. Furthermore, we impose i_{dref}=0, so the electromagnetic torque becomes proportional to statoric current i_q.

In order to control the motor speed n, one modify the electromagnetic torque C_{em} by changing the stator current i_q through the regulation of the voltage component v_q.(Grellet and Clerc,2000).

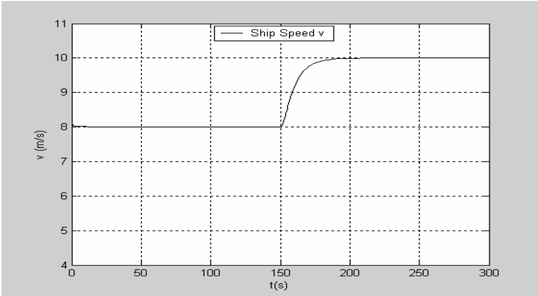

Figure 6: Ship Speed.

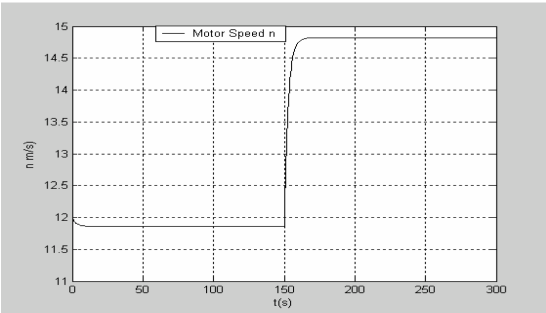

Figure 7: Motor Speed.

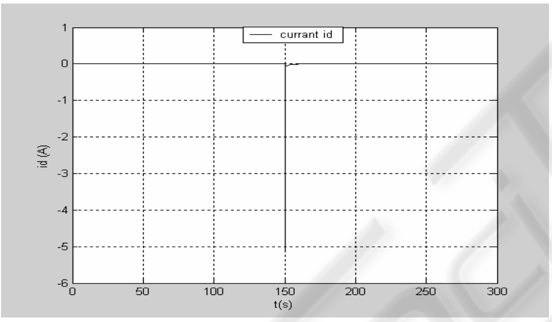

Figure 8: Current id.

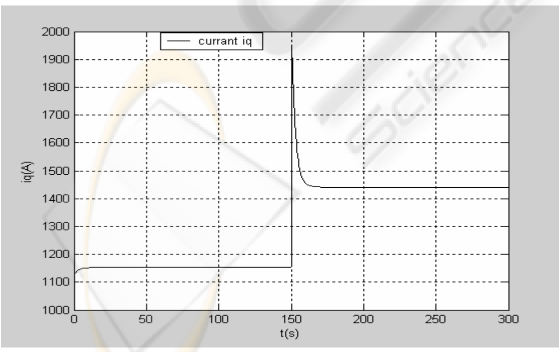

Figure 9: Current iq.

6 CONCLUSIONS

In this paper we have proposed an optimal control law using a Luenberger sate observer to control the ship speed.

The designed observer is used to reconstruct the ship speed in order to complete the control strategy. It has been shown from the simulated results that the proposed estimated state feedback optimal control permits the regulation of the ship speed which converges exactly to the imposed reference.

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