JEAS

JOURNAL OF ENGINEERING
AND
APPLIED SCIENCES

Journal of Engineering and Applied Sciences, Volume 19, Number 1, December 2021, 586 - 596

Performance Evaluation of a Flexible Joint Robotic Manipulator Model

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Abstract
The robotic manipulator acts like a human arm that can perform a repetitive task. The works aims to evaluate the performance of a flexible joint robotic manipulator model. To achieve this, an algorithm was developed using the dynamic model of the flexible joint robot and a simulation was carried out in MATLAB. The method applied for the performance evaluation of the flexible joint robot model involved the step function and bode plotting techniques which evaluated the plant model in time and frequency domains respectively for performance and stability of the system. The step function determines the damping time of the system while the bode plot determines the stability margins of the system. In this work, the flexible joint robotic manipulator model was analyzed for performance and stability in MATLAB. From the results, the flexible joint robot model recorded damping time of infinity and too many oscillations in time domain which shows that the existing system performance was poor. The flexible joint recorded gain margin of 22.8dB and phase margin is 3.21e-12 deg. These results indicate that the system was not stable. As a result, the flexible joint will keep on vibrating until it heats up and break down. This work therefore recommends a robust compensator to be developed for the flexible joint robot to improve its performance and stability.

Keywords: Flexible Joint Robot, Robotic Manipulator, Stability, Gain Margin, Phase Margin

1. Introduction

Robotic manipulators have been widely used in space for docking, assembling, repairing and other on-orbit servicing operations (Dong and Zhu, 2013). They have been very useful and can be applied in various fields (Cai et al, 2021) even in areas where human find difficult or dangerous to work in. Today, the quality and quantity of industrial products and manufacturing processes (Jia, 2019) depends on the performance of the automatic machines in the form of robots available. To manufacture high quality products, high accuracy robot manipulators are needed. This means that the performance of the robot is an important factor that really determines the level of the industrial output quantity and quality. Joint flexibility is an important factor that must be considered in the robot control design if high performance is expected for the robot manipulators (Liu et al., 2011). This is because the flexible joint robot always has small damping and low natural frequencies that can lead to residual vibration (Dubay et al, 2014; Shao et al, 2020).

Flexible joint robots are recently being applied more in the industries due to their numerous advantages over the rigid robots. They are applied in most fields where performance and high accuracy is needed such as the space robot (Ulrich and Sasiadek, 2015), humanoid (Jiang et al, 2017), rescue robot (Pillai and Suthakorn, 2019), collaborative industrial robots (Madsen et al, 2020) and medical cooperative robots (Li et al, 2020). However, compared with rigid robots, number of degrees of freedom becomes twice as number of control actions due to flexibility in the joints, and the matching property between nonlinearities and inputs is lost (Brogliato et al, 1995). The flexible-joint robot manipulator particularly presents serious problems such as nonlinearity, largeness of model, coupling, uncertainty, joint flexibility in the modeling and control (Fateh, 2012) and joint vibration (Sayahkarajy et al, 2016). Most flexible joint robots are equipped with planetary gears which exhibit joint vibration effects (Kahraman and Vijayakar, 2001). The joint vibration problem is primarily caused by the use of harmonic drives, i.e. a type of gear mechanism that is increasingly popular for use in space robotic applications, due to its low backlash, low weight, compactness, high torque capability, wide operating temperature range and good repeatability. However, the flexible joint in the robot is one of the major problems of the robots because it is difficult to control (Khan et al, 2017; Alam et al, 2017; Xiong et al, 2020). To address this issue, a great deal of research interest has been attracted especially in the areas of investigation and control of the tracking performance (Dachang et al, 2020; Wang et al, 2017, Zhang et al, 2021; Iskanderani and Mehedi, 2021) and stability of the robotic manipulators.

The tracking performance and stability investigations involve the examination of the system behavior in time and frequency domains. In time domain the system overshoot and damping or settling time are required to be studied to ascertain the performance of the system. The overshoot is the amount in percentage the system response goes beyond its set amplitude and settling time is the time it takes the system to return to its set-point or equilibrium after encountering a disturbance. Damping time or settling time can also be referred to the time required for the system output to settle within a certain percentage of the input signal amplitude (Agbaraji, 2015). In frequency domain the gain and phase margins are studied to ascertain the stability margins of the system.Gain and phase margins are common terms to describe how stable a system is and the behavior of the system at high frequencies. They are used because they are simple and ideal measurements of stability. Gain Margin (GM) is the reciprocal of the magnitude when the phase of the open-loop transfer function crosses -180. GM > 5dB is accepted for slight or marginal stability but for high robustness stability GM must be greater than or equal to 20dB. Phase Margin (PM) is the difference between the phase angle minus 180 when the magnitude of the open-loop transfer function crosses 0dB. For robust stability PM must be greater than or equal to 40degrees (Agbaraji, 2015; Agbaraji, 2020).

In most research works such as (Iskanderani and Mehedi, 2021; Li et al, 2020; Madsen et al, 2020; Jia, 2019) the system tracking performance investigations were carried out based on time domain without considering the frequency domain characteristics. This measure will affect the system performance in the presence of disturbances which may result to system poor performance or sudden break down. However, in this work, the flexible joint system tracking performance and stability investigations were carried out based on time and frequency domains in order to fully ascertain the system behavior for optimal performance.

2.0 Methodology

Considering the robotic manipulator in figure 1 with elastic gearboxes, i.e., elastic or flexible joints; this robot can be modeled by the flexible joint model. The rigid bodies are connected by torsional spring-damper pairs. The dynamic model of a constrained flexible joint robot is presented as (Spong, 1989):

$$M(q_l)\ddot{q}_l + C(q_l,\dot{q}_l)\dot{q}_l + G(q_l) = K_s\theta + f \tag{1}$$

$$J_m\ddot{q}_l + K_s\theta = \tau_m \tag{2}$$

$$\theta \triangleq q_m - q_l \tag{3}$$

Where $q_l \in R^n$ and $q_m \in R^n$ are the positions of the robot links and the motor shafts, respectively, $M(q_l) \in R^{nxn}$ is the inertia matrix of rigid links, $C(q_l,\dot{q}_l)$ is the Coriolis and centrifugal force matrix, $G(q_l)$ is the gravitational force, $J_m = diag[J_{mi}] \in R^{nxn}$ is the positive definite diagonal matrix of the moments of inertia of the motor, $K_s = diag[K_{si}] \in R^{nxn}$ is the positive definite diagonal matrix of the joint stiffness, $f \in R^n$ is the joint torque contributed by the constraint force and $\tau_m \in R^n$ is the input torque of the motors, J_{mi} and K_{si} (i=1,2,…,n) and the inertia and the stiffness of ith joint, n is the degree of freedom of the robotic manipulator.

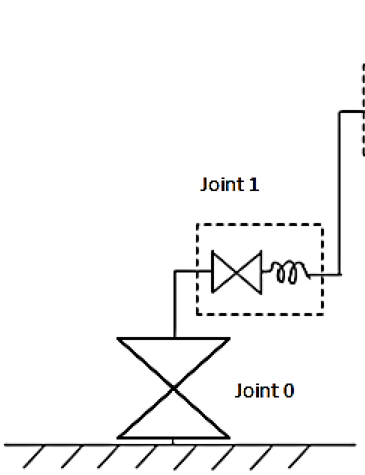

Figure 1: Single line diagram of the flexible joint robotic arm

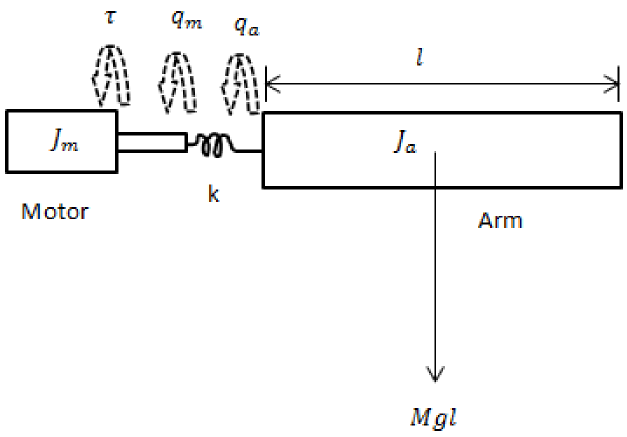

Figure 2: Flexible joint model of the manipulator

The robotic arm rotating on a horizontal plane and actuated with a motor through elastic or flexible joint coupling was considered as illustrated in figure 2.

Let q_a be the link angular displacement and q_m be the motor angular position. A typical flexible joint robotic arm dynamic model can be described by the dynamic equations:

$$J_a\ddot{q}_a + Mglsin(q_a) + k(q_a - q_m) = 0 \tag{4}$$

$$J_m\ddot{q}_m + k(q_a - q_m) = \tau \tag{5}$$

The transfer function, in s-domain, of the flexible joint robotic manipulator is given by as follows:

$$G(s) = \frac{k}{J_aJ_m s^4+(J_a k+MglJ_m +kJ_m)s^2+Mglk} \tag{6}$$

The values and symbols of flexible joint parameters are summarized in Table1.

Table 1: Parameter values of the flexible joint robot (Adel and Jason, 2009)

Symbol	Description	Value
J_a	Inertia of flexible joint robotic manipulator	0.03kgm^2
J_m	Inertia of the flexible joint actuator	0.004kgm^2
g	Gravitational acceleration	9.81N/m
l	Distance to center of gravity of the manipulator rotational link	0.135m
M	Mass of the link	0.6kg
k	Flexibility coefficient of the joint	31.0Nm/rad

Substituting the values of the manipulator parameter values in table 1 into equation 6, gives:

$$G(s) = \frac{258333}{s^4 + 8810\,s^2 + 206667} \tag{7}$$

Step function and Bode plotting function methods were applied in this work for the investigation of the performance and stability of the FJR system. The two methods were applied in MATLAB using the syntax step and bode respectively. Step function method evaluates the flexible joint robotic manipulator plant in time domain while bode plotting function evaluates the system in frequency domain.

These techniques were applied to examine and reveal some hidden characteristics of the system which may affect its performance during physical implementation. The step function deduces the following characteristics of the system: overshoot, settling time and the steady state error. While bode plotting function deduces the stability margins of the system: gain and phase margins. To apply these system performance and stability techniques, a flowchart was developed as shown in figure 3.

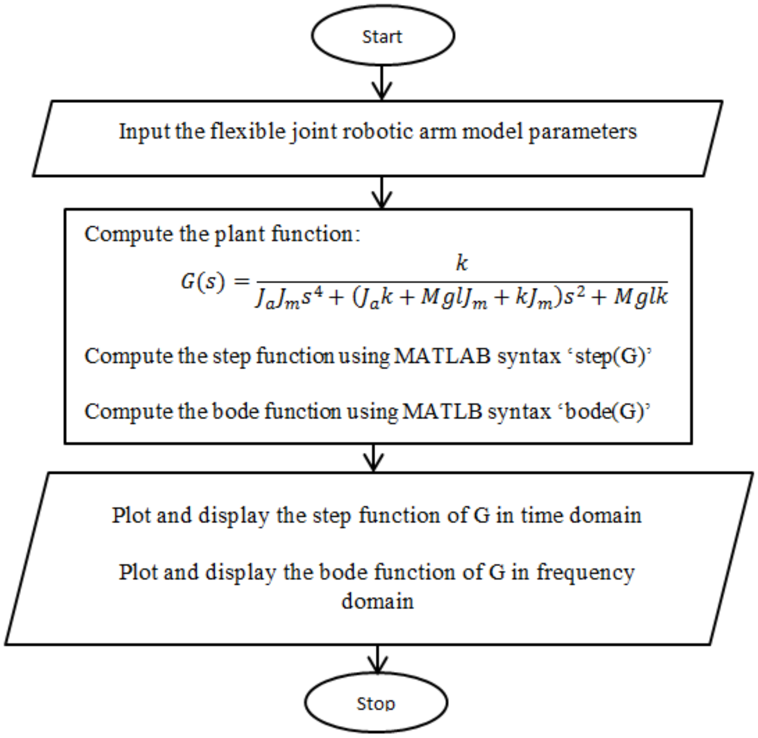

Figure 3: The flowchart of the system tracking performance investigation

The program codes were generated from the algorithm and were applied and executed in MATLAB to produce the results using MATLAB m-file. The source codes are as follows:

```
%Performance analysis using step function technique
%Define the s domain
s=tf('s');
%Input the flexible joint manipulator parameter values
Ja=0.03;
Jm=0.004;
g=9.81;
l=0.135;
M=0.6;
k=55;
%Compute the transfer function model of the system
G=k/(Ja*Jm*s^4+((Ja*k)+(M*g*l*Jm)+(k*Jm))*s^2+M*g*l*k)
%Apply the step function
bode(G)
```

```
%Stability analysis using bode plotting technique
%Define the s domain
s=tf('s');
%Input the flexible joint manipulator parameter values
Ja=0.03;
Jm=0.004;
g=9.81;
l=0.135;
M=0.6;
k=55;
%Compute the transfer function model of the system
G=k/(Ja*Jm*s^4+((Ja*k)+(M*g*l*Jm)+(k*Jm))*s^2+M*g*l*k)
%Apply the bode plotting function
bode(G)
```

3.0. Results and Discussions

The result in figure 4 shows that the damping time is at infinity. This means that the system did not settle or was not damped properly and it is continuously vibrating. As a result, the flexible joint will keep on vibrating until it heats up and break down. The results in figure 5 show that the gain margin is 22.8dB and phase margin is 3.21e-12 deg. The phase margin is very much less than 1deg, which means that the system is unstable. The results indicate that the system requires robust compensation that can help to improve the system stability considering the system uncertainties.

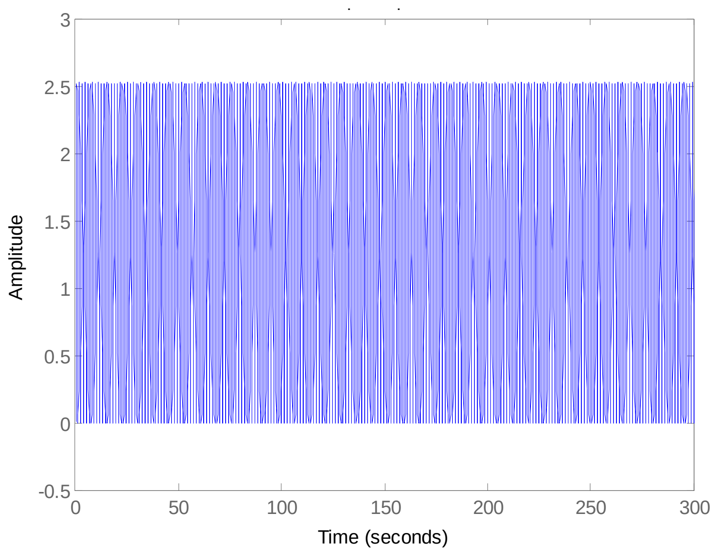

Figure 4: Damping time for the existing flexible joint

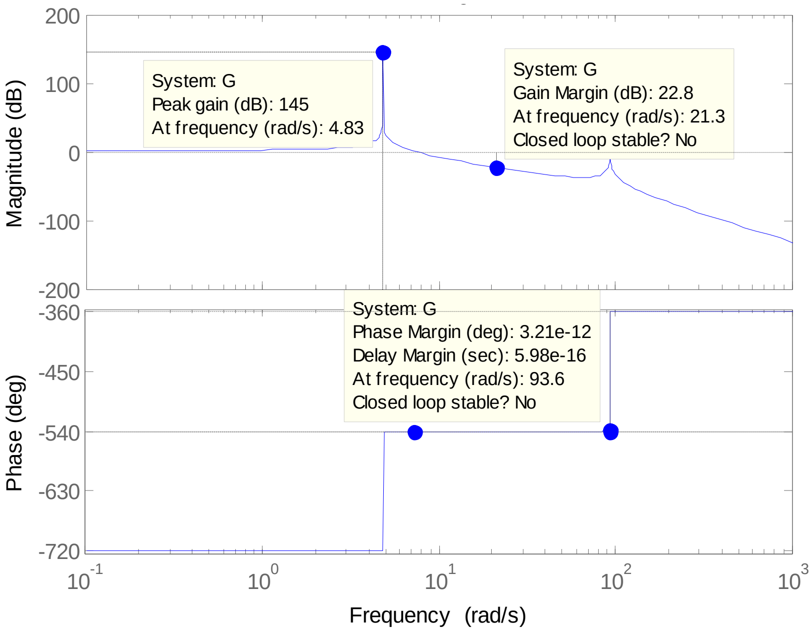

Figure 5: The stability margin graphs for the existing flexible joint

Table 2: Summary of the results

K	Settling Time	Overshoot	GM	PM
33	Infinity	Infinity	22.8	3.21e-12
25	Infinity	Infinity	21.8	-7.51e-12
20	Infinity	Infinity	20.7	2.06e-12
10	Infinity	Infinity	17.2	-7.12e-13

The results in table 2 show that the system maintained very high settling time and overshoot of infinity which indicates significant joint vibration. Secondly, the values of the PM were very low which indicates poor stability of the joint. These show that the existing flexible joint system recorded very poor performance and it is mostly unstable. Thus, it will require an external controller to improve its performance and stability.

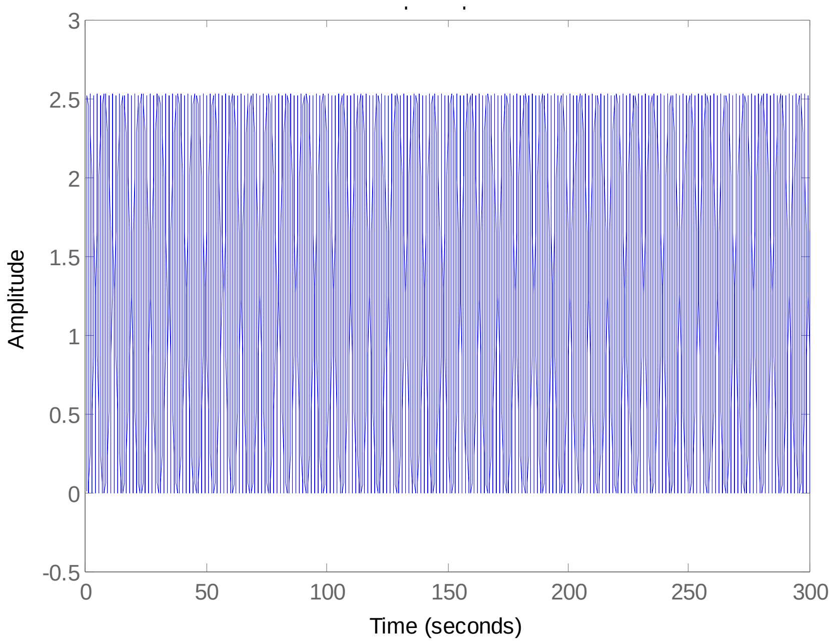

Figure 6: Damping time for the flexible joint when k=25

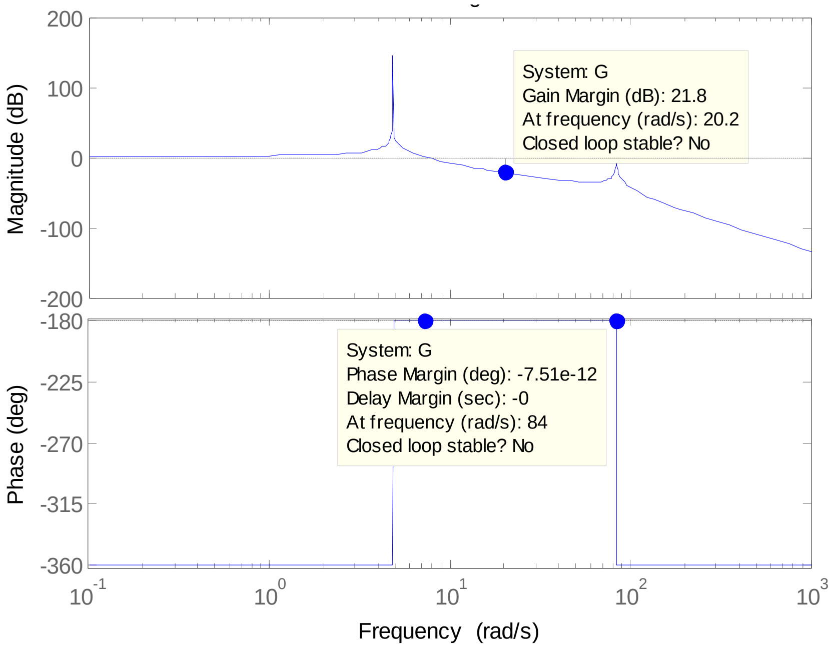

Figure 7: Stability graph for the flexible joint when k=25

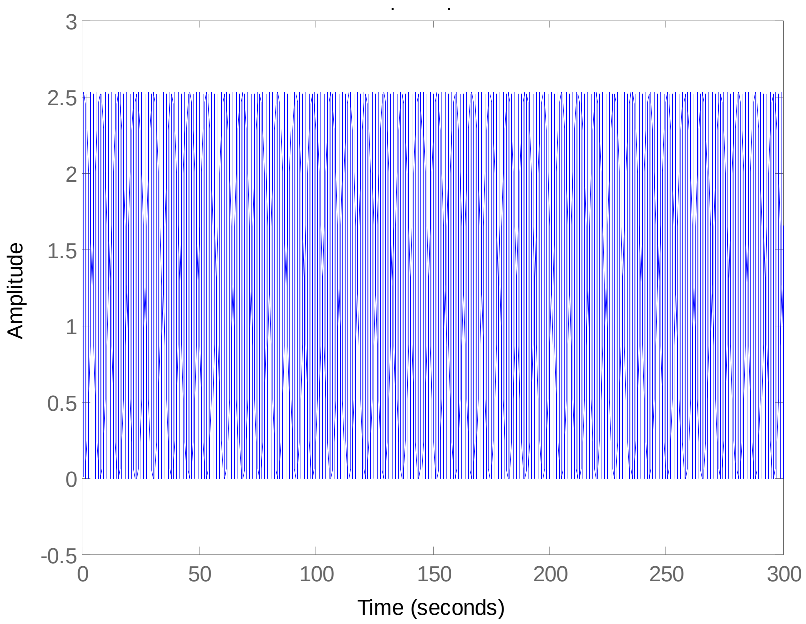

Figure 8: Step response graph for the flexible joint when k=20

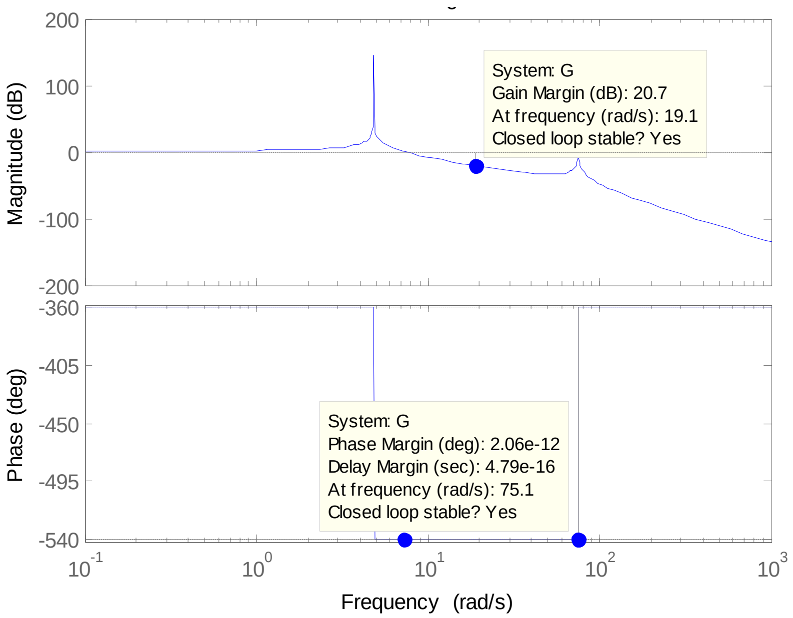

Figure 9: Stability graph for the flexible joint when k=20

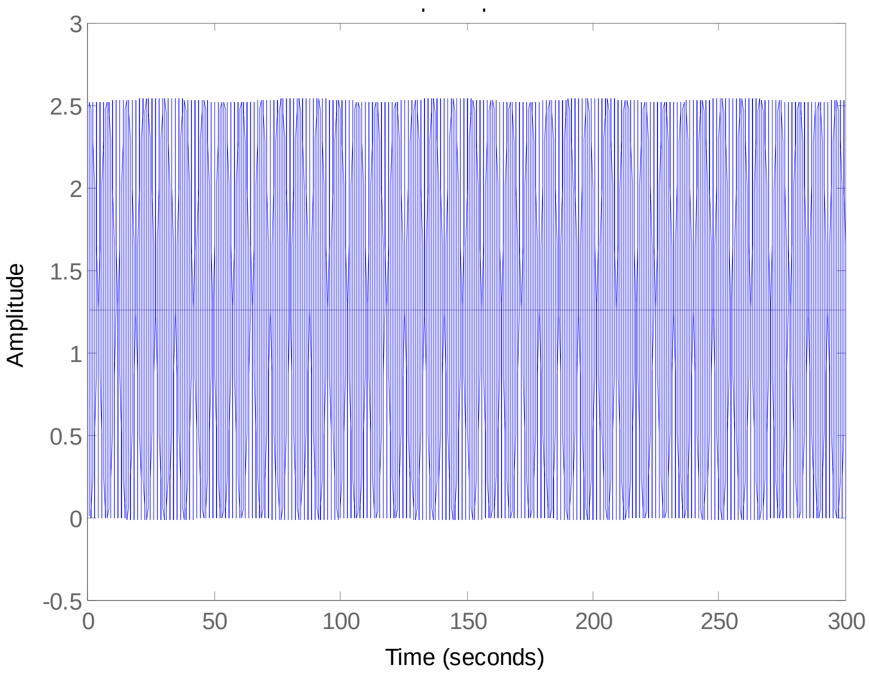

Figure 10: Step response graph for the flexible joint when k=10

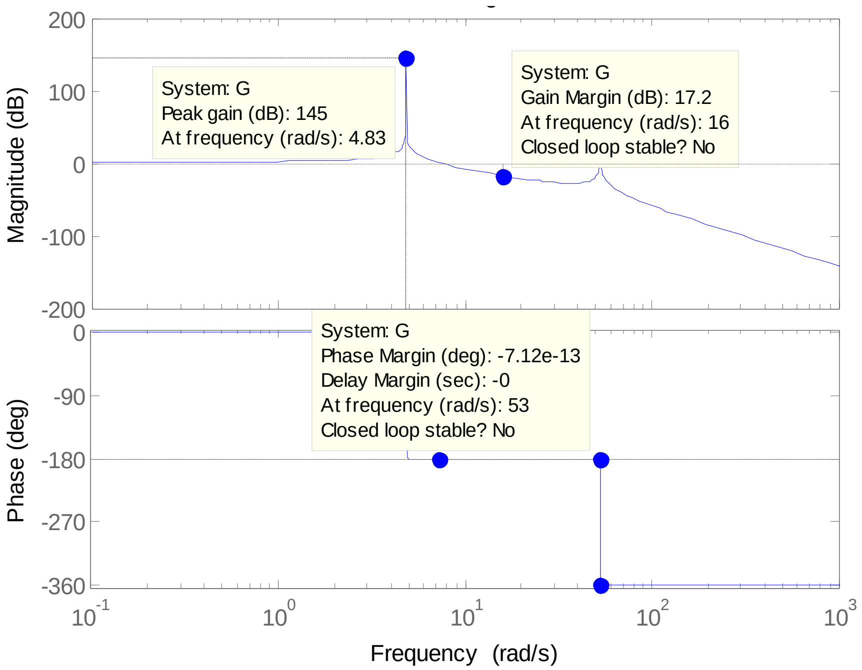

Figure 11: Stability graph for the flexible joint when k=10

4.0. Conclusion

The flexible joint robot model performance and stability were analyzed based on the damping time and the stability margins of the system. Damping time of the joint determines the time it takes the system to go back to its equilibrium or normal condition after experiencing a sudden disturbance. Stability of the joint determines its ability to maintain optimal performance and withstand the effects of disturbances. The step function method was used to analyze the damping time of the flexible joint robotic manipulator for its performance and bode plot technique was applied for the flexible joint stability analysis. From the results, the flexible joint robot model recorded damping time of infinity and too many oscillations in time domain analysis which shows that the system performance is poor without an external controller. The flexible joint robotic manipulator model recorded gain margin of 22.8dB and phase margin is 3.21e-12 deg. These results indicate that the system is not stable without an external controller. This means that the system cannot withstand disturbances during its normal function and cannot perform optimally in the presence of disturbance. As a result, the flexible joint will keep on vibrating until it heats up and break down. This is because the continuous vibration will consume more power and cause wear or total failure of the joint motor.

5.0 Recommendation

This work recommends that a robust compensator should be developed for the flexible joint robot to improve its performance and stability.

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