INTRODUCTION

1. Necessary of the dissertation's topic

Twin Rotor MIMO System (TRMS), developed by Feedback Instruments Ltd (Feedback Co., 1998), is experimental setup which is an opened platform, and has been applied PID control algorithms.

Although TRMS has been fabricated since 1998, nearly 20 years, it was interested by many researchers in a field of Control and Automation, and there are many publications about control strategies for TRMS.

Due to a control point of view, TRMS has been considered as a typical plant in the motion control system with multiple inputs and multiple outputs (MIMO), which is uncertain parameter, high order, nonlinear, and significant coupling system. Therefore the main works of this dissertation is researching to select reasonable control strategies in order to obtain the best tracking performance of the system.

2. Object, Scope and Case study methods

Object of the study: Dissertation researches on TRMS, the typical plant in MIMO motion control system, which is uncertain parameter, high order, nonlinear, and significant coupling system.

Scope of the study: dissertation focuses on the specific characteristics and difficulties of TRMS. Based on the sophisticated characteristics of the process, there are challenges in modeling, analyzing and choosing new control design methods in order to get the high tracking performance.

Case study methods: Dissertation applies the method of analysis, evaluation and synthesis. Through the general literature reviews, the main problems are figured out to be solved both in theory and in algorithm design, then proofed the proposed theories by simulation and experiment.

3. The goals of the dissertation

The goals of this dissertation is to research and design nonlinear control strategies utilizing a state feedback for TRMS, and this results can be applied to other nonlinear systems. In detail the goals of this dissertation can be listed as followings:

- The nonlinear dynamic model of TRMS: the more precise model is a core condition to be successful with any control technique based on the model, so we need to build up a plant model which is reasonable to control design method.

- Design RHC combining with LQR algorithm for the system under the effects of noise. The performance of the control algorithm can be estimated via theory and experiment results. Setting and applying flexibly the control algorithm on the TRMS system.

4. Contributions of the dissertation

Dissertation has detail contributions such as:

- Builds up the mathematical model of the TRMS with the least error in comparison to real model.
- Designs a continuous RHC combining with LQR algorithm for nonlinear system under the present of noise, and unprecise model.

Scientific significance of the dissertation:

- Providing a new theory in robust control for nonlinear system that is combination of RHC and LQR
- Proposes the flexible setting solution in order to improve the effect of the hardware.
- Setting and programming to solve Riccati equation in real-time.

Practical Significance of the dissertation:

- Supporting for investigation about control and automation of University;
- The research results can be applied to other nonlinear system.

5. Structure of the dissertation

Dissertation includes opening statement, 04 chapters and conclusions, and it is organized as following:

Chapter 1. Literature reviews about control strategies for Twin Rotor MIMO System (TRMS)

Firstly, it presents an investigation about the device based on information provided by provider; statistics and analysis of advantages and disadvantages of the modern control methods; the existing control schemes which have been applied for TRMS. Figures out the specific characteristics and difficulties when design a controllers for TRMS, therefore proposes reasonable control strategies for the system deal with nonlinear, parameter uncertainties, coupling, and noises.

Chapter 2. Mathematical model of TRMS

Mathematical model describing dynamics of TRMS is provided in form of Newton second law's equation by provider, which does not contain of influence factors (such as simplifies the system, assumes that dynamics of the system are described by differential equations, or system's friction is viscous, …).

The mathematical model of TRMS in this chapter is built up according to Lagrange equation with a small error in comparison with real model, because it takes influence factors into account (such as the length of pivoted beam, surface effect). A full, and precise mathematical model is a background to design controllers which satisfy the performance requirements of the output response in next sections.

Chapter 3. Design of the position tracking control for nonlinear TRMS system

Control of TRMS is a challenge, but it interests many researchers. Up to now, there have had many different control methods applied to TRMS. Nonlinear system generally or TRMS specifically, it is expected to design controllers in order to overcome the error of the model, and avoid noise effects.

This chapter talks about the proposed control scheme, RHC combining with LQR, for the continuous model of the plant under the presence of noise and model error which is a main contribution of the dissertation.

Chapter 4. Experimental results

The proposed control algorithm is set up and run on real TRMS with Card DS1103. Riccati equation is also solved in real time via Card DS1103. Moment forcing method is used when applying the proposed control algorithm for TRMS in order to compensate dynamics for the actuator. The experimental results indicate that the proposed algorithm is completely right.

Conclusion: Dissertation points out the highlight contributions and Recommendations

CHAPTER 1
REVIEWS OF CONTROL STRATEGIES FOR TWIN ROTOR MIMO SYSTEM (TRMS)

1.1. Introduction to Twin Rotor MIMO system (TRMS)

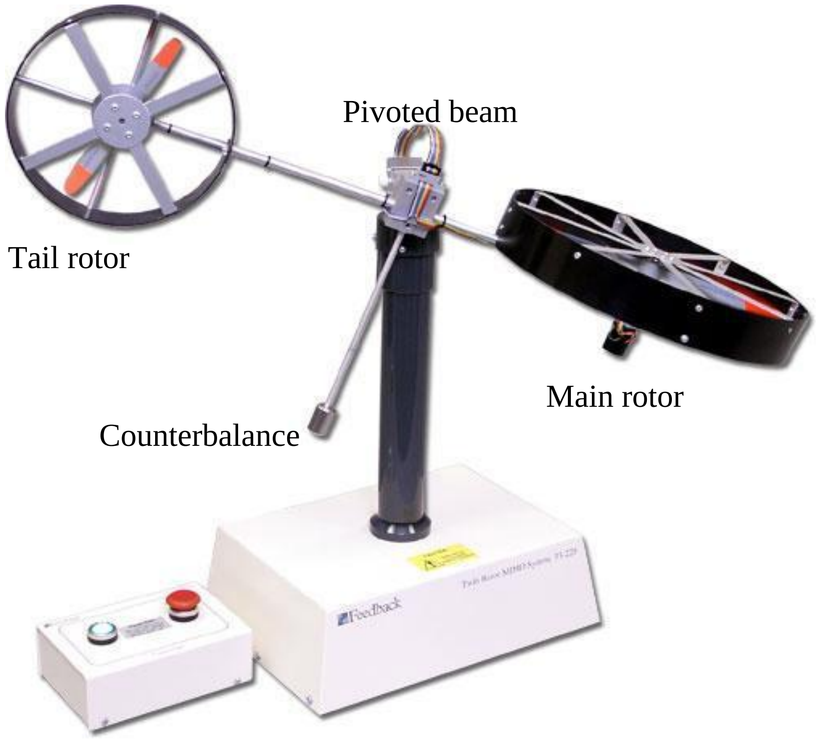


Figure 1.1. Twin Rotor MIMO System (TRMS)

Figure 1.1 describes Twin Rotor MIMO System (TRMS) which is an experimental setup designed by Feedback Instruments Ltd. It is used for developing and testing modern control techniques in laboratory. TRMS includes main and tail rotors which are placed perpendicularly on the free beam.

Each propeller is freely drived by a DC motor where the rotational direction of the propeller can be reversed, and the speed of the motor can be adjusted by changing the voltage. The main propeller creates the thrust to make the free beam move along a vertical plane (denoted by α_v) as seen on Figure 1.2 and Figure 1.3.

Tail propeller provides thrust to move the free beam along horizontal plane (denoted by α_h) as seen on Figure 1.2 and Figure 1.4. Counterbalance beam is perpendicularly placed with the free beam at the center point. The position of the counterbalance can be adjusted in order to change the parameters of the plant during the experimental process.

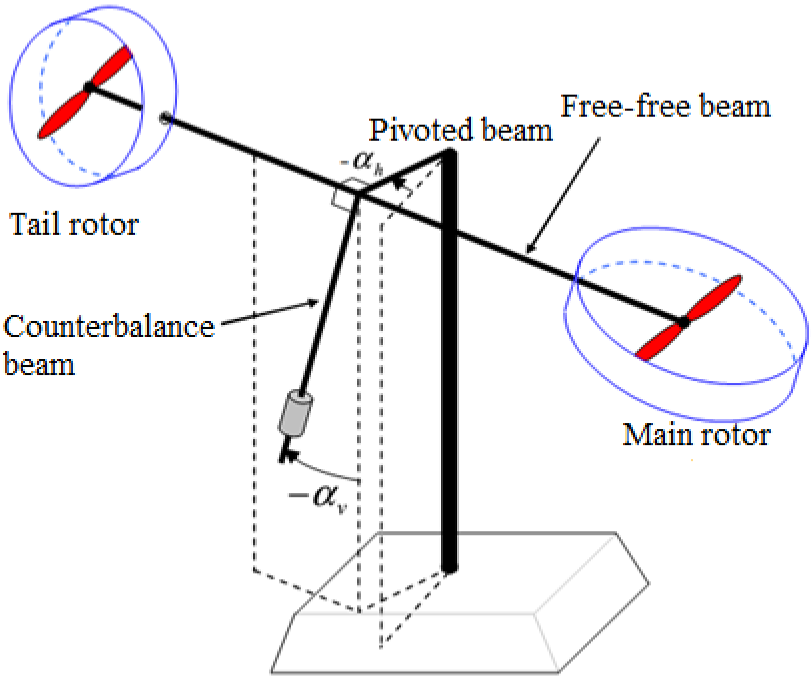


Figure 1.2. Positions in 3D space of TRMS

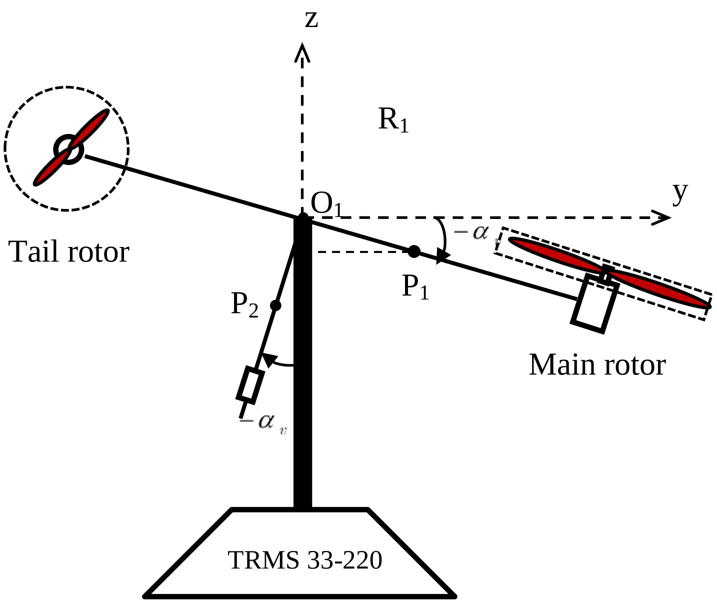


Figure 1.3. Angle position on the vertical plane α_v of TRMS

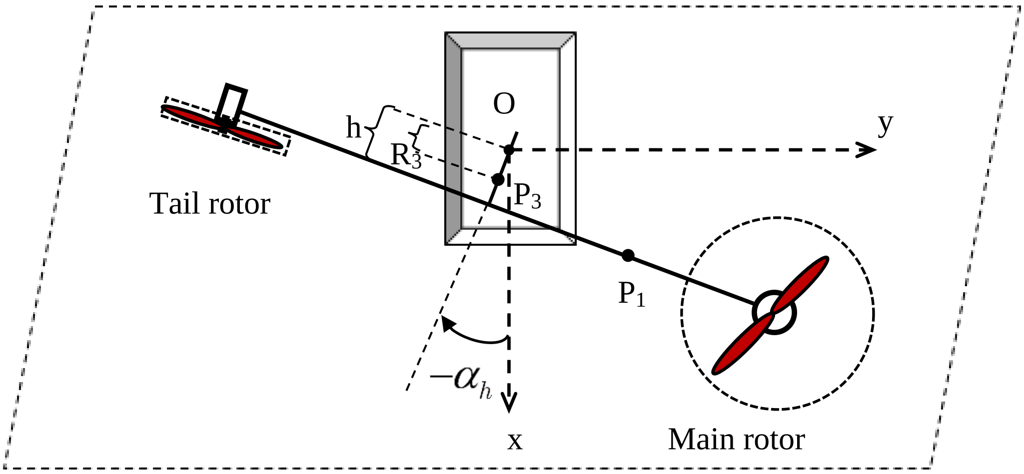


Figure 1.4. Angle position on horizontal plane α_h of TRMS

Besides, TRMS is equipped angle position sensors (encoder) to measure exactly the angle position of the free beam on the horizontal and vertical planes. Each rotor is attached one generator to measure the rotational speed.

1.2. Literature reviews of TRMS research in the world

Although TRMS can not fly, TRMS has many dynamic characteristics of helicopter. TRMS has many versions up to now, but it still remains specific dynamic features. TRMS is typical for a MIMO nonlinear system in the presence of coupling phenomena and noises. Modeling and controlling is an interesting, and challenging problem to researchers. Nowadays, there are many publications about modeling and controlling of TRMS.

1.2.1. Modeling TRMS

TRMS is modeled using Newton and Euler-Lagrange methods. The model based on Euler-Lagrange is more precise like real model than Newton model.

1.2.2. Control of TRMS

TRMS is a popular plant used for testing new control algorithms. The simplest controller for TRMS is PID controller. There are many studies applying AI, fuzzy logic algorithms on the system to find optimal parameters in order to guarantee good features, however these algorithms does not promise the robust characteristics. For the purpose of remaining the robust features, the system should be applied some algorithms like deadbeat, H_∞, SMC, and MPC algorithms.

1.3. Literature reviews of TRMS research in Vietnam

Nowadays there are nowadays not many publications in which MPC is applied on the TRMS control system based on the discontinuous model, and the adaptive control (ISS) controller combining with the PID controller is applied for the speed control loop.

Based on the general reviews of the studies in the world and in Vietnam, this dissertation proposes the RHC combining with LQR control algorithm. The most challenge of the study is to obtain the more precise mathematical model of TRMS, and to apply and run sucessfully the proposed algorithm in real time.

1.4. Conclusion

Chapter 1 presents general reviews of the TRMS system including features and publications about TRMS in the world and Vietnam. In a control point of view, TRMS is considered as a typical plant in MIMO motion control systems with high nonlinear order, significant coupling, model uncertainty and noise acting on it. Thus the tracking performance is a core content. From that we can see the necessaries, goals, and proposed solutions of the dissertation,

CHAPTER 2
DYNAMIC MODEL OF TWIN ROTOR MIMO SYSTEM

2.1. Introduction

The mathematical model of any plant is a system of equations which describes its features. In order to analyze the plant its mathematical model is a first choice, based on that the controller can be designed. The more precise mathematical model we have, the higher control performance we can obtain.

The most popular methods to build the mathematical model of the plant are Newton, and Euler-Lagrange. These methods are called white box models. These methods require the deep understanding about the parameters, structure, and physical features of the plant. The mathematical model built as a black box model requires the input, output data of the plant, GA algorithm is used to identify the model, but this method can cause losing of the structure of the plant model while the advantages of this method are easily to obtain the acceptable mathematical model of the plant. Next contents of this chapter show the mathematical model of the plant established by Euler-Lagrange method. Dynamic model of TRMS is described in the joint variable space.

2.2. Building dynamic mathematical model of TRMS

2.2.1. Assumptions

It is more convenient to build TRMS model based on Euler-Lagrange, if we use the following assumptions:

- Total energy of the system is remained and independent on the time.
- Materials of each component of TRMS should be the same.
- Components of TRMS are rigid links.
- Components of TRMS are considered as a point
- Only takes dynamics of DC motor driving the propeller into account.

2.2.2. Dynamic equations of TRMS

Euler-Lagrange equations of the motion

- Lagrange function:

$$L\left(\alpha_v,\alpha_h,\dot{\alpha}_v,\dot{\alpha}_h,\omega_m,\omega_t\right)=\sum_{i=1}^{5}K_i-\left(V_1+V_2+V_3\right)$$

$$\begin{aligned}L&=a_1\dot{\alpha}_v^2+\left(a_5+a_4\cos^2\alpha_v\right)\dot{\alpha}_h^2+\dot{\alpha}_v\dot{\alpha}_h\left(a_2\cos\alpha_v-a_3\sin\alpha_v\right)\\&\quad+a_6\dot{\alpha}_t^2+a_7\dot{\alpha}_m^2+2a_7\dot{\alpha}_h\cos\alpha_v\dot{\alpha}_m+2a_6\dot{\alpha}_v\dot{\alpha}_t-b_1\sin\alpha_v+b_2\cos\alpha_v\end{aligned} \tag{2.1}$$

$a_1=J_1+J_2+J_{tr},\quad a_2=m_{T2}l_{T2}h,$

$a_3=m_{T1}l_{T1}h,\quad a_4=J_1+J_{mr}-J_2,$

$a_5=J_3+J_4+m_{T2}h^2+m_{T1}h^2+J_2,$

$a_6=J_{tr},\quad a_7=J_{mr},$

$b_1=m_{T1}l_{T1}g,\quad b_2=m_{T2}l_{T2}g,$

$\dot{\alpha}_t=\omega_t,$

$\dot{\alpha}_m=\omega_m$

- Euler-Lagrange equations for freedom orders of the system (2.2)-(2.5):

$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{\alpha}_v}\right)-\frac{\partial L}{\partial\alpha_v}=M_v \tag{2.2}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{\alpha}_h}\right)-\frac{\partial L}{\partial\alpha_h}=M_h \tag{2.3}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{\alpha}_m}\right)-\frac{\partial L}{\partial\alpha_m}=M_m \tag{2.4}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{\alpha}_t}\right)-\frac{\partial L}{\partial\alpha_t}=M_t \tag{2.5}$$

A system of equations (2.2)-(2.5) is rewritten as (2.6)

$$M(\alpha_v)\begin{bmatrix}\ddot{\alpha}_v\\\ddot{\alpha}_h\\\dot{\omega}_m\\\dot{\omega}_r\end{bmatrix}+C(\alpha_v,\alpha_h,\dot{\alpha}_v,\dot{\alpha}_h,\omega_m,\omega_r)\begin{bmatrix}\dot{\alpha}_v\\\dot{\alpha}_h\\\omega_m\\\omega_r\end{bmatrix}+G(\alpha_v)=M_{ext} \tag{2.6}$$

with an inertial matrix $M(\alpha_v) \in \mathbb{R}^{3\times3}$

$$M(\alpha_v) = \begin{bmatrix} a_1 & a_2\cos\alpha_v - a_3\sin\alpha_v & 0 & a_6 \\ a_2\cos\alpha_v - a_3\sin\alpha_v & a_5 + a_4\cos^2\alpha_v & a_7\cos\alpha_v & 0 \\ 0 & a_7\cos\alpha_v & a_7 & 0 \\ a_6 & 0 & 0 & a_6 \end{bmatrix}$$

Coriolis and centrifugal force vectors

$$C(\alpha_v, \alpha_h, \dot{\alpha}_v, \dot{\alpha}_h, \omega_m, \omega_r) = \begin{bmatrix} 0 & \sin\alpha_v(a_4\dot{\alpha}_h\cos\alpha_v + a_7\omega_m) & 0 & 0 \\ c_{21} & -a_4\sin\alpha_v\cos\alpha_v\dot{\alpha}_v & 0 & 0 \\ 0 & -a_7\dot{\alpha}_v\sin\alpha_v & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$c_{21} = -a_4\sin\alpha_v\cos\alpha_v\dot{\alpha}_h - a_7\omega_m\sin\alpha_v + \left(a_2\cos\alpha_v + a_3\sin\alpha_v\right)\dot{\alpha}_v$$

gravitational force vector

$$G(\alpha_v) = \left[b_2\sin\alpha_v + b_1\cos\alpha_v \quad 0 \quad 0 \quad 0\right]^T,$$

moment acting on the system

$$M_{ext} = \left[M_v \quad M_h \quad M_m \quad M_t\right]^T,$$

$$M_v = sign(\omega_m)l_m k_{fv}\omega_m^2 w - sign(\omega_t)k_{tr}\omega_t^2 - B_v\dot{\alpha}_v - F_v sign(\dot{\alpha}_v) - sign(\omega_m)k_g l_m k_{fv}\omega_m^2\gamma\dot{\alpha}_h\cos\alpha_v$$

$$M_h = sign(\omega_t)l_t k_{fh}\omega_t^2\cos\alpha_v - sign(\omega_m)k_{tm}\omega_m^2\cos\alpha_v - B_h\dot{\alpha}_h - F_h sign(\dot{\alpha}_h) - C_c\left(\alpha_h - \alpha_{h0}\right)$$

$$M_m = \tau_m - sign(\omega_m)k_{tv}\omega_m^2 - B_{mr}\omega_m$$

$$M_t = \tau_t - sign(\omega_t)k_{th}\omega_t^2 - B_{tr}\omega_t, \ \gamma = \frac{1}{1 - \left(\dfrac{r_{mr}}{4\left(H + l_m\sin\alpha_v\right)}\right)^2}$$

Thus, Euler-Lagrange model of TRMS described by 4 equations (2.2)-(2.5) or (2.6) in the joint variable space $q = \left(\alpha_v, \alpha_h, \alpha_m, \alpha_t\right)$ with two input variables τ_m, τ_t. While Newton model provided by the provider has two input variables that are the voltage applied to main and tail motors. In some previous works the input variables are speeds of the main and tail motors.

2.3. Simulation and evaluation of the model qualities

In order to evaluate exactly the mathematical model, simulation should be done in Matlab/Simulink and real-time running is implemented with the same reference value. Characteristics of the real model are obtained by real-time running. TRMS is connected to PC, so the results are displayed and saved on PC for comparison and evaluation. Simulation features are compared to experimental features. The characteristics of the simulation model are more closed to those of the real model that means we can conclude which is more precise.

2.4. Conclusion

The mathematical model describing dynamics of TRMS in this dissertation is more exact because we consider to influent factors acting on the system (the length of pivot, surface effects) in comparison with the model provided by supplier. The precise of the model built in this dissertation is verified via simulating and experimenting results. The differences between the model in this dissertation and the model from the experiment are caused by the beginning assumptions. With the full and more precise mathematical model is a base to design the controller that can satisfy the control requirements in next sections.

CHAPTER 3
DESIGN OF A NONLINEAR CONTROLLER FOR TRACKING POSITION OF TRMS

3.1. The existing controllers

Controlling TRMS is a hard problem, there are many challenges, but it attracts researchers. There are up to now many control strategies applied for TRMS such as the classical PID controller or PID combining with decoupling controller. PID has a simple structure, however it is hard to determine the optimal parameters of the controller. Therefore it should be a combination of PID with some other algorithms like fuzzy logic, GA, … Sliding mode control (SMC), LQR, LQG are also applied and completed experimentally for TRMS. SMC is not new, and it has been used for many plants and industrial processes. Its algorithm is tested on TRMS as well. For TRMS with high nonlinear characteristics the nonlinear control is well selected.

It is expected that there are controllers can avoid the noises and model differences. Thus the next section will discuss about a new control strategy for TRMS based on the mathematical model obtained in previous sections.

3.2. The proposed adaptive control RHC combining with LQR

3.2.1. Introduction to the control algorithm based on the background of RHC

RHC method, known as MPC, is a type of the feedback control which has been developed since 1980's years. Based on RHC method, optimization problems are solved by step size in order to determine a set of inputs in the predictive time interval, then apply the first value of this set. In the next step size, this process is repeated to solve a new optimal problem with the predictive time shifted one step. Optimization plays a role of the future estimation based on the measured parameters and each.

RHC is nonlinear control which has input-output constraints and many purpose. Apply RHC, the parameter are control with their physical limits, derived performance gets advantage over linear control. RHC has succeed in applying in many areas, include control process technology and chemistry.

Nowadays RHC attracts attention of scientists to apply to many different objects base on combination with optimal methods. RHC is not only applied in process industries but also in motion controls and robot.

Next section, dissertation proposes the control algorithm RHC with LQR which is applied to object with continuous, perturb and error model. The proposed control algorithm is important attribution of dissertation.

3.2.2. Proposed control method

This section, dissertation presents designing of control algorithm RHC with LQR for nonlinear continuous perturbed system:

$$\begin{cases} \dot{\underline{x}} = \underline{f}(\underline{x},\underline{u}) + \underline{\varsigma} \\ \underline{y} = \underline{g}(\underline{x}) + \underline{\upsilon} \end{cases} \tag{3.1}$$

where:

$\underline{x} = (x_1, \ \dots \ , x_n)^T$ is vector of state,

$\underline{u} = (u_1, \ \dots \ , u_m)^T$ is vector of input signal,

$\underline{y} = (y_1, \ \dots \ , y_m)^T$ is vector of output signal,

$\underline{f}(\underline{x},\underline{u}), \ \underline{g}(\underline{x})$ are vectors of system's function with suitable dimension,

$\underline{\varsigma}, \ \underline{\upsilon}$ are vectors of unknown disturbances

So that output $\underline{y}(t)$ track to the reference $\underline{w}(t)$ stably, with the constrained circumstance of input signal.

The control algorithm: RHC with LQR for nonlinear continuous perturbed system

Step 1. set $\underline{u} = \underline{0}, \ \underline{x}^{/} = \underline{0}$. Choose arbitrarily two symmetric positive matrices Q, R (should choose matrix R enough big in order to have $\underline{u}$ small), $0 < \eta \le 1$ and $\delta > 0$. The constant δ is sampling time of system's state.

Step 2. Measure the vector $\underline{x}$ from system (3.1) and then determine $A, B,$ C as follows:

$$A = \left.\frac{\partial f}{\partial \underline{x}}\right|_{\underline{x},\underline{u}}, \quad B = \left.\frac{\partial f}{\partial \underline{u}}\right|_{\underline{x},\underline{u}}, \quad C = \left.\frac{\partial g}{\partial \underline{x}}\right|_{\underline{x}} \tag{3.2}$$

Step 3. Determine :

$$F = \begin{pmatrix} A & B \\ C & \Theta \end{pmatrix} \tag{3.3}$$

If F is singular, then go back to the step 2. On the contrary move to next step.

Step 4. Measure the vector $\underline{y}$ from system (3.1) and then determine $\underline{r},\ \underline{d},\ \hat{\underline{\varsigma}}, \hat{\underline{\upsilon}}$ as follows:

$$\begin{aligned} \underline{r} &= 2\underline{w} - \underline{y}, \\ \underline{d} &= \underline{f}(\underline{x},\underline{u}) - A\underline{x} - B\underline{u}, \\ \hat{\underline{\varsigma}} &= \frac{\underline{x} - \underline{x}^{/}}{\delta} - \underline{f}(\underline{x},\underline{u}), \\ \hat{\underline{\upsilon}} &= \underline{y} - C\underline{x} \end{aligned} \tag{3.4}$$

and then the current of steady value

$$\begin{pmatrix} \underline{x}_s \\ \underline{u}_s \end{pmatrix} = F^{-1} \begin{pmatrix} -\underline{d} - \hat{\underline{\varsigma}} \\ \underline{r} - \hat{\underline{\upsilon}} \end{pmatrix} \tag{3.5}$$

Step 5. Determine the symmetric positive root L of

$$LBR^{-1}B^T L - A^T L - LA = Q \tag{3.6}$$

Step 6. Calculate $\underline{u}$ as follow:

$$\underline{u} = -R^{-1}B^T L\left(\underline{x} - \underline{x}_s\right) + \underline{u}_s \tag{3.7}$$

And then control system with $\underline{u}$. Set $R = \mu R,\ \underline{x}^{/} = \underline{x}$ and go back step 2.

3.3. Simulation results of control TRMS

3.3.1. Apply proposed algorithm to control TRMS

To apply proposed algorithm to control TRMS, need to convert mathematical model (2.6) to model (3.1). Control structure RHC with LQR for TRMS as Figure 3.4

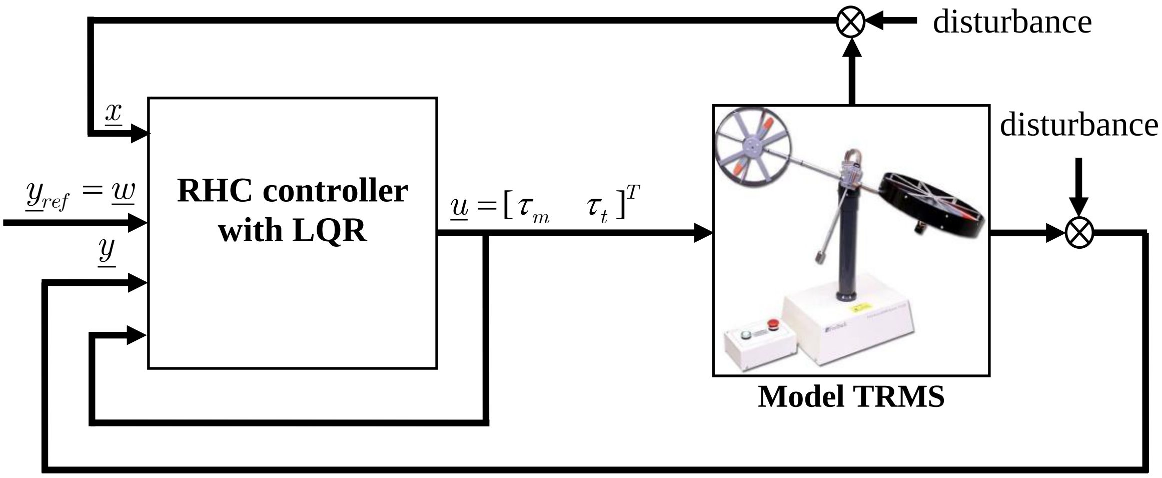


Figure 3.4. Control structure RHC with LQR for TRMS

Dynamic model of TRMS is convert to (3.1), with

$$\begin{aligned}\underline{x} &= \begin{bmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 \end{bmatrix}^T \\ &= \begin{bmatrix} \alpha_v & \alpha_h & \dot{\alpha}_v & \dot{\alpha}_h & \omega_m & \omega_t \end{bmatrix}^T\end{aligned} \tag{3.8}$$

$$\underline{y} = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T, \ \underline{u} = \begin{bmatrix} \tau_m & \tau_t \end{bmatrix}^T \tag{3.9}$$

$$\underline{f}(\underline{x},\underline{u}) = \begin{bmatrix} x_3 & x_4 & f_1(\underline{x},\underline{u}) & f_2(\underline{x},\underline{u}) & f_3(\underline{x},\underline{u}) & f_4(\underline{x},\underline{u}) \end{bmatrix}^T \tag{3.10}$$

where

$$\begin{aligned} f_1(\underline{x},\underline{u}) &= \beta_1(\underline{x}) + \lambda_1(\underline{x})\tau_m + \delta_1(\underline{x})\tau_t, \\ f_2(\underline{x},\underline{u}) &= \beta_2(\underline{x}) + \lambda_2(\underline{x})\tau_m + \delta_2(\underline{x})\tau_t, \\ f_3(\underline{x},\underline{u}) &= \beta_3(\underline{x}) + \lambda_3(\underline{x})\tau_m + \delta_3(\underline{x})\tau_t, \\ f_4(\underline{x},\underline{u}) &= \beta_4(\underline{x}) + \lambda_4(\underline{x})\tau_m + \delta_4(\underline{x})\tau_t, \end{aligned}$$

$$g(\underline{x}) = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T$$

The components $\beta_i, \lambda_i, \delta_i, i = 1,...,4$ are determined as follow

$$\begin{aligned}\beta_i(\underline{x}) = & -x_4^2 a_4 n_{i1} \cos x_1 \sin x_1 + x_3^2 n_{i2}(a_2 \sin x_1 + a_3 \cos x_1) - x_4 n_{i2} f_{rh} \\ & + x_3 x_4 \sin x_1 (2a_4 n_{i2} \cos x_1 + a_7 n_{i3}) - x_4 x_5 a_7 n_{i1} \sin x_1 \\ & + x_3 x_5 a_7 n_{i2} \sin x_1 + x_5^2 sign(x_5)(l_m k_{fv} n_{i1} - k_{tm} n_{i2} \cos x_1 - n_{i3} k_{tm}) \\ & + x_6^2 sign(x_6)(l_t k_{fh} n_{i2} \cos x_1 - k_{tr} n_{i1} - n_{i4} k_{tr}) - x_3 n_{i1} f_{rv} \\ & - x_5 B_{mr} n_{i3} - x_6 B_{tr} n_{i4} - b_1 n_{i1} \cos x_1 - b_2 n_{i1} \sin x_1 \\ \lambda_i(\underline{x}) = & \, n_{i3}, \quad \delta_i(\underline{x}) = n_{i4}\end{aligned} \tag{3.11}$$

where n_{ij} are elements of matrix $M^{-1}(\alpha_v)$.

3.3.2. Verify quality of control algorithm by simulating

Use software matlab- simulink to simulate to verify control algorithm

- Controller and model of object are programmed in S-function
- System is simulated under the influence of disturbance of states and input-output

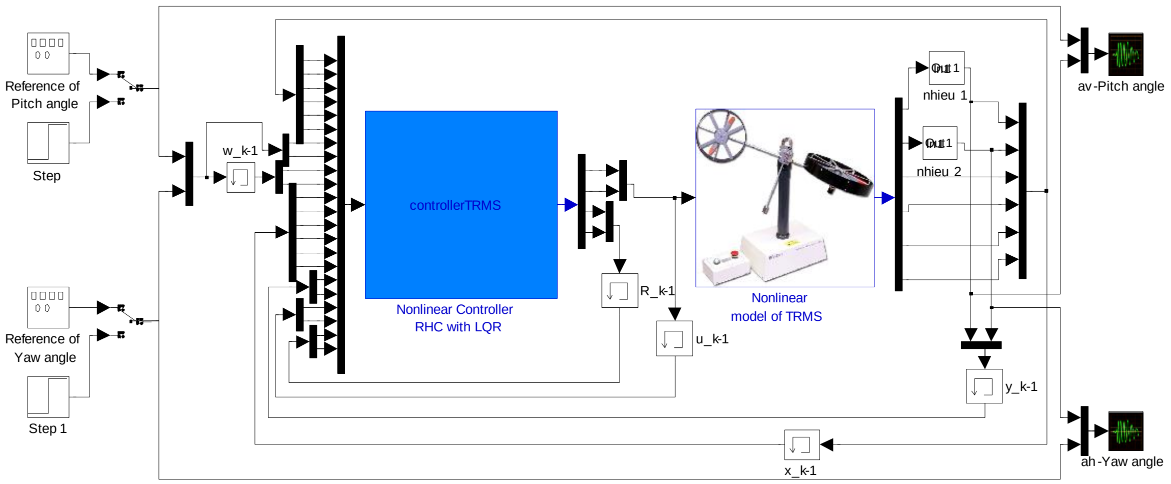


Figure 3.5. Siulation structure of control system TRMS with matrix R decending value

Simulation of control TRMS with sinusoidal -step reference and under influence of disturbance, results as follow:(*pitch angle:* α_v , *yaw angle:* α_h)

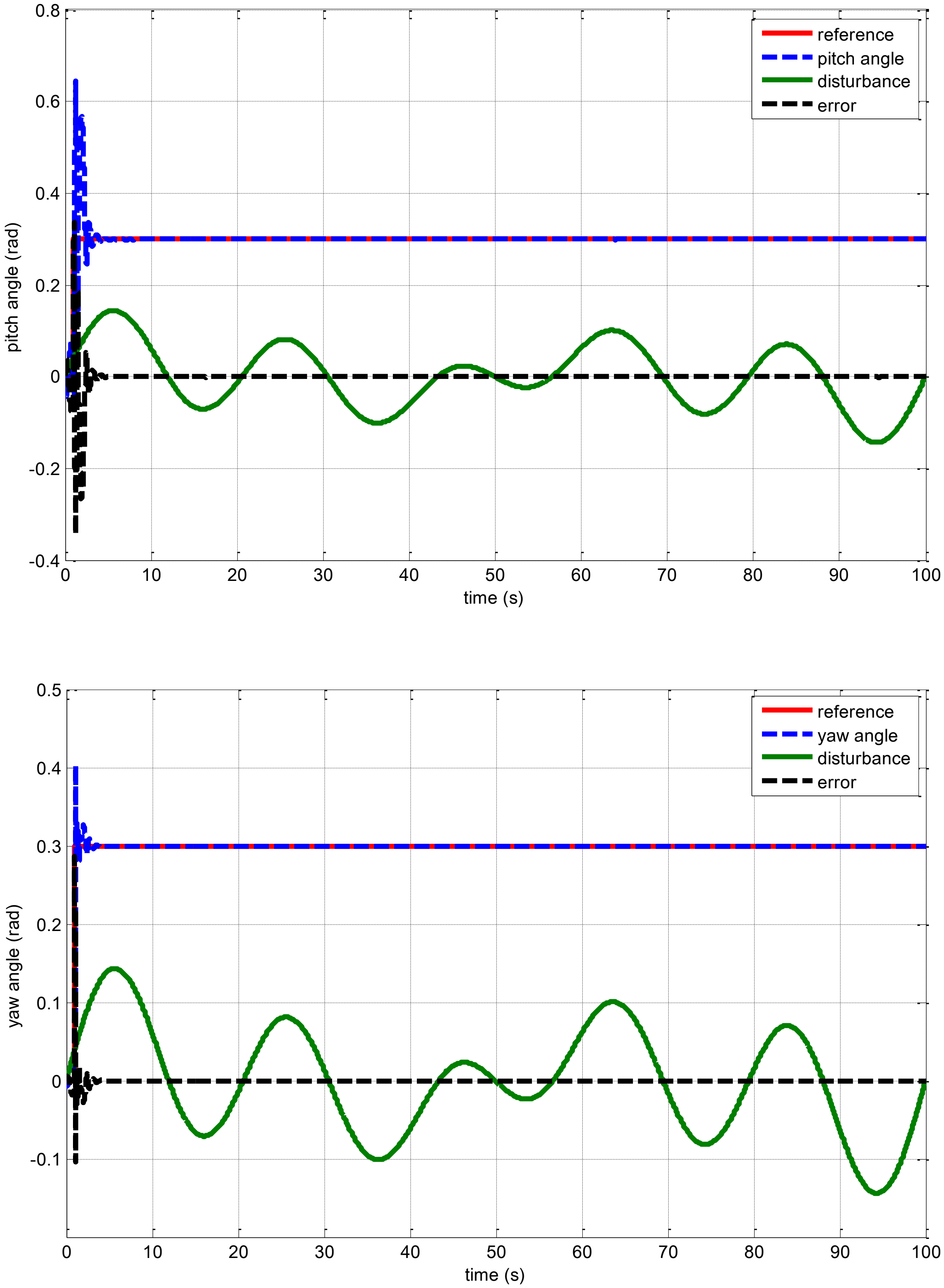


Figure 3.10. Output angle with step reference in 2 plane and disturbance

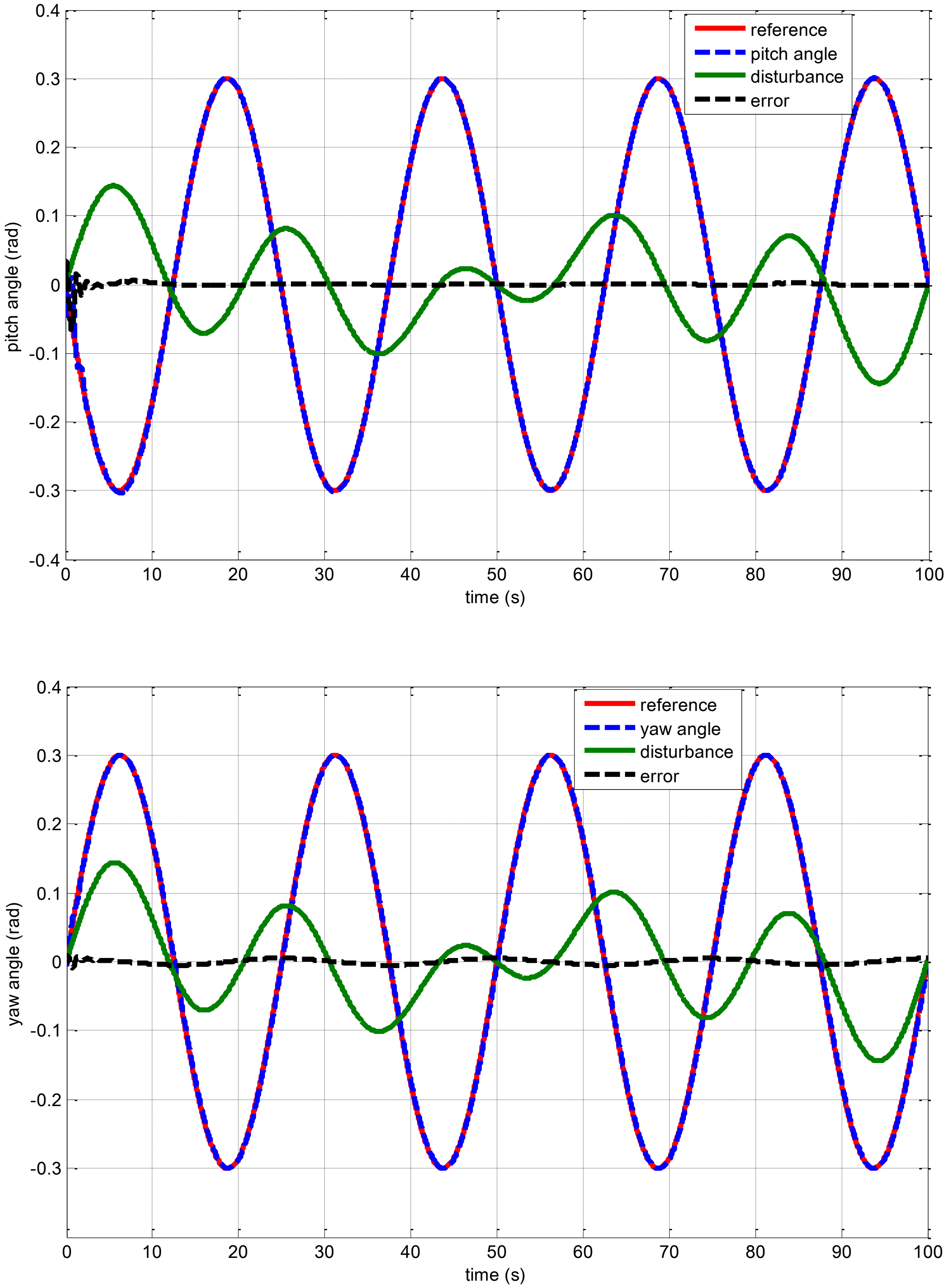


Figure 3.11. Output angle with sinusoidal reference in 2 plane and disturbance

3.3.3. Analyses of simulation results of the control algorithm

The simulation results of the TRMS control using the proposed algorithm shown in Figure 3.10 to Figure 3.11 show that the TRMS works stably, the output angles of the output position follow the set signal, the small deviation and more resistant to noise. In the above cases, the disturbance state is pulsed and slowly changing. In addition to the simulation cases with the above-mentioned noise, the simulator has performed the simulation in the case of noise disturbance on the remaining states, the output response shows that the system remains stable and follows the reference.

3.4. Conclusions

Chapter 3 of the dissertation solves the following problems:

- Proposed algorithms for controlling nonlinear systems to stick to the sample signal. The proposed control algorithms are noted as algorithm 1 and algorithm 2. Stability of the sample signal tracking is confirmed by the theorem 1.

- Based on the mathematical model in Chapter 2, controllers are designed for TRMS. Quality evaluations of the controllers using simulations on Matlab-Simulink are shown in Figure 3.5.

- The simulation results of the TRMS control are shown in Figures 3.10 and Figure 3.11, initially confirming the correctness of the new proposed algorithms and this is the condition for applying the algorithm to the TRMS object control. Because the simulations are conducted in ideal conditions, the gap between the simulated structure to the experimental verification is large.

For the final conclusion on the proposed control algorithm that will be applied in practice, the next section of the dissertation will focus on the experimental installation to control TRMS in real time.

CHAPTER 4
RESULTS OF EXPERIMENT

4.1. Introduction

A proposed control strategy which is only simulated cannot be completly convincible. Thus, an expreriment with real objects needs to be conducted to verify the usefullness of the strategy.

4.2. Control structure RHC with LQR for TRMS

In the experimental system, in order to have $\tau'_m = \tau_m$ and $\tau'_t = \tau_t$, the kinetics of actuators need to be compensated. The simple solution is to set a torque control loop aiming at applying the output torque of the controller to the object. For the sake of simplicity, in this dissertation, a PI controller is designed for the torque control. Thus, the experimental TRMS control structure (Figure 4.1) adds a torque control loop to the structure compared to the simulation in Chapter 3. This addition does not alter the nature of the RHC controller with LQR with the tracking control requirement.

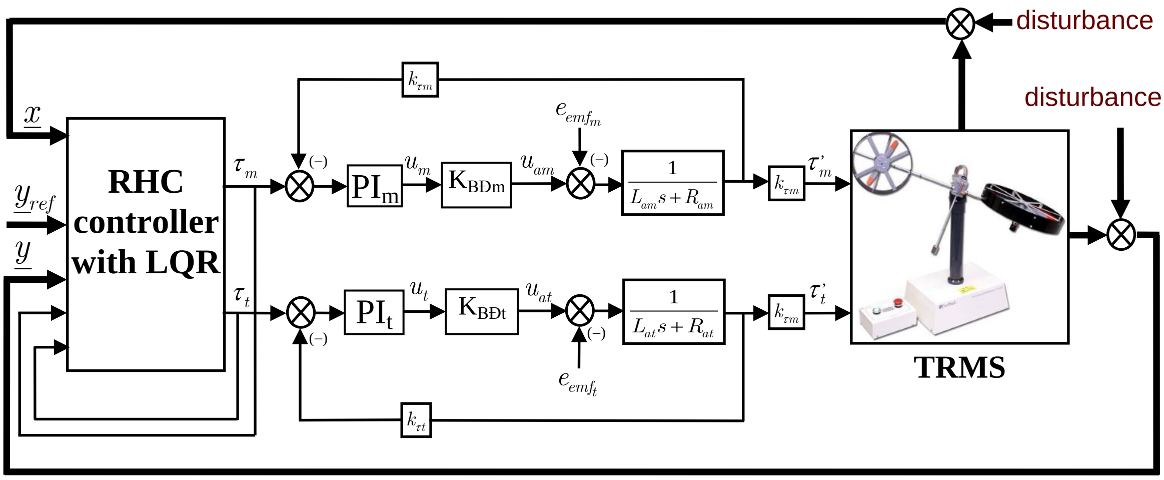


Figure 4.1. Control structure TRMS with an extra torque control loop

With the state vector $\underline{x}$ of TRMS, the RHC controller with LQR identifies the state vector $\underline{x} = [\alpha_v \quad \alpha_h \quad \dot{\alpha}_v \quad \dot{\alpha}_h \quad \omega_m \quad \omega_t]^T$, in which four state variables $\alpha_v, \alpha_h, \omega_m$, ω_t are measured from the encoder and the speed generator. The two state variables are approximated as follows: $\dot{\alpha}_v = \left(\alpha_{v_k} - \alpha_{v_{k-1}}\right) / \delta_k, \dot{\alpha}_h = \left(\alpha_{h_k} - \alpha_{h_{k-1}}\right) / \delta_k$. Input position $\underline{y}_{ref}$ (with a given sample signal $\underline{w}(t)$) ; where α_{v_k} is the angular displacement in the vertical plane at the sampling time k; $\alpha_{v_{k-1}}$ is the angular displacement in the vertical at the pre-sampling time $k-1$. The angular displacement α_{hk} in the horizontal plane at the sampling time k is the angular displacement in the transverse plane at the sampling interval. δ_k is the sampling period of the system.

The input of the controller $\underline{y}_{ref}$ is also the position reference vector, $\underline{y}$ is the vector of the output position. In the control structure $k_{\tau m} = k_{\tau t}$ = 0.0202 (Nm / A) is the torque factor of a permanent magnet DC motor, u_{am} / u_{at} is the output voltage of the power amplifier applied to the armature of the motors driving the main and tail rotor.

Controller RHC with LQR and PI controller of the torque control are implemented on card DS1103. The general scheme for connection is shown as in Figure 4.2

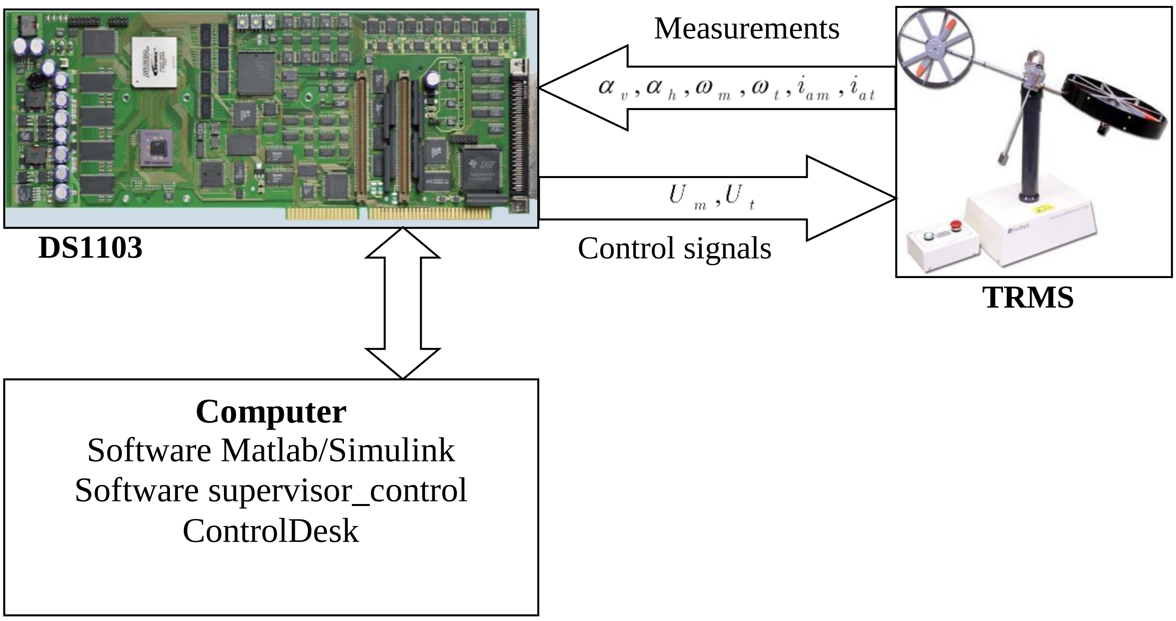


Figure 4.2. Control structure for TRMS using DS1103

4.3. Hardware and software demands

Based on the structure in Figure 4.1 and Figure 4.2, the following items need to be available: The TRMS system, feedback sensors, real-time DS1103, computers, programming software MATLAB/Simulink and supervisory control and data acquisition ControlDesk.

TRMS

TRMS has been introduced fully in the kinetic modeling of the system. Two permanent magnet DC motors drive the main and tail rotors. A driver device is to receive signals from DS1103 to control the speed of DC motors.

Sensors for feedback signal

Position sensors to measure angles in vertical and horizontal planes. Speed generators is to measure angular velocity of the main rotor and the tail rotor. Armature current measurement modules for the DC motors of the main and tail rotors.

Real-time card DS1103

Card DS1103 is equipped with a high-speed processor, huge memory storage and ControlDesk interface to guarantee real-time control tasks.

Computer

A computer which is connected to card DS1103 needs to have MATLAB/Simulink and ControlDesk on it. Tasks on the real experimental system are executed on the computer such as parameter settings, harvesting the feedback signal and so on.

Software MATLAB/Simulink and ControlDesk

Beside the harware mentioned above, softwares for the system modeling, supervisory control and data acquisition are neccesary. Control strategies are programed and simulated by MATLAB/Simulink. The simulink model is connected to the real time card by ControlDesk with tool blocks in a real time interface library.

4.4. Experimental system

Figure 4.13. The experimental system TRMS

- Sampling time: $Ts = 0.005s$
- Parameters of Controller PI_m: $Kp_m = 0.2$; $Ki_m = 50$
- Parameters of Controller PI_t: $Kp_t = 0.1$; $Ki_t = 50$
- Output signals of 2 encoder for angular position α_v / α_h connected to 2 encoder channels
- Output signals of 2 angular speed generators ω_m / ω_t connected to 2 A/D pins of DS 1103: ADCH17, ADCH18
- 2 output signals of current sensors i_{am} / i_{at} connected to 2 A/D pins of DS 1103: ADCH19, ADCH20
- 2 control signals connected to 2 D/A pins: DACH1, DACH2

4.5. Experimental results and comments

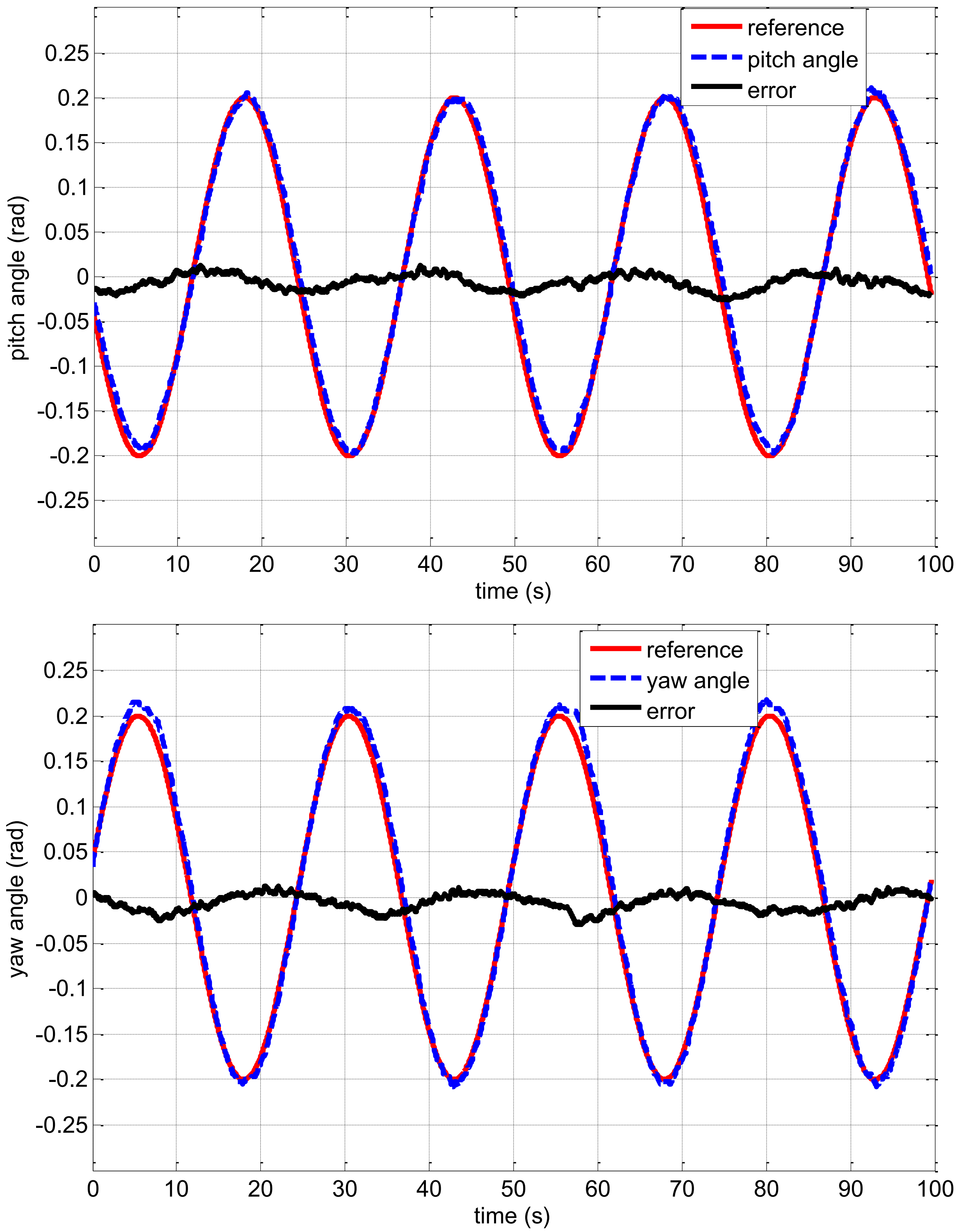
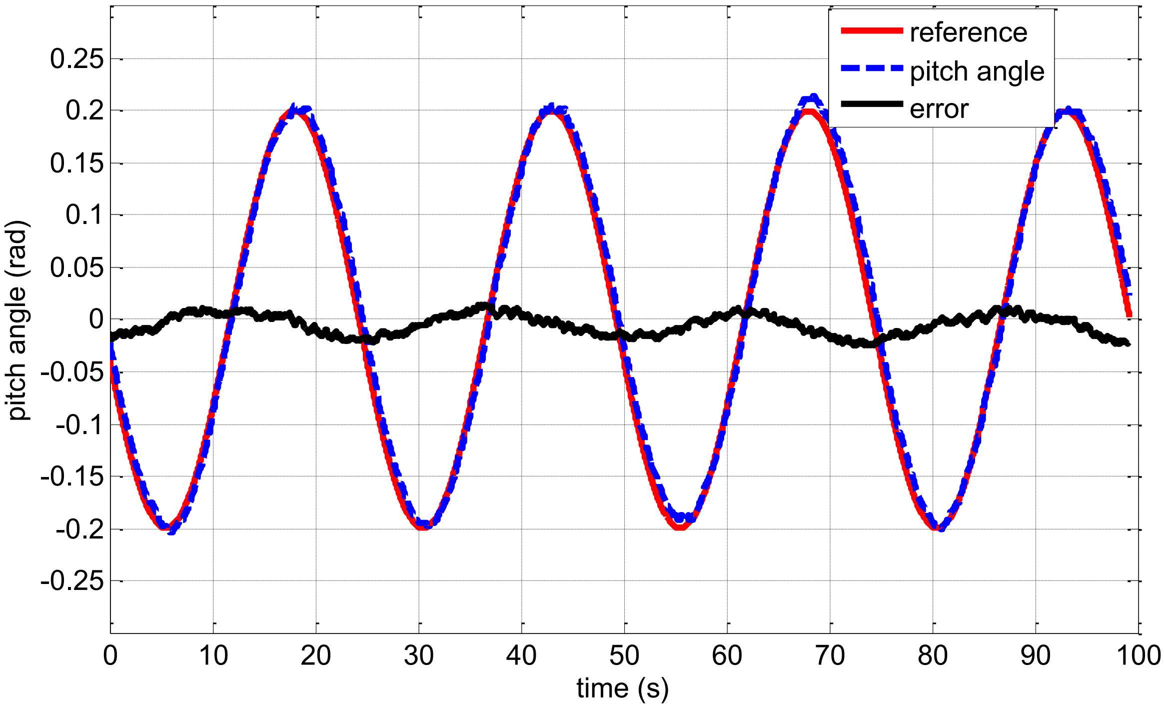


Figure 4.21. Response of angles in two planes with sinusoidal-sinusoidal signal references



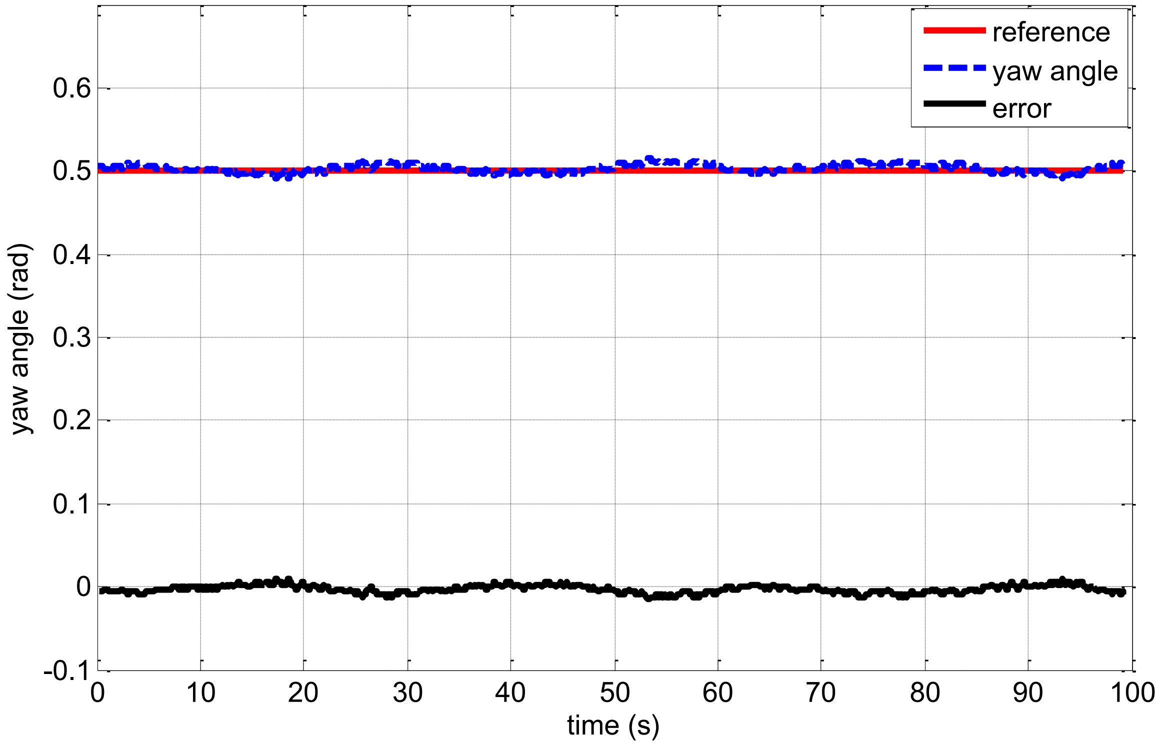


Figure 4.21. Response of angles in two planes with sinusoidal-constant signal references

4.6. Conclusions

Chapter 4 deals with the following issues:

- Set up a TRMS test system with a torque converter to compensate for kinetics of the actuator. The manufacturer's original system does not incorporate torque or current sensors. Therefore, in order to apply the proposed algorithm for position control with the application of torque, the dissertation has used the sensor due to high sensitivity current for the control circuit to apply torque.

- The proposed control algorithm is verified on the TRMS system, the output control signal depends on the solution of the Riccati equation. Usually, Riccati equation is solved and the result set is applied to the controller, but the proposed algorithm requires solving this equation repeatedly in each sampling cycle. With that request, the dissertation was installed and programmed to solve the Riccati equation on the DS1103 Card in real time.

- Flexible installation of proposed control algorithms for TRMS. Control algorithms are tested on TRMS with sine and step signals.

So, the experimental results again confirm the correctness of the control algorithm proposed by the dissertation and the feasibility of applying it to the real object.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Some new contributions of the dissertation are expressed as follows:

1. Building a mathematical model for TRMS with the smallest error compared to the real model: Based on the complete information about the parameters, the structure and physical nature of the object, the mathematical model using the Newton method is defined. In this dissertation, the Euler-Lagrange method is used to model the TRMS system.

2. Research on the control algorithm RHC with LQR, continuous nonlinear system has disturbances and model errors: TRMS control is a difficult problem so it is challenging and attractive to many researchers. To improve control quality, many studies have applied nonlinear controls to TRMS. A new algorithm called continuous RHC combining with LQR for nonlinear system under the present of noise, and unprecise model is proposed and designed.

Recommendations

Although the dissertation has solved the TRMS control problem in the joint-variable space, there are still some issues that will be solved in the future.

1. In future work, the proposed control algorithm would be employed for advanced objects in practice as UAV.

2. Both simulation and experimental results on the TRMS show that the matrices Q and R have influences on the qualities of the output responses. Therefore, it is necessary to propose algorithm for optimizing matrices Q and R of the control algorithm RHC with LQR.

3. The state observer needs to be used to the control algorithm RHC with LQR for real systems for better performance.