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MODEL-BASED OPTIMAL CONTROL DESIGN FOR THE ORBIT FEEDBACK SYSTEM AT SIAM PHOTON SOURCE*

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Abstract

A model-based optimal control approach has been developed for the slow orbit feedback (SOFB) system to enhance orbit stability in the Siam Photon Source (SPS) storage ring. The control strategy utilizes a Linear Quadratic Regulator (LQR) based on a multi-input, multi-output (MIMO) state-space model of the linear SPS storage ring, derived through system identification using MATLAB and SIMULINK. The necessary and sufficient conditions for controllability and boundedness of the dynamic system are established. Experimental simulations were conducted to assess the performance of the LQR controller in a practical SPS storage ring. The results demonstrate that the proposed control method effectively minimizes the quadratic cost function and error signals between setpoints and process variables for both horizontal and vertical orbit positions while ensuring system stability and robustness. The study also outlines the fundamental principles of optimal control theory, system identification, and future development directions.

INTRODUCTION

The Siam Photon Source (SPS), Thailand's first synchrotron light source, has played a crucial role in advancing scientific research and technology development in the region. The history of SPS dates back over two decades when a dedicated group of Thai scientists and educators successfully secured a second-generation synchrotron machine from Japan. Originally designed for X-ray lithography in integrated circuit manufacturing, the machine was repurposed to serve the growing demand for synchrotron radiation research in Thailand and beyond. Today, the Synchrotron Light Research Institute (SLRI) operates SPS as a national facility, supporting over 4,000 hours of user experiments annually with a high availabil-ity rate of 95% [1, 2].

Over the past 20 years, continuous upgrades and improvements have enhanced the performance of SPS. These developments include extending photon energy into the hard X-ray region, improving beam positional stability, and increasing machine reliability. The SPS complex consists of a 40 MeV linear accelerator (LINAC), a 1 GeV booster synchrotron (SYN), and a 1.2 GeV electron storage ring (STR). As part of ongoing efforts to further upgrade its capabilities, the booster synchrotron energy is being increased to 1.2 GeV, necessitating enhancements in the RF cavity and magnet systems. These upgrades aim to support the increasing demand for higher energy X-ray applications and ensure the long term sustainability of synchrotron operations in Thailand. A critical aspect of maintaining high quality synchrotron radiation is beam stability, particularly in terms of orbit correction.

To address beam stability challenges, a model-based optimal control approach was developed for the SOFB system at the SPS. This approach utilizes a Linear Quadratic Regulator (LQR) based on a MIMO state-space model of the SPS storage ring, derived using MATLAB and SIMULINK system identification techniques. By ensuring system controllability and stability, this strategy enhances the precision and robustness of beam position correction [3].

This paper outlines the LQR-based SOFB system's implementation, covering its theoretical framework, system identification, and simulation-based validation. Results confirm the control methodology's effectiveness in minimizing orbit deviations while maintaining stability. Future development directions for SPS and orbit correction enhancements are also discussed.

SYNTEM IDENTIFICATION

System identification involves creating a mathematical model of a dynamic system using observed input-output data, analyzing system responses to various inputs to construct an accurate representation of its behavior. The primary objective is to develop a model that supports effective controller design, ensuring optimal system performance and stability.

An ideal model is of the lowest possible order while accurately capturing the system's dynamics. Low-order models simplify analysis, reduce computational demands, and improve control implementation efficiency. However, they must encompass critical dynamic characteristics, such as time delays, oscillations, and nonlinearities, to ensure reliable predictions and robust control performance.

A well-crafted model forms the basis for designing control strategies, including PID controllers, state-space controllers, or adaptive systems, tailored to specific performance needs. Thus, striking a balance between model simplicity and accuracy is essential for successful system identification [4, 5].

System Identification Using MATLAB

The MATLAB System Identification Toolbox offers powerful tools for building dynamic system models from experimental data. It supports pre-processing, model selection, and parameter estimation to ensure accurate representation of system behavior. Its strength lies in generating simplified yet precise models, even from noisy time-series data, making it ideal for control design, signal processing, and forecasting. The toolbox supports various model structures, providing flexibility in system modeling. (Fig. 1).

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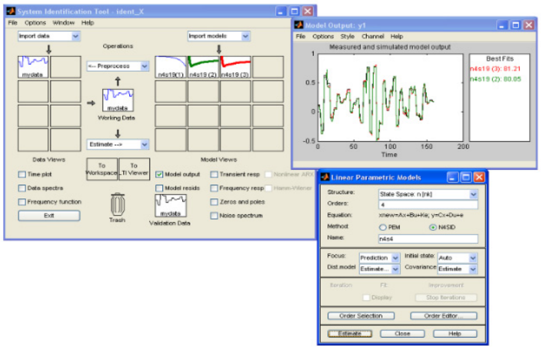

Figure 1: MATLAB system identification toolbox.

OPTIMAL CONTROL THEORY

Optimal control theory is a mature mathematical discipline with plenty of applications in both science and engineering. The basic principle of optimal control is to find a controller that provides the best performance of the dynamic system with respect to some given/available measurements. Moreover, this optimal control procedure is applicable to MIMO processes for which classical control designs are difficult to apply [5, 6].

An LQR controller is an optimal control technique used in control systems engineering to design a feedback controller for linear systems. It aims to minimize a quadratic cost function that balances the system's state deviation from a desired state and the control effort required.

State Space Model

A state space model relates the inputs and outputs of a system using the following first-order vector ordinary differential equation as follows:

$$\begin{aligned} \dot{x} &= f(x,u) \\ y &= g(x,u) \end{aligned}. \tag{1}$$

Here, we focus our attention to linear time-invariant (LTI) systems for the functions $f(x, u)$ and $g(x, u)$. In this case, Eq. (1) has the special form:

$$\begin{aligned} \dot{x} &= Ax + Bu, \\ y &= Cx + Du \end{aligned} \tag{2}$$

where $A \in \Re^{nxn}$, $B \in \Re^{nxm}$, $C \in \Re^{pxn}$, $D \in \Re^{pxm}$, and m, n and p are the number of states (x), control signals (u) and outputs (y), respectively.

Quadratic Cost Function

The LQR controller to design a state-feedback controller that minimizes the following *quadratic cost function* (J_{LQR})

$$J_{LQR} \quad = \quad \int_0^\infty (x^T Qx + u^T Ru)\, d(t)\,. \tag{3}$$

$Q \in \Re^{pxp}$ is a positive semi-definite matrix that penalizes state deviations (ensuring the system stays close to the desired state) and $R \in \Re^{mxm}$ is a positive definite matrix that penalizes control effort (keeping control inputs reasonable). The goal is to find the control input *u(t)* that minimizes J_{LQR}.

Optimal Control Law

The LQR controller computes the optimal feedback gain matrix K such that:

$$u = -Kx\,. \tag{4}$$

The gain K is derived by solving the *Algebraic Riccati Equation* (ARE):

$$A^T P + PA - PBR^{-1}B^T P + Q = 0\,, \tag{5}$$

where P is a positive definite matrix, and the feedback gain is:

$$K = R^{-1}B^T P\,. \tag{6}$$

SIMULATION AND RESULTS

This section presents the simulation framework and outcomes that validate the proposed model-based control strategy for the SOFB system at the SPS. The process begins with constructing a high-fidelity state-space model through system identification using experimental data from the SPS storage ring. This model captures the essential dynamics required for precise orbit correction. Building on this foundation, an optimal LQR controller is designed to enhance system stability and minimize orbit deviations. The following subsections detail the methodology and results of both the model validation and the implementation of the LQR feedback control system.

System Identification and Model Validation

A comprehensive dataset comprising 21,600 data points was acquired over a six-hour period to characterize the open-loop behavior of the SPS storage ring. This dataset included output signals from 40 Beam Position Monitors (BPMs); 20 horizontal (BPMX) and 20 vertical (BPMY), and input signals from 28 corrector magnets, with 16 horizontal and 12 vertical elements. These measurements formed the basis for constructing a dynamic model of the system.

To ensure robust model identification, input setpoints were updated every 5 seconds in real time, with uniformly distributed random noise ranging from 0.0 to 1.0. This approach satisfied the condition of "persistent excitation", which is essential for activating all relevant dynamic modes and obtaining reliable parameter estimates.

The resulting state-space model demonstrated strong alignment with the observed system behavior, achieving fit accuracies of 85.80% for horizontal (X) and 87.21% for vertical (Y) data. These high fidelity metrics confirm the

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model's capability to capture the essential dynamics of the SPS storage ring, providing a solid foundation for the subsequent design and implementation of the optimal LQR control strategy (see Fig. 2).

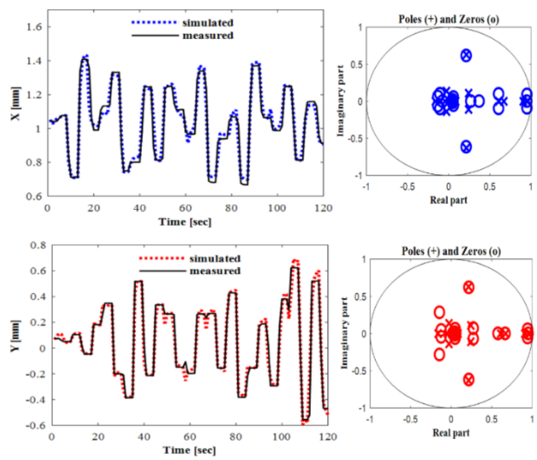

Figure 2: Measured and simulated X-Y outputs of the BPM no. 5.

Figure 2 demonstrates the accuracy of the system identification for BPM number 5, presenting both horizontal (X) and vertical (Y) orbit data. On the left side of each plot, solid lines represent the measured outputs, while dashed lines indicate the simulated responses generated by the identified model. The close alignment between these curves confirms the model's ability to replicate the system's dynamic behavior. On the right side, the pole-zero plot offers a visual representation of the system's transfer function in the complex plane, revealing essential characteristics such as stability margins and the region of convergence.

Optimal Feedback LQR Controller Design

Following system identification, an optimal LQR controller was designed to manage the SPS storage ring's complex dynamics, involving 28 control inputs and 40 measurement outputs. Using the mathematical framework outlined in Eqs. (1) to (6), the controller ensures stable operation even under the influence of measurement noise, external disturbances, and parameter variations. MATLAB Simulink was employed to implement the control system, providing a robust and flexible platform for modeling, simulation, and real-time tuning of control parameters.

The controller's performance hinges on the careful selection and tuning of the weighting matrices Q and R, which define the trade-off between rapid convergence to setpoints and minimal control effort. This balance is critical for achieving a responsive and stable closed-loop system that effectively suppresses fluctuations, minimizes orbit deviations, and maintains beam stability across a wide range of operating conditions.

Figures 3 and 4 illustrate both the structure and effectiveness of the LQR controller. Figure 3 presents the MATLAB Simulink block diagram, detailing the control architecture, including state-space model integration, feedback loop configuration, and signal flow between system components. Figure 4 shows simulation results, where multiple state trajectories from various BPMs converge smoothly to their respective targets. This behavior confirms the controller's ability to dampen oscillations, reduce transient responses, and maintain system stability despite dynamic disturbances.

These results validate the LQR controller's adaptability, precision, and robustness, demonstrating its suitability for real-world synchrotron operations. Its consistent performance under varying conditions reinforces its role in enhancing orbit correction and supporting the SPS's reliability and long-term operational excellence as a national research facility.

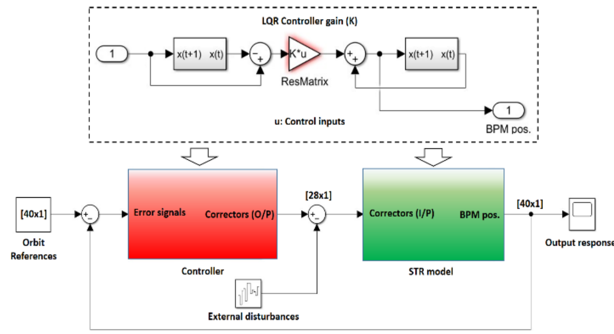

Figure 3: MATLAB Simulink design and simulation.

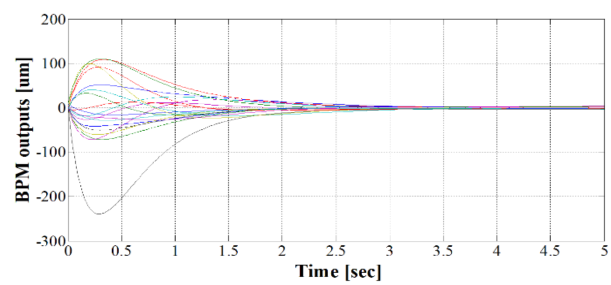

Figure 4: LQR controller and simulation results.

CONCLUSION

Simulation results demonstrate that the optimal feedback control strategy using an LQR, based on a state-space model, ensures robust and stable closed-loop control for linear systems. The controller effectively minimizes orbit deviations and maintains stability under varying operating conditions. Its performance remains reliable despite mismatches between the model and actual system dynamics, and it consistently delivers accurate responses even in the presence of noise and parameter disturbances. These results highlight the LQR approach's resilience, adaptability, and suitability for precision orbit correction in synchrotron applications.

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