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Parameter Estimation of Magnetic Growing Rod with Output Error Method

1th Alper YILDIRIM
Mechatronics Engineering Department
Marmara University
Istanbul,Turkey
yildirim.alper@marmara.edu.tr

2nd Gazi AKGÜN
Mechatronics Engineering Department
Marmara University
Istanbul,Turkey
gazi.akgun@marmara.edu.tr

3rd Safer Çokatar
Mechatronics Engineering Department
Marmara University
Istanbul,Turkey
safercokatar@marmara.edu.tr

4th Uğur DEMİR
Mechatronics Engineering Department
Marmara University
Istanbul,Turkey
udemir@marmara.edu.tr

***Abstract*— This study focuses on a magnetic controlled growing rods (MCGR) used in the treatment of early-onset scoliosis. In this study, the Lyapunov direct method-based output error method, which is iterative adaptive by online, is used as a parameter estimation method to predict the velocity of the telescopic bar during the MCGR distraction process. The system parameters are estimated. by the proposed model. The main purpose is to minimize the error between the actual and desired states by the online configuration of the controller's parameters. By using online models, we can continuously update and refine system parameters to improve prediction accuracy.**

Keywords—Observer, output error method, magnetic growing rod (MCGR)

I. INTRODUCTION

Early-onset scoliosis is a potentially life-threatening spinal deformity which leads to avoid the development of lung and heart in the growing child. Surgical intervention is performed for its treatment. The ultimate goal of surgical treatment is to halt the progression of the curvature while allowing for maximum growth of the spine, lungs, and chest cage. Growth-friendly implant systems have been developed for surgical treatment. The aim of these implant systems is to promote spinal growth in patients with early-onset scoliosis without the progression of scoliosis [1, 2].

As seen in Figure 1, the implanted rod on the patient can be distracted by the amount determined by the physician during clinical examinations every periodic times [3]. During, the distraction, the magnets inside the external control unit (shown in Figure 1.a) generate a rotating magnetic field, exciting the magnets of implant (Figure 2) attached to the patient's spine and creating a torque on the telescopic bar. This arrangement is like a fixed magnet motor with separate stator and rotor components [1].

Although magnetically growing rods are capable to solve many problems compared to traditional rods, there are lots of complications in the literature [4]. These complications basis of the mechanical faults including rod slippage due to bearing, loss of distraction, the formation of debris caused by abrasion, rod breakage, actuator locking pin breakage, and wear of the gear mechanism [5, 6]. To overcome these complications, Demir et al. studied on the design optimization methods, particularly for those related to bearing and design issues [4].The main reason for the mismatch between the target and achieved distraction among these problems is the inability of the controller to read the speed or position information of the telescopic bar, which is extended by the controller through the patient's spine and over the skin, during the distraction process.

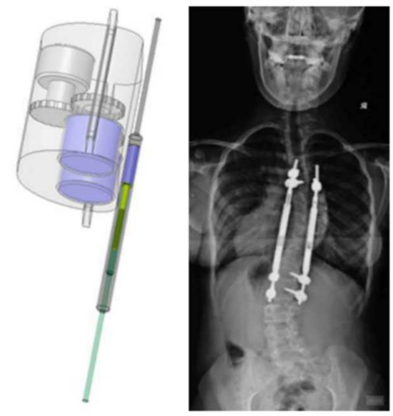

Fig. 1. Double assembly with MAGEC®magnetic rod: external lengthening system, and radiograph of the magnetic rod in the position [6].

The aim of this study is to estimate the system parameter such as speed and position state of the telescopic bar by using the state information obtained from the controller. Finally, the estimated results are validated by the experimental data.

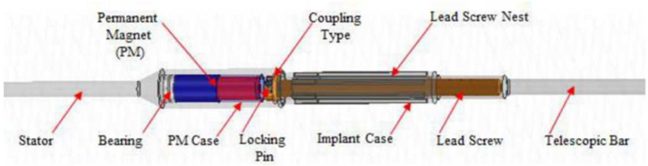

Fig. 2. Cad model of Magnetic Growing Rod

In this study, an experimental setup with an approximate model that operates similarly to MCGR has been designed to perform parameter estimation processes. All testing and experiments are performed on this experimental setup. The performance, accuracy and reliability of the approximate model are evaluated. In addition, studies are conducted on the model's ability to adapt to the specific characteristics and needs of patients and its potential to develop individualized control strategies.

This experimental setup provides a fundamental resource for designing, testing, and optimizing an MCGR-like approximate model. Performing all tests and experiments on this set of experiments increases the reliability and validity of the results and ensures the adaptability of the findings to other clinical applications.

As a briefly, this study aims to evaluate the effectiveness and applicability of the approximate model in a MCGR-like system. Tests and experiments on the test rig aim to predict position of telescopic bar without using any sensor. In this way, the proposed approach can provide the improvement of the treatment process of patients with early-onset scoliosis and provide a safer and more effective therapeutic approach by promoting progress in this field.

The application of parameter estimation purposes tto achieve more effective and safer outcomes in the treatment of early-onset scoliosis by optimizing the course of treatment, reducing the risk of complications, and developing an individualized treatment approach.

II. Materials and Methods

A. *Magnetic Growing Rod Experimental Setup*

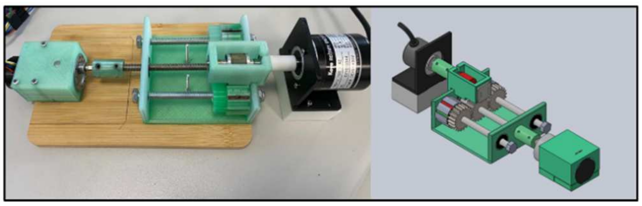

Fig 3. Experimental Setup

In the designed experimental setup, two cylinders made up of multiple magnets are manipulated using a DC motor with an internal encoder. This model represents an external control unit. To emulate the magnetic growing rod on the cylinders, a rotor with fixed magnets is placed, as seen in Figure 3. The angular position and velocity of this rotor can be measured using an incremental encoder.

In the test rig shown in Figure 3, the utilization of magnetically growing rods with a similarity to the working principle of a magnetic gear mechanism offers several advantages. Magnetic gears are mechanisms that rely on magnetic interactions between components to enable rotation or movement. Similarly, magnetically growing rods can move by establishing magnetic interactions with each other. [11] These rods are typically configure by using magnets or magnetic materials. The magnetic attraction and repulsion forces between the rods function similarly to the interaction between gears in a gear mechanism. Through these magnetic interactions, the rods can achieve the desired rotations or movements. The magnetically growing rods serve various purposes within the designed experimental setup and are utilized on various applications such as investigating complex magnetic interactions or controlling mechanical motion. The versatility and controllability of these rods make them valuable tools for studying magnetic phenomena and conducting experiments that involve precise manipulation of mechanical systems. The design allows for flexibility in exploring different configurations and arrangements, offering insights into the behavior of magnetic fields and their effects on the rod's movements. Moreover, the ability to finely adjust the magnetic forces between the rods provides opportunities for precise control over their motions, facilitating experimental investigations and allowing for the development of innovative applications in fields such as robotics, materials science, and magnetic levitation technology.

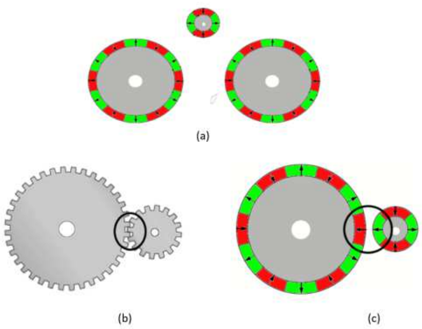

Fig 4. Magnetic gear

There are many ways for transmitting mechanical power, one of them is magnetic gears which are a gear system utilizing the attractive and repulsive properties of magnets between two or more revolving pieces. Instead of physical tooth contact like traditional gears do, magnetic gears work through the laws of magnetism. An electromagnetic gear is typically designed with three essential parts: the driving rotor, the driven rotor, and an intermediate disk or ring that acts as a magnetic coupling or air gap. The input shaft is attached to the driving rotor, while the output shaft is attached to the driven rotor. The intermediate ring, which serves as a spatial separator, is sandwiched between these two rotors. Magnets of alternating polarity are arranged and placed around the periphery of the driving rotor, while the driven rotor also includes a corresponding magnet array. [12]

The placement of magnets in the arrays is such that there exists an air gap between the driven rotor magnets and the driving rotor magnets with opposite poles.

Even if without any physical interaction between the rotors, the torque transfer between them is due to how the magnetic fields of the driving rotor and driven rotor intermingle while in movement. During the rotation of the driving rotor, the magnets in the rotors converse through forces of attraction and repulsion through the air gap.

The gear ratio is comprised of a range of magnets that can be shifted to manipulate the step of the driving and driven rotors. As the rotary force moves, magnetic fields entice the driven rotor to follow suit, then complete the transfer of mechanical energy. The magnetic coupling acts as the medium for transmitting torque from the driving rotor to the driven rotor.

Magnetic gears have superior advantages such as remarkable efficiency, avoiding physical contact therefore prevention friction, less maintenance, less noise, reliable system such as avoiding the overload.

As can be understood from Figure 5, the magnets manipulated by a DC motor with fixed magnets operate the represent of the magnetic rod. Here, the state space model of the DC motor with growing rod is as follows;

$$\begin{bmatrix} \dot{i_M}(t) \\ \dot{\omega_2}(t) \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & -\frac{K}{L} \\ \frac{K}{J_{PM}} & -\frac{d}{J_{PM}} \end{bmatrix} \begin{bmatrix} i_M(t) \\ \omega_2(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} . v(t) \quad (1)$$

Here $i(t)$, the current of armature, $\omega_2(t)$ is the velocity of the rod, $R, L, J_{PM}, K, v(t)$ is resistance, inductance, inertia, motor constant and input voltage respectively with assuming $k \cong 0$ and $\frac{N_1}{N_2} \cong 1$.

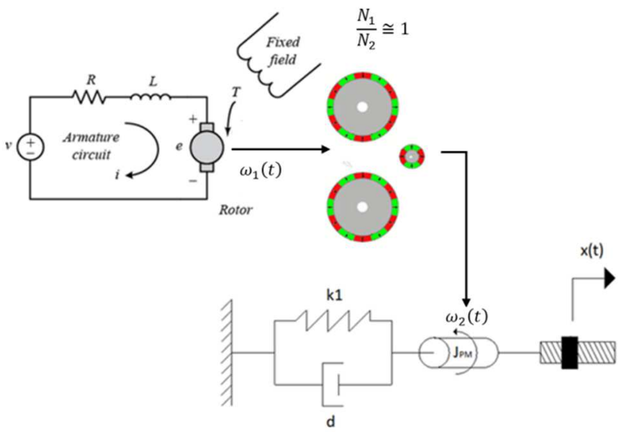

Fig 5. The model of the system

The dynamics of the system is given considering static friction;

$$J_{PM}\dot{\omega}_2 + d\omega_2 + F_S sgn\ \omega_2 = Ki_M \quad (2)$$

Here f_s is static friction, If we take the system as follows;

$$\dot{x_1} = x_2 \quad (3)$$
$$\dot{x}_2 = -ax_2 + bu - f_s \operatorname{sgn}(x_2)$$

Here, $x1$, $x2$, and u represent the position, velocity, and current values, respectively. The viscous friction coefficient is denoted by a (d/J_{PM}), the static friction is coefficient is denoted by f_s $\left(\frac{F_s}{J_{PM}}\right)$, the input gain is denoted by b (K/J_{PM}).

B. Online Adaptive Parameter Estimation

In the literature, there are various method for online parameter estimation to predict unknown parameters. Some of them include the output error method based Lyapunov direct method, equation error method, and recursive least square method. In this particular study, the output error method is employed. The dynamic equation of the system is provided below [9].

$$\dot{x}_2 = -ax_2 - f_s \operatorname{sgn}(x_2) + bu, \ x_2(0) = 0 \quad (4)$$

In the given equation, a, b, and f_s represent the unknown parameters that need to be determined. The equation involves the state variable x_2 and the input u of the system. Both the state variable and the input are either measured or observed. To begin the estimation process, we derive the estimators based on the assumption that $a > 0$, $f_s > 0$, and u is upper-bounded. The estimation procedure, also known as the update law, for the unknown parameters a, b, and f_s will be guided by the error in state estimation.

$$\epsilon = x_2 - \hat{x}_2 \quad (5)$$

The estimated state variable of the system, denoted as $\hat{x}_2$, is calculated using the estimated values of the unknown dynamic parameters. When the estimated parameters $\hat{a}$ and $\hat{b}$ are used, the system equation 1 can be expressed as follows

$$\dot{\hat{x}}_2 = -\hat{a}\hat{x}_2 - \hat{f}_s \operatorname{sgn}(\hat{x}_2) + \hat{b}u, \ \hat{x}_2(0) = (\hat{x}_2)_0 \quad (6)$$

Equation 6 represents the parallel model configuration, which is a specific formulation used in the context of parameter estimation. The output error method is an estimation technique employed with this equation. By utilizing the dynamic equations, the derivatives of the unknown parameters a , b and f_s can be computed as follows.

$$\dot{\hat{a}} = -\gamma_1 \epsilon x_2, \quad \dot{\hat{b}} = \gamma_2 \epsilon u, \ \dot{\hat{f}}_s = \gamma_3 \epsilon sgn(x_2) \quad (7)$$

C. Parameter Projection

Applying the gradient projection method to the output error method results in the utilization of adaptive online estimators for the unknown parameters. These estimators are designed to incorporate the projection mechanism, which effectively constrains the estimated parameter values within a predefined boundary in the parameter space. By employing this approach, the adaptive online estimators dynamically adjust their behavior based on the estimated parameter values, ensuring improved stability and robustness in the parameter estimation process [10].

$$\dot{\hat{a}} = \begin{cases} -\gamma_1 \epsilon x_2 & \text{if } a_{lb} \leqslant \hat{a} \leqslant a_{ub} \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

$$\dot{\hat{b}} = \begin{cases} \gamma_2 \epsilon u & \text{if } b_{lb} \leqslant \hat{b} \leqslant b_{ub} \\ 0 & \text{otherwise} \end{cases}$$

$$\dot{\hat{f}}_s = \begin{cases} -\gamma_3 \epsilon \mathrm{sgn}(x_2) \text{ if } f_{lb} \leqslant \hat{f} \leqslant f_{ub} \\ 0 \text{ otherwise} \end{cases}$$

In the given equations, a_{lb}, a_{ub}, b_{lb}, b_{ub}, f_{lb}, and f_{ub} represent the lower and upper bounds for the estimated parameters $\hat{a}$, $\hat{b}$, and $\hat{f}$, respectively. These bounds define the permissible ranges within which the estimated parameter values are constrained. By setting these lower and upper bounds, the parameter estimation process ensures that the estimated values for $\hat{a}$, $\hat{b}$, and $\hat{f}$ remain within the specified limits during the estimation procedure.

D. Persistent Excitation

To ensure successful adaptive online parameter estimation, it is crucial that the input signal to the system contains sufficient information to accurately estimate the parameters. This requirement is necessary to stimulate all the modes of the plant and achieve correct parameter estimation. Therefore, in this study, a sinusoidal signal is chosen as the input to the system. The selection of a sinusoidal signal allows for the inclusion of an adequate number of frequencies that can stimulate all the modes of the plant, thus facilitating the estimation of the unknown system parameters .

III. Results and Discussion

As shown in Figure 6, when the model is iteratively executed, the dynamic parameters of the system converge to certain values. The results in Figure 6 were obtained through experiments conducted starting from the "0" initial point and running the model between the upper and lower bounds of the obtained values. Here, the viscous friction was calculated as $a \cong 3.129, b \cong 0.8$, and $f_s \cong 0.001$.

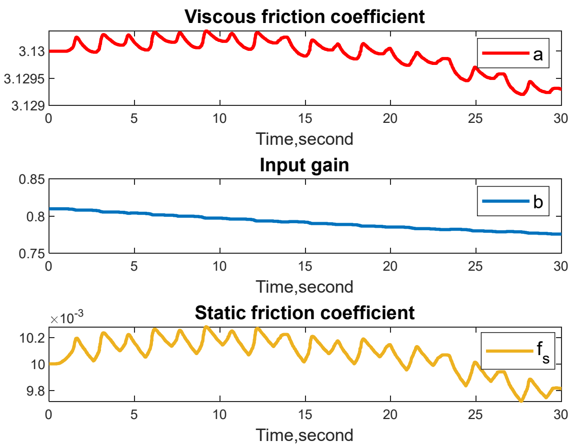

Fig 6. Change of parameters by time

Figure 7 shows the variation of the calculated velocity value by the model and the measured velocity value obtained from the encoder over time. From this, we can conclude that we can estimate the velocity value with a small error.

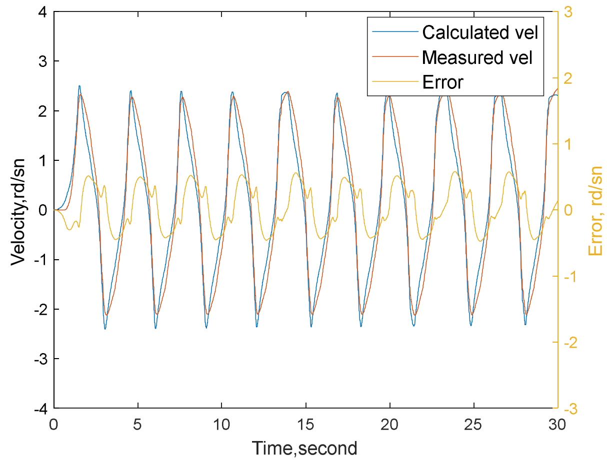

Fig 7. Comparison between calculated and measured velocity $\omega_2(t)$ as output

The values obtained using the output error method based on the Lyapunov direct method can be maintained within a certain range and used in real-time. This allows the estimated model, which can adapt to potential changes in the system, to feed the fundamental model.

IV. Conclusion

This paper presents that the Lyapunov direct based iterative adaptive method is proposed to perform online parameter estimation for MCGR due to improve the accuracy of the parameter estimation, which contributes to improving the stability and robustness of control systems.

According to the obtained results from experimental tests to estimate the dynamic parameters and speed of the system, the running the model tries to perform continuously to the convergence of the dynamic parameters in the system to certain values.

The proposed method for parameter estimation in this study is a quite successful approach to improve the accuracy of the MCGR implant. To provide the better clinical outcomes for patients with early-onset scoliosis, accurate estimation of the speed of the telescopic rod is key point during the MCGR extension process. The proposed method is also tested on a simulated MCGR implant, and it is observed that is able to accurately predict the velocity of the telescopic bar under the various of conditions.

Consequently, this study shows that the efficient way to estimate the online parameters is Lyapunov direct based iterative adaptive method.

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