Research on the Control of the Mechanical System of Satellite Monitoring Antenna in Different Environmental Conditions

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Abstract. This paper presents the results of position control and path control for the mechanical systems of satellite surveillance antenna systems under different environmental conditions. A traditional and highly reliable PID control system is considered and used for antenna system works in the conditions of wind and without wind effect. The control parameters are found based on the strong toolbox module of MATLAB software. The contents of this study are the next development of the results of the kinematics and dynamics analysis that have been published previously. The mathematical model and the differential equations of motion of the system are established based on the multi-bodies mechanics' theory and the Lagrange - Euler equations. The control analysis results show that there is a clear difference in the different operating conditions of the system. This is an important basis in the fabrication of the antenna system in reality.

Keywords: Monitoring antenna · Satellite · Dynamics · Control

1 Introduction

As mentioned in previous publications as [1] and [2], the designing, manufacturing, and controlling of satellite surveillance antennas is a specific scientific field and depends heavily on the development level of each country. Currently, only a few countries have mastered this space technology [3–9]. The issue of space technology transfer between countries is quite difficult due to national security and technology secrets. Therefore, developing countries like Vietnam need to be proactive in all of the researching problems related to the antenna and satellite system themselves.

A few works related to solving the dynamics problem of the geostationary satellite antennas are published such as in [10–14] and they have been reviewed and described in [2]. The PID control of the Antenna system is considered in [15] to ensure the delay compensation of the received and transmitted signals over a large area. This Antenna system connects to the NIGCOMSAT-1 satellite. The Bang-Bang control method is used in [16] to control the position of a geostationary satellite surveillance antenna system. The control system used is a microcontroller and the remote-control method. An antenna position control system with location data stored and sent via infrared signals

N. V. Khang et al. (Eds.): ASIAN MMS 2021, MMS 113, pp. 391–400, 2022.
https://doi.org/10.1007/978-3-030-91892-7_37

is described in [17]. Antenna position control system with satellite recognition capability is considered in [18]. Accordingly, the satellite is identified through its radiation signal, from which the position of the satellite will be input to the antenna control system. The main problem with this system is that the recognition ability will decrease if affected by weather or environmental conditions. Another antenna position control system is considered in [19]. The satellite position to be tracked is sent via the smartphone and decoded by the Raspberry Pi system. The control quality of the system is mainly affected by the signal delay. The PID control system incorporating LQR was developed in [20] to control the antenna position through the DC Servo motor. The result is a faster response time than a traditional PID system. The antenna position control system in [21] is built on the basis of the traditional PID system with the parameters found by the Ziegler-Nichols method and the 2nd order optimization system. The PID control system incorporating the H system was built to control the antenna and ensure the stability of the system is described in [22].

This paper presents the results of position and trajectory control for a geostationary satellite monitoring antenna system. A traditional and highly reliable PID control system is used with found control parameters based on the strong toolbox module of MATLAB software. The control problem is considered in case the system is affected by the wind and without the wind. Calculation results and numerical simulations show that when the antenna is affected by the wind, the control error is large and the actuators for the joints must maintain a state of continuous operation with high intensity to ensure the accuracy and stability of the antenna system.

2 Research Contents

2.1 Dynamics Modeling

The dynamic model of the satellite surveillance antenna in Fig. 1 and Fig. 2 has been clearly described in [2] with two main parts which are the rotating cluster (directional cluster) and the satellite pan cluster. The movement of the rotating cluster is done by the rotating joint q_1 which is driven by motor 1. The satellite pan cluster height is performed by rotating joint q_2. This joint is driven by motor 2 through the translational joint A and rotational joint B. However, these joints are only responsible for driving the joint q_2, so it is not considered in the kinematic problem. The center of the rotating cluster is G_1, the satellite pan assembly center is G_2.

Select a fixed coordinate system $(OXYZ)_0$ attached to the ground. The $(OXYZ)_i$ coordinate systems are respectively mounted at the positions shown in Fig. 2. In particular, taking point G_2 is the end-effector point representing the satellite pan cluster.

The position of G_2 point is determined according to the fixed coordinate system based on the setup of the DH parameter table and the homogeneous transformation matrix [2] as follows:

$$
\begin{aligned}
x_{G2} &= \cos q_1 (a_2 + a_4 \cos q_2 - d_5 \sin q_2) \\
y_{G2} &= \sin q_1 (a_2 + a_4 \cos q_2 - d_5 \sin q_2) \\
z_{G2} &= d_0 + d_1 + d_3 + a_4 \sin q_2 + d_5 \cos q_2
\end{aligned}
\tag{1}
$$

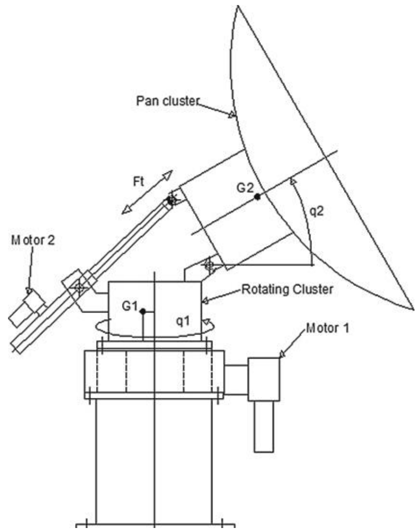

Fig. 1. Preliminary mechanical system

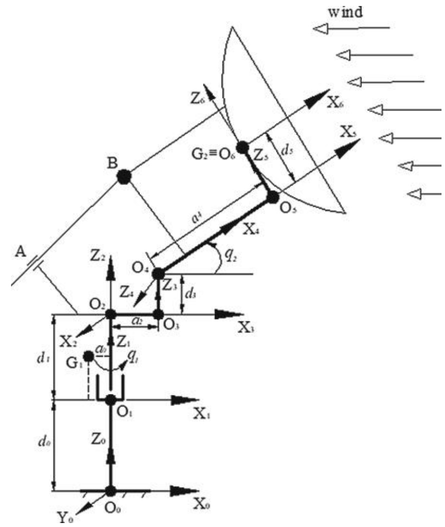

Fig. 2. Mathematical model

The position of the center mass G_1 of the rotating cluster ($\mathbf{R}_{C1}$) and the center mass G_2 of the pan cluster ($\mathbf{R}_{C2}$) in the fixed coordinate system are shown as follows

$$\mathbf{R}_{C1} = \left[-a_0 \cos q_1 \; -a_0 \sin q_1 \; d_0 + \tfrac{d_1}{2} \right]^T, \quad \mathbf{R}_{C2} = \left[x_{G2} \; y_{G2} \; z_{G2} \right]^T \tag{2}$$

The dynamic equations of the antenna system are presented as

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \boldsymbol{\tau} + \mathbf{f}^* \tag{3}$$

Where, $\mathbf{M}(\mathbf{q})$ is the mass matrix, $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})$ is the Coriolis matrix which is determined in [14, 15], $\mathbf{g}(\mathbf{q})$ is the gravity potential energy vector, $\boldsymbol{\tau} = \left[\tau_1 \; \tau_2 \right]^T$ is the driven torque vector at the joints q_1, q_2 and $\mathbf{f}^* = \left[Q_1^*, Q_2^* ..., Q_n^* \right]^T$ is the external force vector. In this study, the external force acting on the antenna system is the wind load. It is assumed that the influence of wind on the rotational cluster is ignored, only considering the effect of wind load on the pan cluster. The value of force caused by the wind on the pan cluster is calculated specifically in [23]. In this case, in order to reduce the calculating complexity, assumed that the wind force is always parallel and opposite to the axial direction OX. The distributed wind load is assumed to be concentrated force acting at the center of mass G_2. The maximum value of the wind load on OX axis is $F_{x\max} = 22174(N)$ and on OY axis is $F_{y\max} = 30670(\mathrm{N})$ in the case $q_2 = 0$ with velocity of the wind is 25(m/s) [23]. The driven torque vector can be found as follows

$$\boldsymbol{\tau}(t) = \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) - \mathbf{f}^* \tag{4}$$

2.2 PID Control System

The PID controller is a popular control system, which is used a lot in industry because of its simplicity, stability and ability to be controlled in many different working conditions.

The efficiency of PID system is limited in the nonlinear system. However, the PID controller is highly effective and stable for the systems which is explicitly mathematical. The quality of controlling depends on selecting the suitable control parameters including k_P, k_I, k_D. With the desired position and trajectory of the joint variable $\mathbf{q}_{desired}(t) = \left[q_{1d} \ q_{2d} \right]^T$, the PID control system needs to ensure that it finds a value of $\boldsymbol{\tau}(t)$ that meets the above requirements with the error $\mathbf{e}(t) = \mathbf{q}_{desired}(t) - \mathbf{q}_{actual}(t)$ moving towards zero with $\mathbf{q}_{actual}(t)$ being the actual value of the joint variable response. Thus, the control law is built as follows

$$\boldsymbol{\tau}(t) = \mathbf{K}_P \mathbf{e}(t) + \mathbf{K}_D \frac{d\mathbf{e}(t)}{dt} + \mathbf{K}_I \int_0^t \mathbf{e} ds \tag{5}$$

Where $\mathbf{K}_P = \left[k_{p1} \ k_{p2} \right]^T$, $\mathbf{K}_D = \left[k_{d1} \ k_{d2} \right]^T$, $\mathbf{K}_I = \left[k_{i1} \ k_{i2} \right]^T$ are the parameter vectors of the PID control system corresponding to each joint variable q_1, q_2. The control diagram of the antenna system is shown in Fig. 3.

2.3 Numerical Simulation Results

The basic parameters of the expected antenna system to be designed and manufactured are as follows

$a_0 = 0.33(m), a_2 = 0.39(m), d_0 = 3.62(m), d_1 = 0.87(m), d_3 = 0.2(m), a_4 = 1.15(m),$
$d_5 = 0.21(m), m_1 = 1050(kg), m_2 = 1350(kg).$

The given paths of joint variables are $q_1 = \frac{\pi}{4}\sin(\frac{t}{4})(rad)$ and $q_2 = \frac{\pi}{4}\sin(\frac{t}{6})(rad)$ (Fig. 5). The inverse dynamics problem solving diagram is described in Fig. 6.

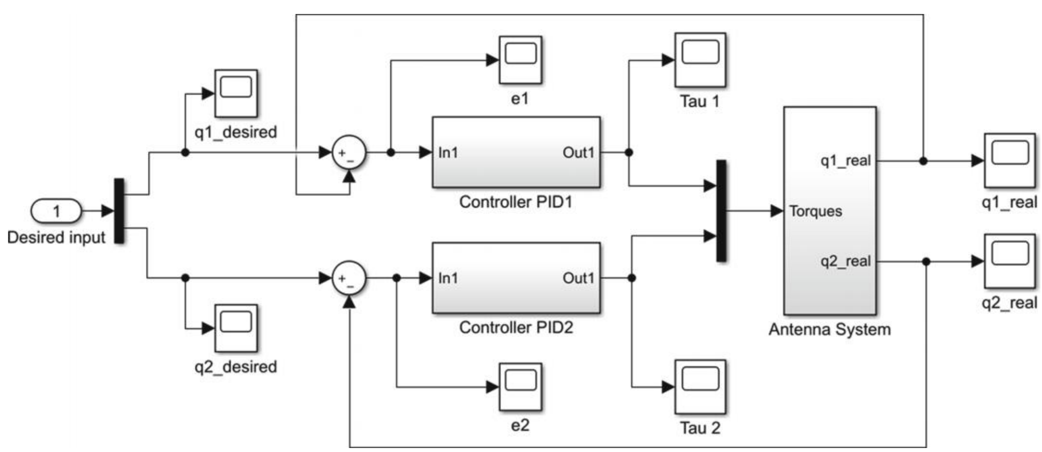

Fig. 3. The PID control diagram of the antenna system

Block "Antenna System" is established as in Fig. 4 with wind force vector $\mathbf{F}_{wind} = \left[F_{ox} \ F_{oy} \right]^T = \left[22174 \ 30670 \right]^T (N)$.

The dynamics and control problems are divided into 2 cases corresponding to 2 different working environmental conditions.

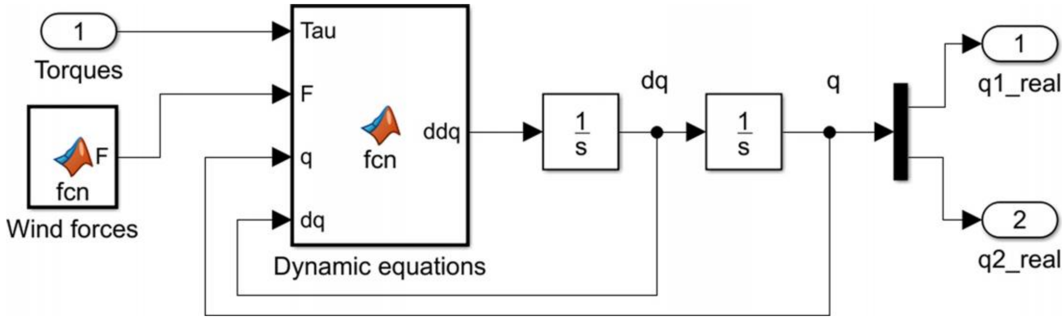

Fig. 4. The mathematical diagram in block "Antenna System"

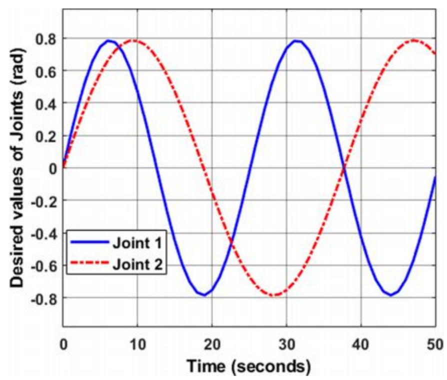

Fig. 5. The given joint variable paths

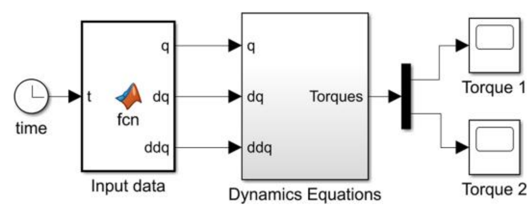

Fig. 6. The inverse dynamics solving diagram

Case 1: the antenna system works in the conditions of wind influence ($\mathbf{F}_{wind} = 0$)
Case 2: the antenna system works in the condition without the wind ($\mathbf{F}_{wind} \neq 0$)

The results of the inverse dynamics problem are shown in Fig. 7 and Fig. 8.

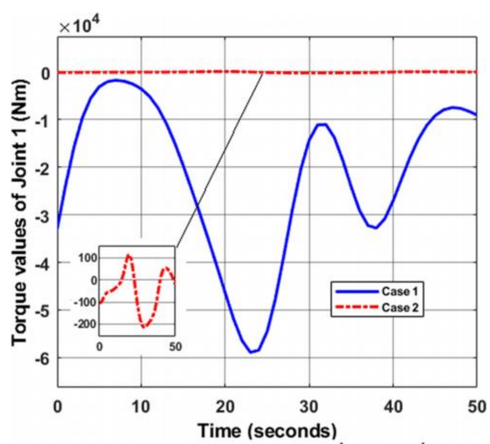

Fig. 7. The torque value of joint 1

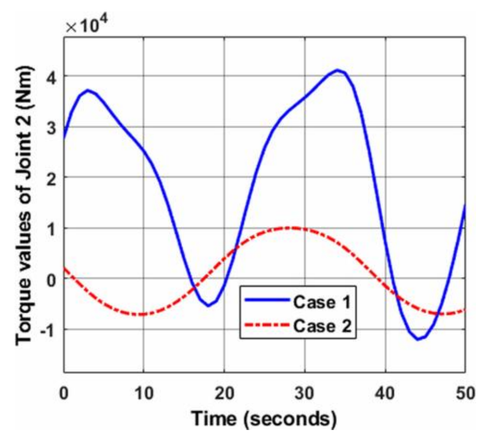

Fig. 8. The torque value of joint 2

Accordingly, the driving torque value in case 1 is higher than in case 2. The laws of torque values are also changed due to the influence of the wind with the largest value at joint 1 is $5.8 \times 10^4 (Nm)$ (Fig. 7), joint 2 is $4.2 \times 10^4 (Nm)$ (Fig. 8). Without the wind, the torque value in both joints is much lower.

The position and trajectory control parameters of the PID system in the two cases are shown in Table 1.

Table 1. PID parameters

PID control	Case 1	Case 2
Position control	$k_{p1} = 2.72 \times 10^5, k_{i1} = 2.64 \times 10^5,$ $k_{d1} = 0.62 \times 10^5, k_{p2} = 7.95 \times 10^5,$ $k_{i2} = 21.2 \times 10^5, k_{d2} = 0.58 \times 10^5$	$k_{p1} = 3.2 \times 10^4, k_{i1} = 1.3 \times 10^4,$ $k_{d1} = 1.9 \times 10^4, k_{p2} = 7.95 \times 10^5,$ $k_{i2} = 21.2 \times 10^5, k_{d2} = 0.58 \times 10^5$
Trajectory control	$k_{p1} = 2.95 \times 10^5, k_{i1} = 3.75 \times 10^5,$ $k_{d1} = 0.57 \times 10^5, k_{p2} = 2.02 \times 10^5,$ $k_{i2} = 4.8 \times 10^5, k_{d2} = 3.9 \times 10^5$	$k_{p1} = 2.72 \times 10^5, k_{i1} = 3.5 \times 10^5,$ $k_{d1} = 0.49 \times 10^5, k_{p2} = 5.6 \times 10^5,$ $k_{i2} = 12.8 \times 10^5, k_{d2} = 0.58 \times 10^5$

The results of the position control problem with input $q_1 = \frac{\pi}{5}(rad), q_2 = \frac{\pi}{7}(rad)$ are shown from Fig. 9, Fig. 10, Fig. 11 and Fig. 12.

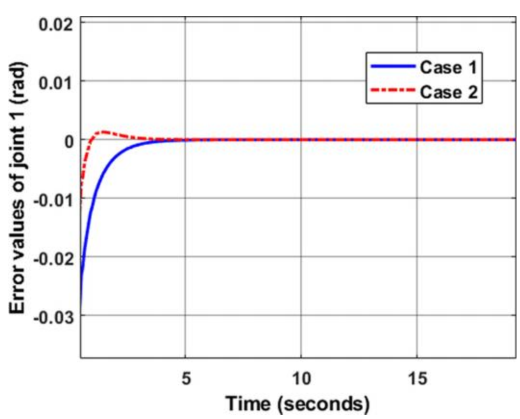

Fig. 9. The control error in joint 1

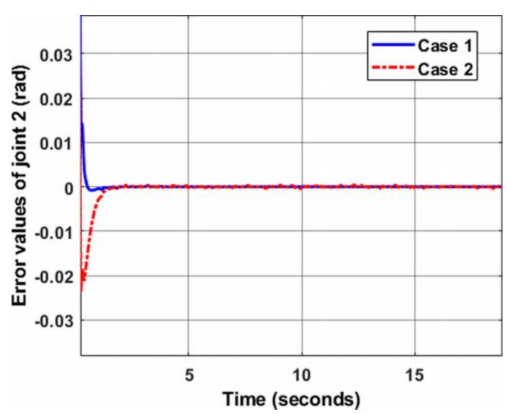

Fig. 10. The control error in joint 2

With joint 1 (Fig. 9), the control error value in case 1 at the initial time is larger and longer stable than in case 2. With joint 2 (Fig. 10), the control error value in case 1 is bigger and fast stable than in case 2.

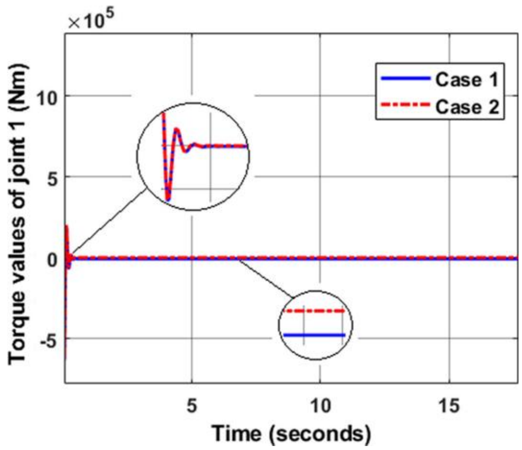

Fig. 11. The torque value of joint 1

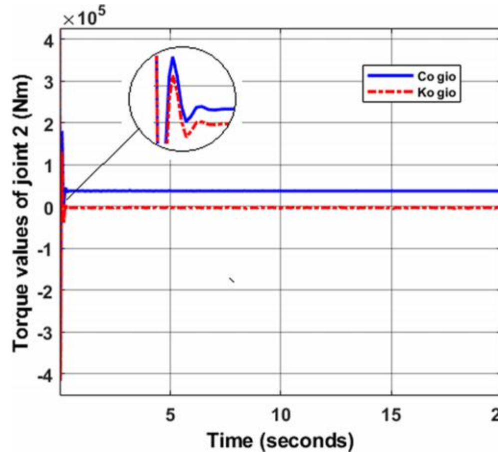

Fig. 12. The torque value of joint 2

Figure 11 and Fig. 12 show that the antenna is driven to the desired position with the driving torque value at the joints being stable. However, in case 1, the torque at the joints still needs to maintain a value to keep the system in the desired position due to the continuous influence of the wind. The driving torque in case 1 is greater than in case 2.

The joint trajectories $q_1 = \frac{\pi}{4}\sin(\frac{t}{4})(rad)$ and $q_2 = \frac{\pi}{4}\sin(\frac{t}{6})(rad)$ are input data to the trajectory control problem and the results are shown in Fig. 13, Fig. 14, Fig. 15 and Fig. 16.

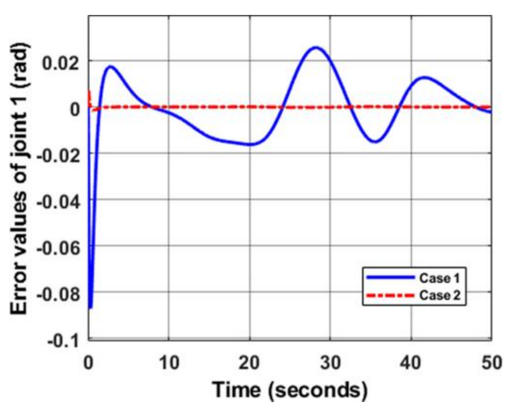

Fig. 13. The control error in joint 1

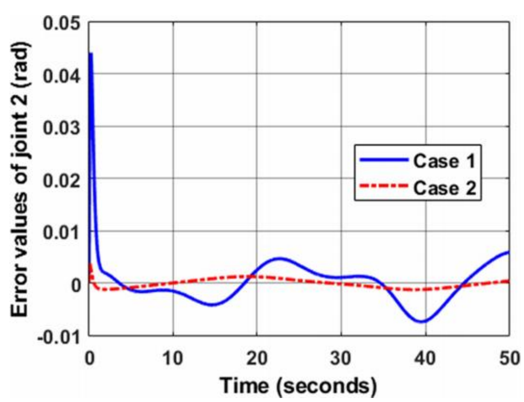

Fig. 14. The control error in joint 2

Figure 13 and Fig. 14 show that the value of control error in case 2 (without wind) is smaller than in case 1. The error value in case 2 has a clearer law than that in case 1. Similarly, the driving torque value at the corresponding joints in case 1 also varies with a large difference and is not as clear-cut as in case 2 (Fig. 15 and Fig. 16). The torque values at the joints are quite similar to the results in the inverse dynamics problem.

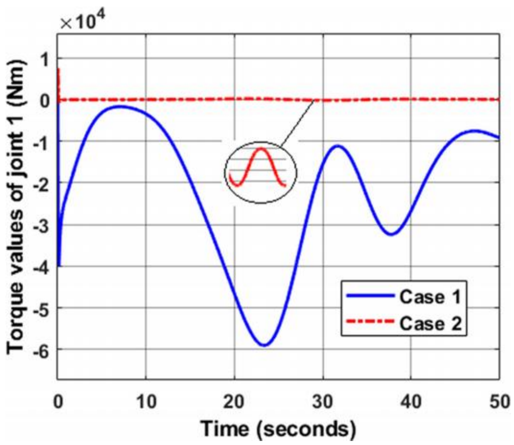

Fig. 15. The torque value of joint 1

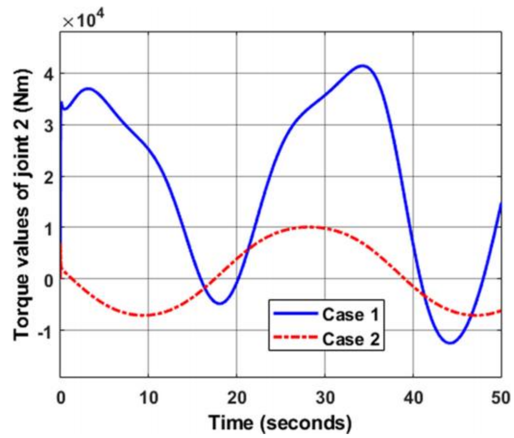

Fig. 16. The torque value of joint 2

3 Conclusion

In summary, this paper has presented some research results on the position and trajectory control of the satellite surveillance antenna with a traditional PID control system. The control system parameters are found through the efficient support of tools on MATLAB software. The control problem is built for antennas operating under two different environmental conditions. The numerical simulation results show that the control error of the antenna system under the influence of wind is higher than in the case without wind. The driving torque at the joints must also maintain a certain value to ensure compensation for deviations due to wind action. The results of this study have important value in calculating and selecting the transmission system with suitable joints, ensuring the antenna system can move in the right position and desired trajectory in case of continuous environmental impact. In fact, based on the research results on dynamics and control, the mechanical antenna system has been completely built and put into operation in reality (Fig. 17).

Fig. 17. A monitoring satellite antenna was fabricated and controlled

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