MINISTRY OF EDUCATION AND TRAINING

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RESEARCHING AND BUILDING MODEL PREDICTIVE CONTROL ALGORITHMS FOR CONTINUOUS NONLINEAR OBJECT

Speciality: Automation and Control Engineering

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ABSTRACT OF DOCTORAL DISSERTATION IN TECHNOLOGY

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Reviewer 1:

Reviewer 2:

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The dissertation will be defended at the Dissertation committee in National level COLLEGE OF TECHNOLOGY- TNU

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The dissertation can be found at:

- National Library;
- Learning Resource Center - Thai Nguyen University;
- Library of College of Technology – TNU.

INTRODUCTION

1. The science and necessity of dissertation

Model Predictive Control (MPC) for linear systems have been developed, approved and applicated for the industry processes and some other fields. We do not apply MPC for linear systems with nonlinear systems, especially it has noise. There are two difficult issues for MPC as:

- Identify the plant or build the predictive model.
- Solve a nonlinear optimal problem with the constrained conditions.

The nonlinear optimal problem with the constrained conditions does not solve, these cases the control algorithm becomes infeasible. There are no general solutions, so we usually use nonlinear programming such as SQP, GA … in the studies. Thus, the caculating volume of nonlinear model predictive control (NMPC) uses numerical methods also much more heavier than the linear MPC.

If using nonlinear predictive model to identifiable problem for nonlinear systems, especially it is difficult for nonlinear systems with uncertain parameter because we must be solve the nonlinear optimal problem with constraints and limits, hence we need to answer these questions:

- Nonlinear optimal problem that can solve it? Currently, there is no solve method the general nonlinear optimal problem, there are three optimal control methods, they are: the dynamic programming of Bellman, the maximum principle of Pontriagin and the variational method.

- How much is the predictive horizon of MPC to closed system also stable guarantee?

- How stability of the closed-loop system when the predictive horizon towards infinity?

- Can closed systems ensure on-time calculations to satisfy real-time in industrial control?

From the analysis above, we see that with MPC of the general nonlinear systems still have many issues need to be continue studying and finishing:

- Constructing predictive model reflects truly a nonlinear objects;

- Choose the suitable cost function for each object, particularly when the conflicting goals need to have solutions "compromise" between the objectives in order to choose the most suitable cost function;

- Find out new methods for solving the nonlinear optimal problem and install them on the MPC.

2. The objectives of the dissertation

The aim of the dissertation is study and propose a new algorithm for solving the optimal problem in nonlinear model predictive control MIMO system.

Specific objectives:

- Researching methodology to build the MPC for nonlinear systems (in general) and bilinear systems (in particular).

- Propose a new algorithm to solve optimal problem in nonlinear MPC system.

In which: optimized block is built based on the nonlinear programming method and applied for discontinuous model of objects. Propose an optimized block, applying variational method, to apply for continuous model. Both blocks of these optimization are expanded into optimal control sticking to the desired trajectory, not merely stable control. Give control algorithms for a class of nonlinear objects.

- Survey TRMS and install MPC algorithm above on the specific TRMS and simulate verification.

3. Research object, scope and methodology of the dissertation

- ***Researching Object*:** nonlinear MPC, the algorithms solve the optimal problem in nonlinear MPC; The Twin Rotor MIMO System (TRMS).

- Researching scope:

+ To study and design the status feedback nonlinear MPC sticking to the sample output signal with finite predictive horizon which using the SQP algorithm to solve optimal problem.

+ To study and design the status feedback nonlinear MPC so that the output signal sticking to the sample output signal for continuous nonlinear system with infinite predictive horizon which using variational method to solve the optimal problem.

+ The results of the theoretical research are verified by simulation and experimental on TRMS (no mention the impact of noise and cross-coupling channels in vertical and horizontal directions).

- Researching Methods:

+ Theoretical study: Analysis and evaluation of the study were published in the papers, magazines, reference materials about nonlinear MPC; the algorithms to solve optimal problems in nonlinear MPC. Researching and designing the status feedback nonlinear MPC sticking to the sample output signal for both discontinuous and continuous nonlinear systems with finite and infinite predictive horizon;

+ Simulation in Matlab - Simulink to verify the theory;

+ Experiments on nonlinear system to verify the theoretical results.

4. The main contributions of the dissertation

- Construct the methodology to design the nonlinear MPC and propose a new solution in one optimization strategy of the nonlinear MPC, namely: the nonlinear MPC based on variational method. I speeched and proved a theorem about stable tracking follow the sample output signal for continuous nonlinear systems when the predictive horizon is infinity.

- Using the 2.1 and 3.1 algorithms into install for control the TRMS and simulation on the software Matlab-Simulink.

- New algorithm that the dissertation proposed is installed and implemented to control a real object in Electric - Electronics Engineering laboratory of Thai Nguyen University of Technology, through which verified and confirmed the feasibility of the offered algorithm.

5. Theoretical significance and practical significance

5.1. Theoretical significance

Develop a methodology to design predictive controller for nonlinear systems and propose a new solution in one optimization strategy of predictive control for MIMO nonlinear systems.

5.2. Practical significance

- A new proposed algorithm has been tested through simulations and experiments on real systems, thereby confirming the feasibility of the algorithm that the dissertation proposal.

- The results of the dissertation have reduced computational time when solving optimization problems in the strategic optimization of the model predictive control has confirmed the feasibility of the controllers used in industrial systems;

- The results of the dissertation will be a reference for students, master students and PhD students in automation control interested in researching to design nonlinear MPC. Ability to install additional components on the algorithms for nonlinear MPC with infinity predictive horizon in the toolbox of Matlab - Simulink.

6. Structure of dissertation

Besides the introduction, conclusion and appendix, the content of the dissertation is presented in four chapters:

Chapter 1. Overview of nonlinear model predictive control

Chapter 2. Nonlinear model predictive control based on nonlinear programming methods

Chapter 3. Propose a new method for the continuous nonlinear model predictive control based on variational method

Chapter 4. Proven experimental quality method proposed in the TRMS

Chapter 1

OVERVIEW OF THE NONLINEAR MODEL PREDICTIVE CONTROL

1.1. Overview of research about nonlinear model predictive control on the world

Nonlinear Model Predictive Control (NMPC) is a problem that is researching by many scientists. Nowadays, studies NMPC main focus on stability, sustainability while the problems of time has not been recalculated due attention.

In recent years, the Model Predictive Control (MPC) is one of the calculating techniques of modern optimal control that growing both the theory and application, and has been had an important position in the general control field and in controlling industrial processes in particular due to the MPC has outstanding advantages such as:

- Suitable for a large class of control problems, from the process has large time constants and large time delay to the fast change nonlinear systems,

- Apply for the processes have the large number of control variables and variables is controlled,

- Easily meet the control problems with both in state and control signals constraints,

- The controlling objects change and device breakdown,

- MPC is a problem-based optimization so it should be able to enhance the robustness of the system for model error and disturbance.

According to Qin (2000) has more than 3000 applications of MPC has been commercialized in various fields including petrochemical refining technology, food processing technology, automotive technology, space technology, pulp and paper technology etc.

Most of the objects to control in fact are nonlinear, in order to control these nonlinear objects, first you must build the model, the nonlinear models need to perform modeling using approximate analysis or artificial intelligence based on experrience as neural network and wavelets. Each of the model class has advantages and disadvantages. In many cases, the nonlinear models can be performed entirely using multivariate linear model or adaptive linear model.

The MPC for nonlinear systems is also the author used different methods, such as the MPC has a finite predictive window, the MPC has almost infinite predictive window, the MPC uses state - space model, adapted MPC, min - max MPC, robust MPC, robust output feedback MPC…

Author Rahideh Akbar (2009) mentioned a relatively complete and detailed nonlinear systems TRMS, when constructing the MPC to control the nonlinear object TRMS in dissertation above, besides it still has limited in the scope of specific research follows:

- Using only unique method SQP to solve the optimal problem in order to find the minimum value of the cost function. This is one of the methods of nonlinear programming to solve the optimal problem.

- Considering the stability of nonlinear systems based on the end - point constraint method, given penalty function but did not specify a ruler to find how that penalty function.

- Finite predictive window (($N_p = 20$; $N_c = 15$).

In MPC, either extremely important job is to solve the nonlinear optimal control problem with the constraints. In most studies of optimal control for nonlinear systems, the authors have used two strategies to solve basic optimal problem: nonlinear programming and optimal control.

1.2. The nonlinear programming methods

1.2.1. Nonlinear is unconstrained

1.2.1.1. Line search methods are Gadient method, Newton - Raphson method (Quasi Newton), Gauss - Newton method

+ *Advantages:* Simple, easy to install ...

+ *Disvantages:* Can find local optimal solution, can not find global optimal solution.

1.2.1.2. Search no direction includes: Method of Levenberg - Marquardt, Trust Region Methods.

+ *Advantages:* Simple, easy to install ...

+ *Disvantages:* Can find local optimal solution, can not find global optimal solution.

1.2.2. The problem of nonlinear optimization is constrained, includes: penalty function Techniques and blocking function Techniques, SQP and GA Method.

+ *Advantages:* Easy to process the constrained conditions, including the constrained conditions about the control signal values, the number of control signals and state variables of system.

+ *Disvantages:* Only applying for discontinuous system and with finite predictive window. Therefore, in order to ensure the stable quality or stable sticking under the desired value must be selected a suitable penalty function.

1.3. Methods of the optimal control, including: variational method, maximum principle, dynamic programming method.

+ *Advantages:* Easily applicable to continuous nonlinear system and not stop, not just bilinear system; The proposed method uses infinite predictive window so we should not need an additional penalty function, which is very difficult, even without any helpful hints for identifying them.

+ *Disvantages:* Difficult to handle the complex constrained conditions.

1.4. The researches on predictive control of the nonlinear system in the country

Author Do Thi Tu Anh (2015) did not focus on the study of optimization strategies in MPC which mainly refers to the construction of feedback output MPC following the principle of separation for nonlinear system to consider the asymptotic stability of the system, thus not mentioned the sticking stability of the MPC system for nonlinear system, the author still has used discontinuous predictive model.

Author Tran Quang Tuan (2012) has done modeling online adaptive parameters based on estimate the fuzzy model parameter for nonlinear object, which has uncertain component, is a function. This dissertation does not study the optimization strategy in MPC that go into building the model.

1.5. These issues need to continue researching on the predictive control for nonlinear system and user research dissertation

MPC still has some outstanding issues to be further studied perfection:

- Improve the accuracy of predictive model, these models have more accurately predicted, the qualities of predictive control have more high etc ...

- Never works that mentioned in the choice and compromise between the opposite cost function when performing optimization algorithms for nonlinear predictive control.

- Finding a new algorithm is to solve the optimal problem so that it improves computing speed and improves the accuracy, stability, extended - range prediction for nonlinear predictive control, especially for bilinear systems.

Researching direction of the dissertation

The author has proposed researching direction of the dissertation are:

Researching and building a new algorithm to solve optimal problem of optimization strategies for nonlinear predictive control with the aim of expanding the predictive window to infinity in order to improve the stability and accuracy of the system. Also shorten calculating time when solving the optimal problem than the methods have mentioned before.

Chapter 2

PREDICTIVE CONTROL OF NONLINEAR SYSTEM BASED ON NONLINEAR PROGRAMMING METHOD

2.1. Working principle of nonlinear model predictive control.

Nonlinear model predictive control works with principle:

1. First, build the predictive object model of the future outputs for a determined range, called the predictive range N_p, at each time of sampling k. These predictive outputs, denoted by $\hat{\boldsymbol{y}}(k+i|k), i=1,2,\ \dots\ ,N_p$, from the time k, will depend on the

future control signal $\boldsymbol{u}(k+i|k),\ i=1,2,\ \ldots\ ,N_p-1$ and $\boldsymbol{u}(k+i|k)=\boldsymbol{u}(k+N_c\,|k)$, in that $i>N_c$ with N_C the control range.

2. Second, the future control signals are calculated to optimize the output $\boldsymbol{y}$ of the process sticking to the set trajectory $\boldsymbol{y}_{ref}$ when the set signal or the output signal processes are approximated. Commonly used cost function is a error quadratic function between the predictive output signal and the predictive reference trajectory. In all cases, the control target is to minimize or maximize the cost function.

3. Third, based on the strategic concept gradually translate to the future, the first part of the control signal, $\boldsymbol{u}(k|k)$, is sent to the process.

2.1.1. The structure of model predictive control.

The structure of model predictive control consists of three blocks: block of predictive model, block of cost function and block of optimization.

+ Block of predictive model is function block using the model described the object to predict the output signals in its future.

+ Block of cost function: the purpose of block is the signal y_k that was followed by desired signal y_{ref} . In model predictive control**,** people often use the cost function containing the error component or the cost function quadratic form.

+ Block of optimization: The mission of this block is to find the optimal solution in the cost function so that the cost function reaches the minimum value (or maximum).

2.1.2. Technical install of model predictive control based on nonlinear programming methods

There are many optimization methods used in order to install the algorithm to find optimal solution for the problem $\mathcal{U}^*=\arg\min_{\mathcal{U}\in U} J(\mathcal{U})$ of the model predictive control. Such as:

1. With the unconstrained optimal problem ($U=\mathrm{R}^{mN_p}$) use the algorithms such as Gradient, Newton and Quasi Newton, Gauss - Newton, Levenberg - Marquardt…

2. When having more constrained conditions ($U \subset \mathrm{R}^{mN_p}$), the suitable algorithms would be penalty function and blocking function techniques or QP or SQP or genetic algorithms, interior point methods, ...

2.2. Applies for predictive control for a class of bilinear systems

2.2.1. Algorithm of nonlinear model predictive control for bilinear systems

Predictive model for bilinear systems in the whole of the current predictive window $\left[k, k+N_p\right)$ as follows:

$$\begin{cases} \boldsymbol{x}(k+i+1|k) = \mathcal{A}(k+i)\boldsymbol{x}(k+i|k) + \mathcal{B}(k+i)\boldsymbol{u}(k+i|k) \\ \boldsymbol{y}(k+i|k) = \mathcal{C}(k+i)\boldsymbol{x}(k+i|k) \end{cases} \tag{2.16}$$

Predictive output sequence values obtained in the current predictive window:

$$\mathcal{Y} = M(\mathcal{U})\boldsymbol{x}(k|k) + N(\mathcal{U})\mathcal{U} = M(\mathcal{U})\boldsymbol{x}_k + N(\mathcal{U})\mathcal{U} \tag{2.20}$$

The cost function for the system will be:

$$\begin{aligned} J(\mathcal{U}) &= \sum_{i=1}^{N_p} q_i \left|\boldsymbol{e}_{k+i}(\mathcal{U})\right|^2 + \sum_{j=0}^{N_c-1} r_j \left|\boldsymbol{u}(k+j|k)\right|^2 + s\left(\boldsymbol{x}(k+N_p|k)\right) \\ &= \left(\mathcal{Y}_{ref} - \mathcal{Y}\right)^T Q \left(\mathcal{Y}_{ref} - \mathcal{Y}\right) + \mathcal{U}^T R \mathcal{U} + s(\mathcal{U}) \\ &= \left[\mathcal{Y}_{ref} - \left(M(\mathcal{U})\boldsymbol{x}_k + N(\mathcal{U})\mathcal{U}\right)\right]^T Q \left[\mathcal{Y}_{ref} - \left(M(\mathcal{U})\boldsymbol{x}_k + N(\mathcal{U})\mathcal{U}\right)\right] + \\ &\qquad + \mathcal{U}^T R \mathcal{U} + s(\mathcal{U}) \end{aligned} \tag{2.21}$$

2.2.2. Model predictive control based optimization under error control signal

***Algorithm 2.1*:** Status feedback model predictive control feedback for bilinear systems follow closely sample output signal with finite predictive window.

1. Select the penalty function $s\left(\widehat{\boldsymbol{x}}(k+N_p|k)\right)$, predictive window N_p, control window N_C and two weight matrixes Q, R symmetric positive definite. Select sampling cycle T . Assign $k=0$ and $\boldsymbol{u}_{-1}=(0,0)^T$.

2. Measure $\boldsymbol{x}_k=\boldsymbol{x}(k|k)$. Determine $\widehat{\boldsymbol{x}}_k=col(\boldsymbol{x}_k,\boldsymbol{u}_{k-1})$, the matrixes $\widehat{\mathcal{A}}(\widehat{\boldsymbol{x}}_k)$, $\widehat{\mathcal{B}}(\widehat{\boldsymbol{x}}_k)$, $\widehat{\mathcal{C}}(\widehat{\boldsymbol{x}}_k)$ from discontinuous model (2.14) of the bilinear system follow by (2.26).

3. Construction of cost function $J(\widehat{\mathcal{U}})$ follow by (2.25) and constrained set U follow by (2.23).

4. Find the solution $\widehat{\mathcal{U}}^*$ of the optimal problem (2.30) by the nonlinear programming methods, such as SQP or interior point methods.

5. Put $\boldsymbol{u}_k=\boldsymbol{u}_{k-1}+\left(I\ ,0\ ,\ \dots\ ,0\right)\widehat{\mathcal{U}}^*$ into bilinear control systems for the period $kT\le t<(k+1)T$, which I is the unit matrix. Assign $k:=k+1$ and return 2.

There will be plenty of different options to install these algorithms and they are separated in the selection method of specific nonlinear programming to find optimal solution $\widehat{\mathcal{U}}^*$ for optimal problem with constraints U (2.25), i.e the 4th step of the algorithm above. This is a nonlinear optimal problem with constraints, suitable methods will be SQP, gradient projection, blocking function, penalty function techniques, genetic algorithm. However, this dissertation will consistently use only SQP.

Chapter 3

PROPOSE A NEW METHOD FOR CONTROLLING PREDICTIVE OF NONLINEAR CONTINUOUS SYSTEM BASED VARIATIONAL METHOD

3.1. Basic contents of variational method

Optimal control Problem for object control described by continuous model (3.2) is understood as we determine the optimal control signal $\boldsymbol{u}^*(t),\ 0\le t\le T$, satisfy the constrained condition $\boldsymbol{u}\in U$ to take system away from the first state point $\boldsymbol{x}_0=\boldsymbol{x}(0)$ to the final state point $\boldsymbol{x}_T = \boldsymbol{x}(T)$ in the period T, called interval occurs optimization process, so that the costs of transition that state, calculated by:

$$J(\boldsymbol{u}) = \int_0^T \boldsymbol{g}(\boldsymbol{x},\boldsymbol{u})dt \tag{3.3}$$

reached the minimum value. The function (3.3) is often called the cost function of optimal control problem.

3.1.1. Variational principle

Variational principle: If $\boldsymbol{u}^*$ the solution of optimal problem with $\boldsymbol{x}_0$, T are desired and U was also given an open set, then the solution must satisfy:

$$\left.\frac{\partial H}{\partial \boldsymbol{u}}\right|_{\boldsymbol{u}^*} = \mathbf{0}^T \tag{3.4}$$

(derivative at the optimum point) in which:

- $\partial / \partial \boldsymbol{u}$ denotes the Jacobi's derivation of a function of several variables.

- $\mathbf{0}^T = (0, \ \ldots \ ,0)$

$H = \boldsymbol{p}^T \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u}) - \boldsymbol{g}(\boldsymbol{x},\boldsymbol{u})$, Hamilton functions named, with $\boldsymbol{p}$ the co-state variable vector, satisfying the Euler - Lagrange relations:

$$\dot{\boldsymbol{p}} = -\left(\frac{\partial H}{\partial \boldsymbol{x}}\right)^T \tag{3.5}$$

and boundary conditions $\boldsymbol{p}(T) = \mathbf{0}$ when the end point is any state.

3.1.2. Controllers LQR (Linear Quadratic Regulator)

We can see the application of the principle of variational method 3 steps above are absolutely not simple for nonlinear systems because until now we have not been method to find solution explicitly of nonlinear differrential equation systems. So we usually only apply for problem with system (3.2) in the form of constant linear parameters:

$$\dot{\boldsymbol{x}} = A\boldsymbol{x} + B\boldsymbol{u} \tag{3.6}$$

we have $T=\infty$, cost function (3.3) in quadratic form:

$$J(\boldsymbol{u})=\int_0^\infty\left(\boldsymbol{x}^T Q\boldsymbol{x}+\boldsymbol{u}^T R\boldsymbol{u}\right)dt \tag{3.7}$$

and the end point x_T is any, in which Q is the positive part - definite symmetric matrix ($Q=Q^T\geq 0$), R is the desired positive definite symmetric matrix ($R=R^T>0$) given.

Optimal solution $\boldsymbol{u}^*$ under variational method will find on - line form [5]:

$$\boldsymbol{u}^*=-R^{-1}B^T L\boldsymbol{x}=R_{LQR}\boldsymbol{x} \quad \text{với } R_{LQR}=R^{-1}B^T L \tag{3.8}$$

in which L is the positive part - definite symmetric solution of algebraic Riccati equation:

$$LBR^{-1}B^T L-A^T L-LA=Q \tag{3.9}$$

This time R_{LQR} is given by formula (3.9) will be called the state feedback optimal controller.

3.1.3. The sufficient condition for the stability of the system LQR

If one of the conditions give below are satisfy (sufficient), we always confirm LQR system is stable:

- The problem has $Q=Q^T>0$, matrix Q is positive definite, is not just positive part - definite.

- Solution L founded in the equation Riccati (3.9) is positive definite (and not just positive part - definite)

- Pair matrixes (A,Q) is observed.

3.1.4. Apply principles LQR control for optimal control stick steady linear output value given

To acquire the ability to use the LQR controller above to the model predictive control of bilinear system sticking to the given output value, the dissertation will take a little change of LQR controller

(3.8) to be applied optimal control problem of constant linear parameter system:

$$\begin{cases} \dot{\boldsymbol{x}} = A\boldsymbol{x} + B\boldsymbol{u} \\ \boldsymbol{y} = C\boldsymbol{x} + D\boldsymbol{u} \end{cases} \tag{3.10}$$

so that its output $\boldsymbol{y}$ sticking to the desired sample output value $\boldsymbol{y}_r$.

This problem is called the problem of sticking optimal control.

First, by not any sticking control problem also has solution, so we need to have the following assumptions for the sticking optimal control problem:

- The sticking optimal problem of parametric linear constant systems (3.10) have solution $\boldsymbol{u}_e$ in established regime, in which the index notation e to say that it is a signal that it may be $\boldsymbol{y} \to \boldsymbol{y}_r$.

- When the system has sticked to the sample value $\boldsymbol{y}_r$, it means when have $\boldsymbol{y} = \boldsymbol{y}_r$, the system will set the state's establishment $\boldsymbol{x}_e$.

With two assumptions above, obviously must have:

$$\begin{cases} \mathbf{0} = \dot{\boldsymbol{x}}_e = A\boldsymbol{x}_e + B\boldsymbol{u}_e \\ \boldsymbol{y}_r = C\boldsymbol{x}_e + D\boldsymbol{u}_e \end{cases} \tag{3.11}$$

and this equivalent to:

$$\begin{pmatrix} \mathbf{0} \\ \boldsymbol{y}_r \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} \boldsymbol{x}_e \\ \boldsymbol{u}_e \end{pmatrix} \Leftrightarrow \begin{pmatrix} \boldsymbol{x}_e \\ \boldsymbol{u}_e \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{0} \\ \boldsymbol{y}_r \end{pmatrix} \tag{3.12}$$

Next we set a new variable:

$$\delta = \boldsymbol{x} - \boldsymbol{x}_e \text{ và } \rho = \boldsymbol{u} - \boldsymbol{u}_e$$

when excluding each side of (3.10) and (3.11) each, will be (called a wrong number):

$$\dot{\delta} = A\delta + B\rho \tag{3.13}$$

and sticking control problem following the desired output value $\boldsymbol{y}_r$ for original linear constant parameter system (3.10) has become a stability control problem for error system (3.13).

Apply LQR method for error system to the cost function:

$$J(\rho) = \int_0^{\infty} \left(\delta^T Q \delta + \rho^T R \rho \right) dt \tag{3.14}$$

there are two positive definite symmetric matrices Q, R, we have:

$$\rho^* = -R^{-1} B^T L \delta \quad \text{với } R_{LQR} = R^{-1} B^T L \tag{3.15}$$

In which $L = L^T > 0$ is positive definite symmetric solution of Riccati equation (3.9). Of course this LQR controller (3.15) would be stabilize the error system (3.13), because Q is a positive definite matrix.

From controller LQR (3.15) of error system (3.13), we also derive sticking optimal controller following the desired output value for the original linear constant parameter system (3.10) as follows:

$$\boldsymbol{u}^* = \boldsymbol{u}_e - R^{-1} B^T L (\boldsymbol{x} - \boldsymbol{x}_e) \tag{3.16}$$

3.2. The proposed method for predictive control with infinite predictive window for the continuous bilinear system, followed by the output value given

3.2.1 The main idea of the method

Considering MIMO bilinear system, do not stop, have the input signal with the output signal, described by a continuous models:

$$\begin{cases} \dot{\boldsymbol{x}} = A(\boldsymbol{x},t)\boldsymbol{x} + B(\boldsymbol{x},t)\boldsymbol{u} \\ \boldsymbol{y} = C(\boldsymbol{x},t)\boldsymbol{x} + D(\boldsymbol{x},t)\boldsymbol{u} \end{cases} \tag{3.17}$$

In which $\boldsymbol{u} \in \mathrm{R}^m$ is the vector of m input signal, $\boldsymbol{y} \in \mathrm{R}^m$ the vector of m the output signal and $\boldsymbol{x} \in \mathrm{R}^n$ the vector of n state variables in the system. The matrixes $A(\boldsymbol{x},t)$, $B(\boldsymbol{x},t)$, $C(\boldsymbol{x},t)$ and $D(\boldsymbol{x},t)$ containing the elements is the dependent function of variable state $\boldsymbol{x}$ as well as time t.

Assuming all $A(\boldsymbol{x},t)$, $B(\boldsymbol{x},t)$, $C(\boldsymbol{x},t)$, $D(\boldsymbol{x},t)$ are continuous matrixes following $\boldsymbol{x}$ and t. Meanwhile, at the present time t_k and in small sufficient time $t_k \le t < t_k + T_k$, bilinear system (3.17) will approximate by the linear constant parameter model:

$$H_k:\begin{cases}\dot{\boldsymbol{x}}=A_k\boldsymbol{x}+B_k\boldsymbol{u}\\ \boldsymbol{y}=C_k\boldsymbol{x}+D_k\boldsymbol{u}\end{cases} \tag{3.18}$$

where:

$A(\boldsymbol{x},t)\approx A_k$, $B(\boldsymbol{x},t)\approx B_k$, $C(\boldsymbol{x},t)\approx C_k$, $D(\boldsymbol{x},t)\approx D_k$

when $t_k \le t < t_k + T_k$ (3.19)

The approximation above is totally acceptable due to the assumption of continuity of the model parameter matrixes (3.17) always have:

$$\lim_{T_k\to 0} A(\boldsymbol{x},t)=A_k,\ \lim_{T_k\to 0} B(\boldsymbol{x},t)=B_k,\ \lim_{T_k\to 0} C(\boldsymbol{x},t)=C_k,\ \lim_{T_k\to 0} D(\boldsymbol{x},t)=D_k$$

and T_k is the computational time required for a loop of the model predictive control, so very small. It also is about shifting the predictive window. The control steps in a loop will be:

Thought of the proposed method:

1. At the present time t_k, measured value $\boldsymbol{x}(t_k)=\boldsymbol{x}_k$ and determine the constant matrixes of LTI models (3.18) include A_k,B_k,C_k,D_k, according to the formula:

$$A_k=A(\boldsymbol{x}_k,t_k),\ B_k=B(\boldsymbol{x}_k,t_k),\ C_k=C(\boldsymbol{x}_k,t_k),\ D_k=D(\boldsymbol{x}_k,t_k) \tag{3.20}$$

2. Define the control signal $\boldsymbol{u}(t)$ so that LTI system (3.18) sticking to the sample output signal value $\boldsymbol{y}_r$.

3. Put $\boldsymbol{u}(t)$ has found into bilinear system control (3.17) and then return to step 1 to perform the new loop at the next time is t_{k+1}.

3.2.2 Building control algorithm

Algorithm 3.1: *Status feedback predictive control is the output signal sticking to the sample output signal for continuous bilinear system with infinite predictive window.*

1. Select the rule to change the positive definite Q_k,R_k symmetric weight matrixes. Assign $t_0=0$ and $k=0$.

2. Measure $\boldsymbol{x}_k=\boldsymbol{x}(t_k)$ and approximate constant matrixes A_k,B_k,C_k,D_k of LTI models (3.18) from $A(\boldsymbol{x},t),B(\boldsymbol{x},t),C(\boldsymbol{x},t),D(\boldsymbol{x},t)$ follow the formula (3.20).

3. Determine $\left(\boldsymbol{x}_e[k],\boldsymbol{u}_e[k]\right)$ from $\boldsymbol{y}_r$ follow (3.22).

4. Find L_k the symmetric solution, positive part - definite of algebraic Riccati equations (3.25). Calculated $\boldsymbol{u}^*$ by (3.26).

5. Put $\boldsymbol{u}^*$ into the continuous bilinear objects control and then assign $k := k+1$ and return 2.

Chapter 4

EXPERIMENTAL PROOF METHOD QUALITY HAS PROPOSED IN TRMS OBJECTS

4.1. Mathematical model of TRMS systems

Mathematical model of TRMS object with 6 parameters given in the state (4.1):

$$\frac{d}{dt}\begin{pmatrix}\omega_h\\ S_h\\ \alpha_h\\ \omega_v\\ S_v\\ \alpha_v\end{pmatrix}=\begin{pmatrix}-\dfrac{(k_{ah}\varphi_h)^2}{J_{tr}R_{ah}}\omega_h-\dfrac{B_{tr}}{J_{tr}}\omega_h-\dfrac{f_1(\omega_h)}{J_{tr}}+\dfrac{k_{ah}\varphi_h}{J_{tr}R_{ah}}f_6(U_h)\\ \dfrac{l_t\gamma_t f_2(\omega_h)\cos\alpha_v-f_7(\Omega_h)-f_3(\alpha_h)}{D\cos^2\alpha_v+E\sin^2\alpha_v+F}\\ S_h+\dfrac{k_m\omega_v\cos\alpha_v}{D\cos^2\alpha_v+E\sin^2\alpha_v+F}\\ -\dfrac{(k_{av}\varphi_v)^2}{J_{mr}R_{mr}}\omega_v-\dfrac{B_{mr}}{J_{mr}}\omega_v-\dfrac{f_4(\omega_v)}{J_{mr}}+\dfrac{k_{av}\varphi_v}{J_{mr}R_{av}}f_8(U_v)\\ \dfrac{f_5(\omega_v)(l_m\gamma_m+k_g\Omega_h\cos\alpha_v)-f_9(\Omega_v)+g\left[(A-B)\cos\alpha_v-C\sin\alpha_v\right]-0.5\Omega_h^2H\sin 2\alpha_v}{J_v}\\ S_v+\dfrac{k_t}{J_v}\omega_h\end{pmatrix} \tag{4.1}$$

4.2. Design the model predictive control based on nonlinear programming

4.2.1. Design and install the model predictive control for TRMS systems

Installing the controller with SQP algorithm

When installing the predictive controller with SQP algorithm for TRMS object with the cost function $J(\widehat{\mathcal{U}})$ given by (2.25) and the constrained conditions U obtaining simulation results corresponding to the different desired signal form as Figures from 4.3 to 4.6.

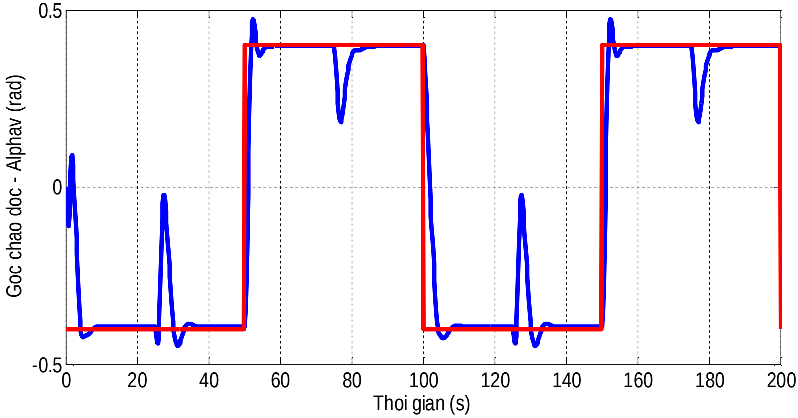

Figure 4.3 The response of the pitch angle control loop with respect to a square - wave

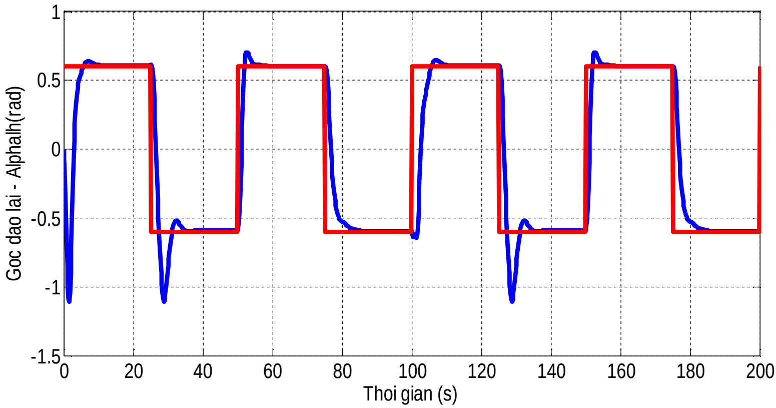

Figure 4.4. The response of the Yaw angle control loop with respect to a square - wave

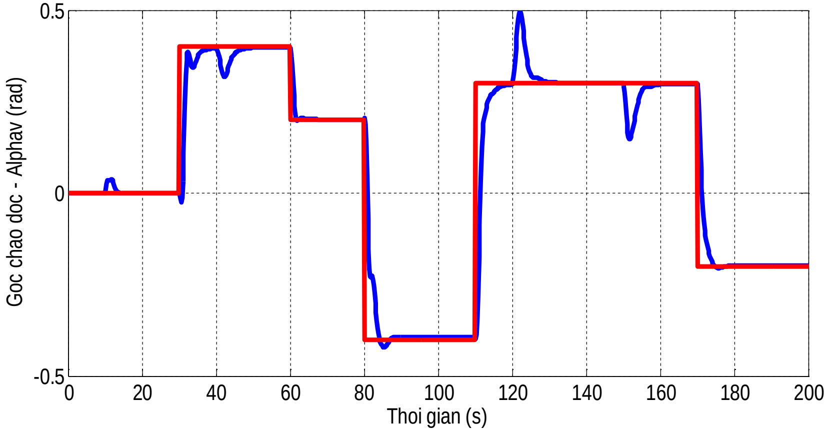

Figure 4.5. The response of the pitch angle control loop with respect to a substep

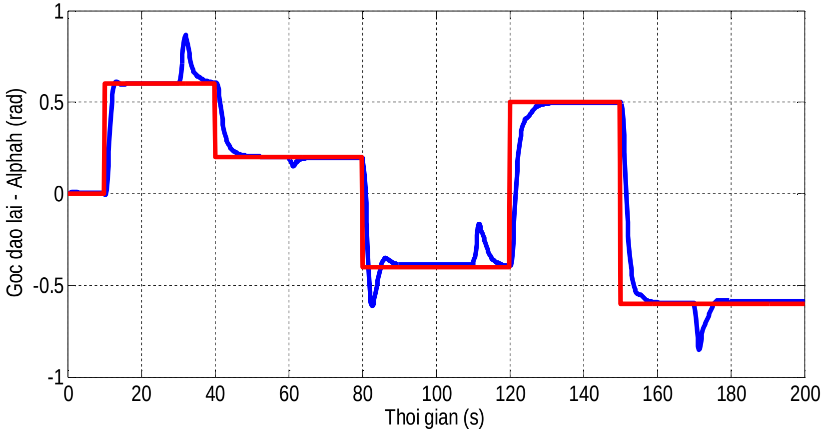

Figure 4.6.The response of the Yaw angle control loop with respect to a substep

4.3. Design the predictive controller based on variational method

4.3.2. Simulations in MatLab and comparative, quality evalution

Matlab simulation: Using algorithms 3.1 given in Section 3.2.2, install algorithms for TRMS object with the parameters Q_K, R_K and sampling cycles T as follows:

$$T = 0.1,\ R_K = \begin{pmatrix} 10 & 0 \\ 0 & 10 \end{pmatrix},\ Q_K = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1000000 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1000000 \end{pmatrix}$$

The author obtained the simulation results as Figures from 4.8 to 4.11

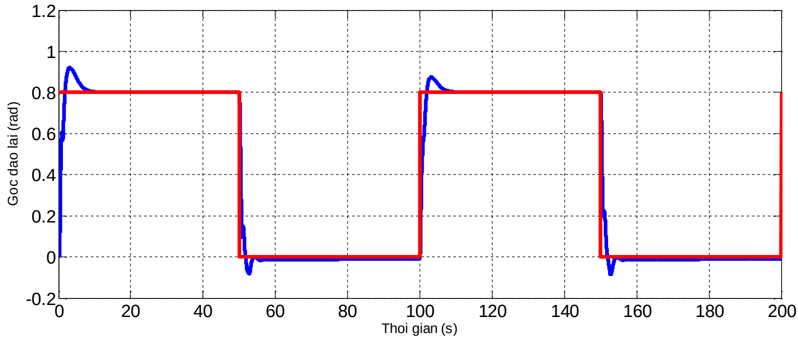

Figure 4.8. The response of the Yaw angle control loop with respect to a square - wave

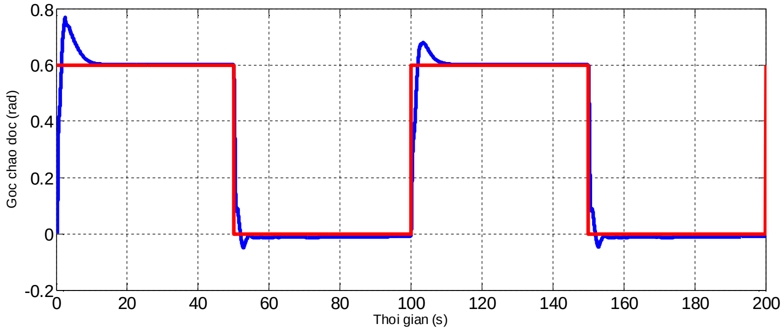

Figure 4.9. The response of the pitch angle control loop with respect to a square - wave

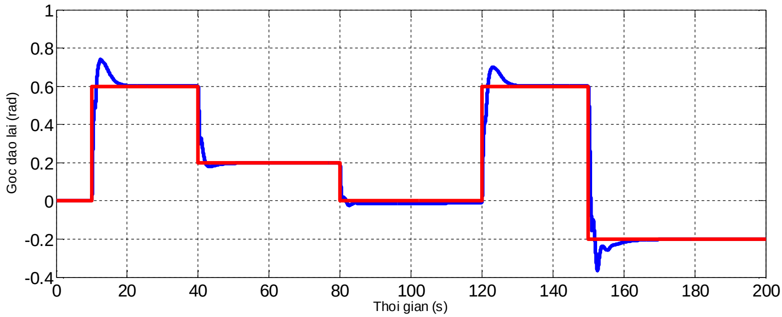

Figure 4.10.The response of the Yaw angle control loop with respect to a substep

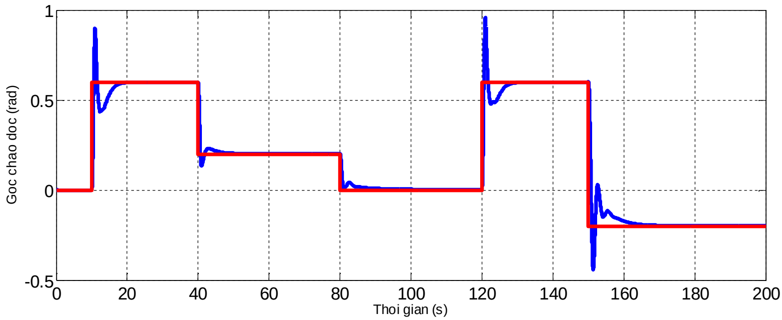

Figure 4.11. The response of the pitch angle control loop with respect to a substep

Compare and quality evalution

Advantages and disadvantages of the optimal methods used nonlinear programming:

Advantages: satisfy the constrained conditions (including status, input and output constraints) fully.

Disadvantages: Time calculate long, hard to install and apply in reality.

To overcome the limitations of the nonlinear programming optimal methos, dissertation proposes using variational method.

Advantages and disadvantages of variational method

Advantages: Time calculate very fast, easy to install and apply in reality, be used to infinite predictive window, stability is almost certainly guaranteed.

Disvantages: Not direct handle the constrained conditions.

To overcome the limitations of variational methods, dissertation proposed the rule to change the weight matrixes Q_K, R_K in the cost function, thus the constrained conditions were satisfied.

4.4. The experiment on physical model of TRMS system

The experimental results are shown on the image from Figure 4.23 to 4.26.

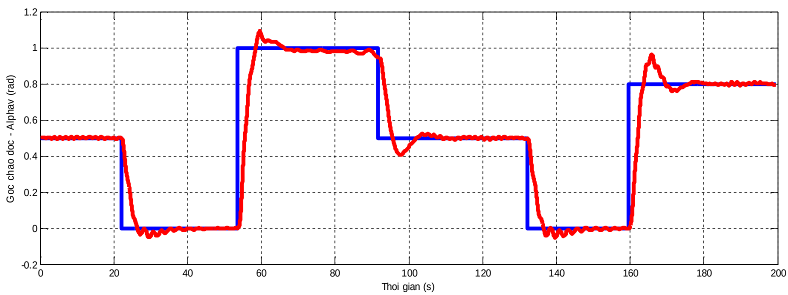

Figure 4.23. The output response of the Pitch angle when using the optimal predictive controller based nonlinear programming

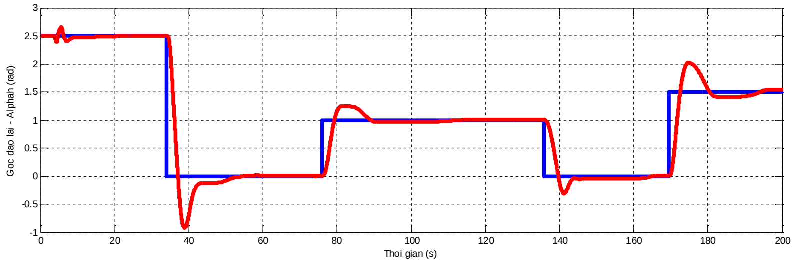

Figure 4.24. The output response of the Yaw angle when using the optimal predictive controller based nonlinear programming

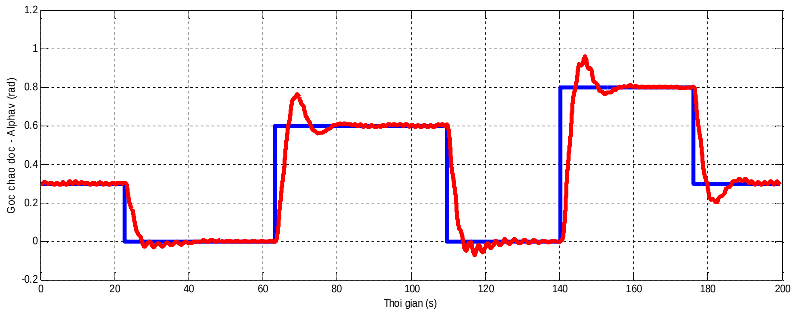

Figure 4.25. The output response of the Pitch angle when using the predictive controller has stabe sticked follow the sample output signal

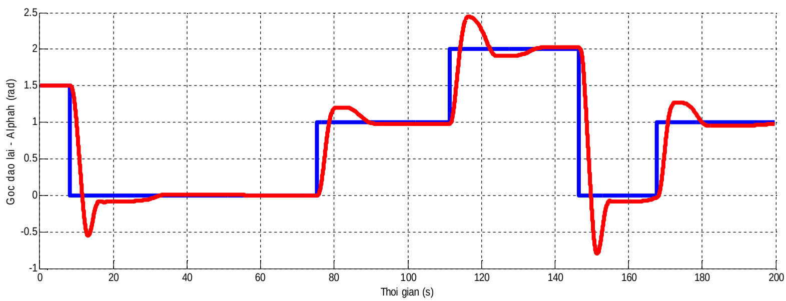

Figure 4.26. The output response of the Yaw angle when using the predictive controller has stabe sticked follow the sample output signal

CONCLUSION AND RECOMMENDATIONS

1. Conclusion

The research results of the dissertaion has some new results follow:

1. Additional improvement algorithms design predictive controller using nonlinear programming method in order to solve optimal problem in optimization strategy of predictive control, extending the applicability of predictive control to control the industrial objects. The study results are verified by simulating program on computers and experimented on physical models of specific TRMS system.

2. Develop a methodology to design predictive controller for nonlinear systems and propose a new solution in one optimization strategy of predictive control for nonlinear systems, namely: nonlinear predictive control based on variational method, dissertation speached and proved theorem about stable sticking follow the sample output signal for continuous nonlinear systems when the predictive window towards infinity. The results of this study overcome the disadvantages of the methods of solving optimal problem based on nonlinear programming and shorten calculating time, improve control quality, expand the applicability and install predictive controller to control the real objects.

3. Install a new algorithm that dissertation made via simulate on computer and implemented control on physical model at the Electric - Electronics Engineering Laboratory, Thai Nguyen University of Technology - Thai Nguyen University, through which verified and confirmed the feasibility of the proposed algorithm.

2. Recommendations and future works

To improve the quality of controller, extending the applicability of model predictive control for controlling the real objects, the next research will continue studied further refining the proposed algorithms and implemented control applications in real systems. Also study and propose further new algorithms having calculating time faster.

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