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Modelling, Simulation and Vibration Analysis of Transmission Line Inspection Robot Based on Mass Spring Damper Concept

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Abstract—**This paper investigates the modeling, simulation and vibration analysis of power transmission line robot modeled based on mass spring damper concept. The robot was design to move along the transmission line with the help of two rollers. The transmission line was assumed to oscillate as the robot moves, thereby generating a disturbance to the robot. A pulse input signal was used as the disturbance to assess the behavior of the robot. Comparative assessments have shown that the vertical position and angular orientation of the robot are dependent on the magnitude of the input disturbance and the weight of the robot.**

Keywords-modeling; simulation; transmission line; inspection robot; mass spring damper

I. INTRODUCTION

Safe and reliable transmission of extra-high voltage (EHV) power for residential and industrial uses is the critical factor of each country's development. Thus, any failure during the transmission could significantly affect the livelihood of the people, national security, health sector, transportation network to mention a few. Traditionally, workers inspect the lines manually by climbing the transmission line or using a telescope to inspect the transmission lines from the ground. These methods have numerous disadvantages which are not limited to long inspection time, high cost, unguaranteed safety of the human operator and power outage [1-2].

To overcome such shortcomings, inspection robots have been introduced by many researchers. Those robots are expected to replace the human operator in order to improve the efficiency of power transmission and minimized inspection cost and time. Inspections of transmission lines employ remotely or autonomously controlled machines that can monitor the condition of the lines and their components using sensing and imaging technologies. Moreover, these technologies should be able to detect and recognize any obstacle such as suspension clamps, spacers, aircraft warning balls etc along the transmission line [3].

Interestingly, for the last three decades, there have been tremendous advances in the field of robotics, many of which focuses on transmission line inspection robots. The Tokyo power company has been designing a prototype called the Expliner [4-5]. The robot can inspect two transmission lines simultaneously. Another robot named Linescout has been developed by Canada hydro-Quebec's research institute [6-7]. However both these robots were big and heavy which made them not only consumes a lot of energy but also difficult to be carried on/off the transmission lines. To provide an alternative to onboard battery power supply, a power supply unit to utilize the generated electromagnetic field by high voltage transmission line is presented [8]. In addition, a three arms transmission line inspection robot has been developed by Shandong institute of science and technology [9-10]. A video submission which describes the recent achievements of American electric power institute has been presented [11]. The design of obstacle avoidance mechanism and other studies were presented in [12]. The concept of mass spring damper system for numerous mechanical structures has been presented in [13]

In this paper, design and modeling of transmission line inspection robot modeled as mass spring damper system is presented. The dynamic model of the system was derived using Newton's second law of motion. The dynamic equations were simulated in the MATLAB software environment. The behavior of the robot subjected to a pulse input disturbance was investigated. These time domain vibration analyses will provide useful information for the selection of appropriate control strategy for an efficient control of the transmission line robot. the proposed robot has three main functions; the fly mode which enables the robot to carry itself from the ground to the line using the flying propellers, the climb mode which allows the robot to climb the line using two grippers and finally, the slide mode which navigates the robot along the transmission line to conduct the desired inspection.

The paper is organized as follows. In section II, the description of the proposed transmission line inspection robot is presented. In section III, the mathematical modeling of the robot using Newton's law of motion is presented. In section IV implementation and discussions of the simulations results is presented. Finally, section V presents the conclusion.

II. THE TRANSMISSION LINE INSPECTION ROBOT

The proposed power transmission line inspection robot is shown in Figure II. The robot consists of two motors for grasping the transmission line, two motors (grippers) for the motion along the transmission line, and four motors for rotation maneuvering in case of obstacle avoidance. The robot has three fundamental functions which are the fly, climb and slide abilities. The flight robot is detachable from the main robot. At present, most of the available inspection robots have to be carried to transmission line manually.

The proposed robot can carry itself to the desired inspection point and back to the ground station with the help of the flight robot. As the case maybe, both the two robots are equipped with inspection capability. Thus, they can inspect the two different points simultaneously. In addition, with the flight robot detached, the sliding robot can conduct inspection faster and over a long period of time since the power consumption is drastically reduced. The stability analysis of the proposed robot has been presented in [14]. Figure I shows the flow chart of the complete robot.

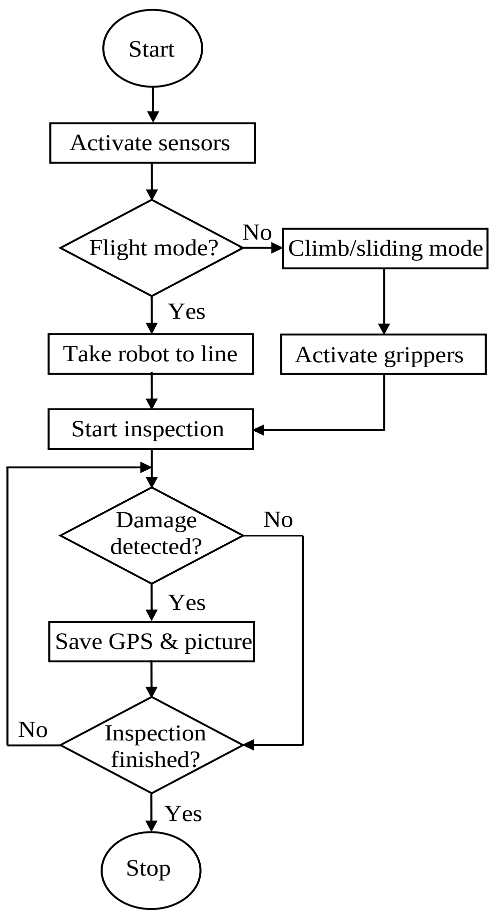

FIGURE I.OPERATIONAL FLOW CHART OF THE ROBOT

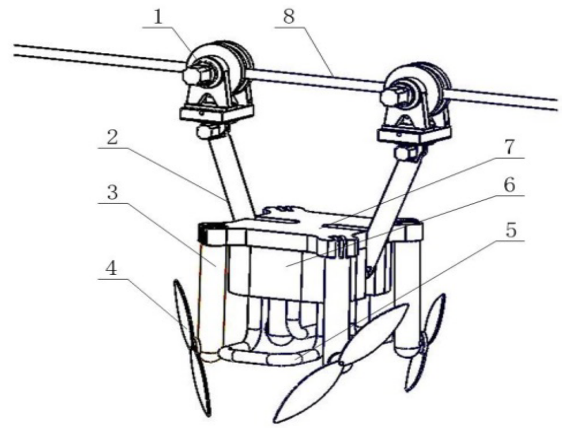

FIGURE II. STRUCTURE OF THE PROPOSED ROBOT

(1) function gripper, (2) bionic arm, (3) rotor arm, (4) rotor propeller (5) – (7) auto gyro landing gear (8) high-voltage transmission line

III. THE DYNAMIC EQUATIONS OF THE ROBOT

The dynamic equations of the proposed robot are presented in this section. As shown in the simplified schematics of Figure III, the robot when moving along the transmission line could be assumed to behave as a mass spring damper system. The vibration induced by the robot on the transmission line is considered to be the input to the system (i.e r_1 & r_2). Thus, the parameters and their respective values used for the simulations are tabulated in Table I. The forces acting at each mass due to the damping coefficients and spring constants are illustrated in Figure IV.

TABLE I. PROPOSED ROBOT PARAMETERS

Parameter	***Value (unit)***
Gripper 1 and 2 disturbances (r_1) & (r_2)	-
Mass of wrist 1 (m_1)	2Kg
Mass of wrist 2 (m_2)	2Kg
Mass of arm 1 (m_3)	3Kg
Mass of onboard electronics (m_4)	2Kg
Mass of arm 2 (m_5)	3Kg
Spring constant between gripper 1 and m_1 (k_1)	2000N/m
Damping coefficient between gripper 1 and m_1 (c_1)	10Ns/m
Spring constant between gripper 2 and m_2 (k_2)	2000N/m
Damping coefficient between gripper 2 and m_2 (c_2)	10Ns/m
Spring constant between m_1 and m_3 (k_3)	800N/m
Damping coefficient between m_1 and m_3 (c_3)	20Ns/m
Spring constant between m_2 and m_5 (k_4)	800N/m
Damping coefficient between m_2 and m_5 (c_4)	20Ns/m
Length of robot base ($\lambda_1 + \lambda_2$) for $\lambda_1 = \lambda_2$	0.25m
Total base load ($M=m_3+m_4+m_5$)	8Kg

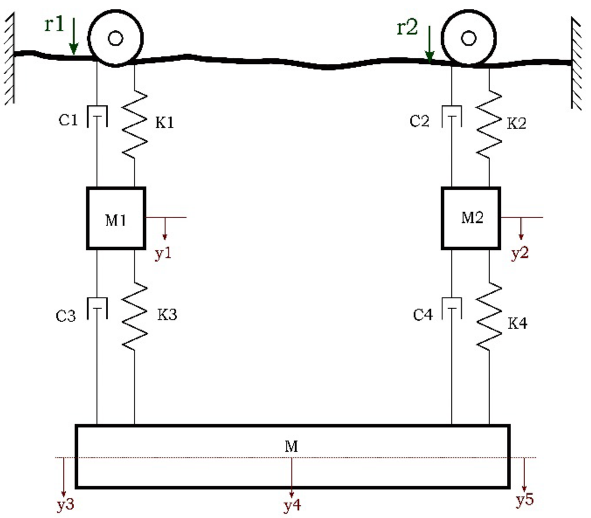

FIGURE III. SCHEMATICS DIAGRAM OF THE ROBOT

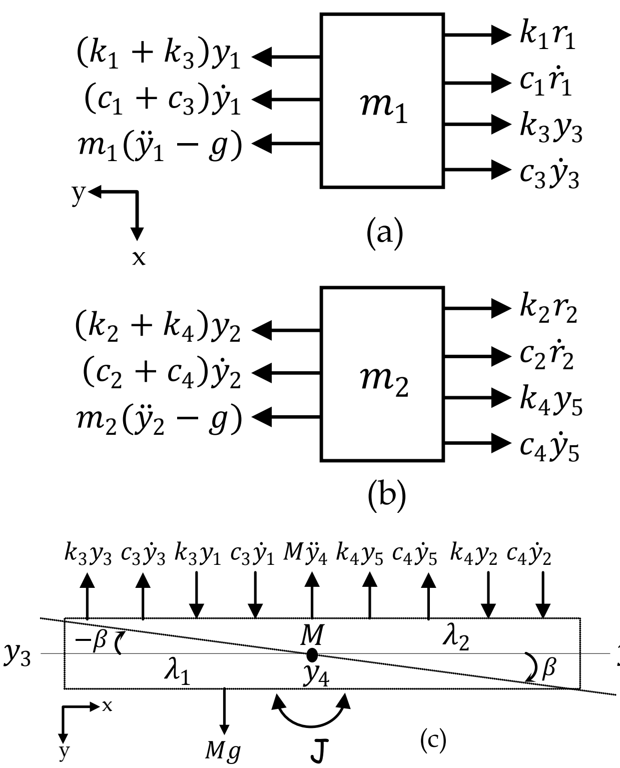

FIGURE IV. FREE-BODY DIAGRAM OF THE ROBOT

From the above diagrams of Figure III and Figure IV (a)-(c), it can be seen that y_3, y_4 and y_5 are at the same initial level and y_4 is at the centre of mass of the base of the robot. Thus, $\lambda_1 = \lambda_2$. Similarly, the robot is assumed to start from equilibrium i.e the effect of gravity is cancelled out by the tension in the transmission cable. In addition, the base of the robot has a moment of inertia, J about the centre of mass to be

$$J = \frac{M(\lambda_1 + \lambda_2)^2}{12} \quad (1)$$

Thus, the dynamic equations can be derived using the free body diagrams as

$$\begin{aligned} m_1\ddot{y}_1 &= -(k_1+k_3)y_1 - (k_1+k_3)\dot{y}_1 + k_1r_1 + c_1\dot{r}_1 \\ &+ k_3y_3 + c_3\dot{y}_3 \end{aligned} \quad (2)$$

$$\begin{aligned} m_2\ddot{y}_2 &= -(k_2+k_4)y_2 - (k_2+k_4)\dot{y}_2 + k_2r_2 + c_2\dot{r}_2 \\ &+ k_4y_5 + c_4\dot{y}_5 \end{aligned} \quad (3)$$

$$\begin{aligned} M\ddot{y}_4 &= k_3y_1 + c_3\dot{y}_1 + k_4y_2 + c_4\dot{y}_2 - k_3y_3 + c_3\dot{y}_3 \\ &- k_4y_5 - c_4\dot{y}_5 \end{aligned} \quad (4)$$

$$\begin{aligned} J\ddot{\beta} &= \lambda_1(k_3y_3 + c_3\dot{y}_3 - k_3y_1 - c_3\dot{y}_1) \\ &- \lambda_2(k_4y_5 + c_4\dot{y}_5 - k_4y_2 - c_4\dot{y}_2) \end{aligned} \quad (5)$$

Where y_1, y_2 and y_4 are the displacements of m_1, m_2 and M respectively, in y-direction. It can be noted that, the y_3 and y_5 displacements of M will change due to angular displacement of β. Thus

$$y_3 = y_3 - \lambda_1 \sin\beta \;\; ; \;\; y_5 = y_5 + \lambda_2 \sin\beta \quad (6)$$

Similarly, for a very small value of β and assuming state variable z,

$$\sin\beta \approx \beta \;\; ; \;\; z = \begin{pmatrix} y_1 & \dot{y}_1 & y_2 & \dot{y}_2 & y_4 & \dot{y}_4 & \beta & \dot{\beta} \end{pmatrix} \quad (7)$$

Therefore the dynamic model of (2) to (5) can be re-written as

$$\begin{aligned} m_1\dot{z}_2 &= -(k_1+k_3)z_1 - (k_1+k_3)z_2 + k_1r_1 + c_1\dot{r}_1 \\ &+ k_3z_5 + c_3z_6 - \lambda_1k_3z_7 - \lambda_1c_3z_8 \end{aligned} \quad (8)$$

$$\begin{aligned} m_2\dot{z}_4 &= -(k_2+k_4)z_3 - (k_2+k_4)z_4 + k_2r_2 + c_2\dot{r}_2 \\ &+ k_4z_5 + c_4z_6 + \lambda_2k_4z_7 + \lambda_2c_4z_8 \end{aligned} \quad (9)$$

$$\begin{aligned} M\dot{z}_6 &= -(k_3+k_4)z_5 - (k_3+k_4)z_6 + k_3z_1 + c_3z_2 \\ &+ k_4z_3 + c_4z_4 + (\lambda_1k_3 - \lambda_2k_4)z_7 + (\lambda_1c_3 - \lambda_2c_4)z_8 \end{aligned} \quad (10)$$

$$
\begin{aligned}
J\dot{z}_7 = &-(\lambda_1^2 k_3 + \lambda_2^2 k_4) z_7 - (\lambda_1^2 c_3 + \lambda_2^2 c_4) z_8 \\
&+ (\lambda_1 k_3 - \lambda_2 k_4) z_5 + (\lambda_1 c_3 - \lambda_2 c_4) z_8 \\
&- \lambda_1 (k_3 z_1 - c_3 z_2) + \lambda_2 (k_4 z_3 - c_4 z_2)
\end{aligned}
\tag{11}
$$

And the state space representation of (8) to (11) can be expressed as

$$
\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \\ \dot{z}_4 \\ \dot{z}_5 \\ \dot{z}_6 \\ \dot{z}_7 \\ \dot{z}_8 \end{bmatrix}
=
\begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-\frac{(k_1+k_3)}{m_1} & -\frac{(c_1+c_3)}{m_1} & 0 & 0 & \frac{k_3}{m_1} & \frac{c_3}{m_1} & -\frac{\lambda_1 k_3}{m_1} & -\frac{\lambda_1 c_3}{m_1} \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & -\frac{(k_2+k_4)}{m_2} & -\frac{(c_2+c_4)}{m_2} & \frac{k_4}{m_2} & \frac{c_4}{m_2} & \frac{\lambda_2 k_4}{m_2} & \frac{\lambda_2 c_4}{m_2} \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
\frac{k_3}{M} & \frac{c_3}{M} & \frac{k_4}{M} & \frac{c_4}{M} & -\frac{(k_3+k_4)}{M} & -\frac{(c_3+c_4)}{M} & \frac{\lambda_1 k_3 - \lambda_2 k_4}{M} & \frac{\lambda_1 c_3 - \lambda_2 c_4}{M} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
\frac{-\lambda_1 k_3}{J} & \frac{-\lambda_1 c_3}{J} & \frac{\lambda_2 k_4}{J} & \frac{\lambda_2 c_4}{J} & \frac{\lambda_1 k_3 - \lambda_2 k_4}{J} & \frac{\lambda_1 c_3 - \lambda_2 c_4}{J} & \frac{-\lambda_1^2 k_3 + \lambda_2^2 k_4}{J} & \frac{-\lambda_1^2 c_3 + \lambda_2^2 c_4}{J}
\end{bmatrix}
\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \\ z_6 \\ z_7 \\ z_8 \end{bmatrix}
+
\begin{bmatrix}
0 & 0 & 0 & 0 \\
\frac{k_1}{m_1} & \frac{c_1}{m_1} & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & \frac{k_2}{m_2} & \frac{c_2}{m_2} \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix} r_1 \\ \dot{r}_1 \\ r_2 \\ \dot{r}_2 \end{bmatrix}
\tag{12}
$$

IV. Implementation and Results

In this section, MATLAB simulation results from the derived equations of motion of the system of (11) are presented. The system is subjected to disturbance inputs from the oscillatory transmission line. A pulse input signal of amplitude 0.1 as shown in Figure V was assumed to be the input. The input will cause the system to move from zero position to 0.1 and then back to zero thereby causing vibration to the robot

Figure VI shows the displacement responses of m_1, m_2 and M respectively for the tabulated values of Table I. In addition, the responses of the system are shown in Figure VII when the mass of the onboard components, M was increased from 8Kg to 10Kg. It can be observed that the displacements and velocities of the masses increase with increase of mass, M shown in Table II.

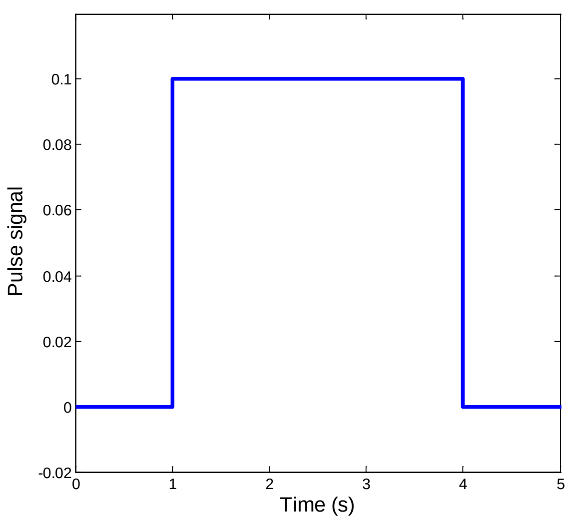

FIGURE V. REFERENCE INPUT DISTURBANCE

Similarly, the angular displacement and velocity for the system is shown in Figure VIII and Figure IX respectively for 8kg and 10Kg masses of M.

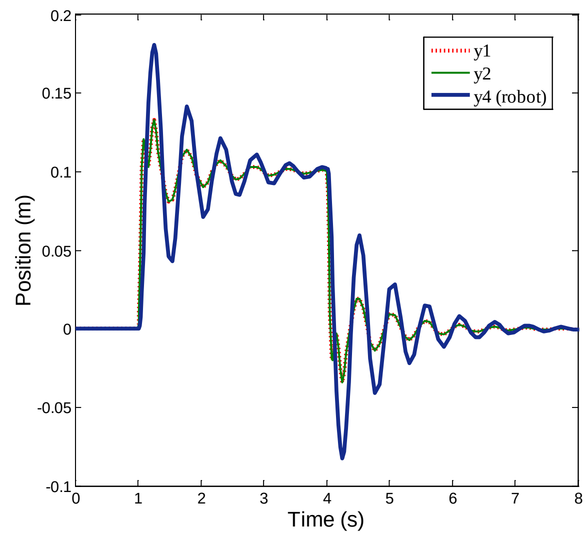

FIGURE VI. LINEAR DISPLACEMENTS FOR M=8Kg.

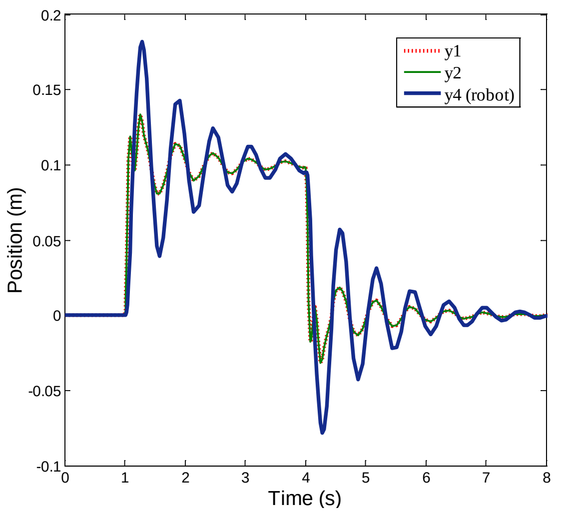

FIGURE VII. LINEAR DISPLACEMENTS FOR M=10KG

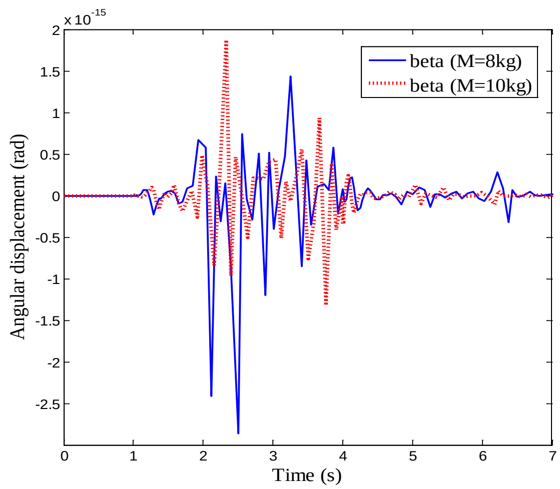

FIGURE VIII. ANGULAR DISPLACEMENT, β.

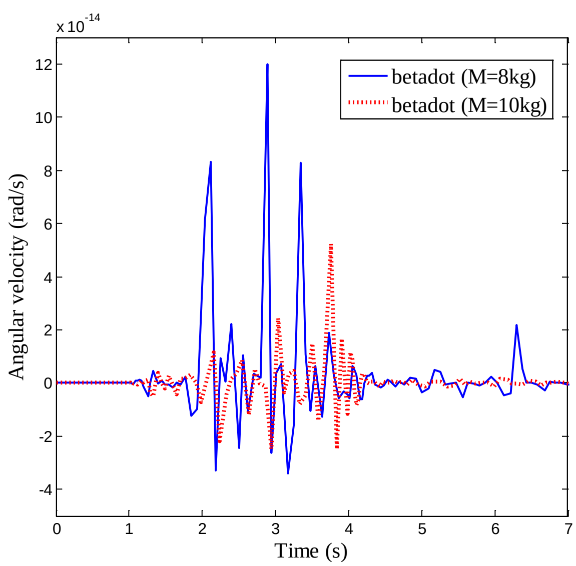

FIGURE IX. ANGULAR VELOCITY, βdot

The vibration analysis of the system presented above in time domain can be summarized in Table II. It can be observed that, increasing the mass of the onboard electronics *M*, increases the displacements of the system whereas decreasing the respective velocities.

TABLE II. SUMMARY OF THE TIME RESPONSE OF THE ROBOT

Variable	***Displacement***		***Velocity***	
	M=8kg	M=10kg	M=8kg	M=10kg
Y_1	0.13m	0.14m	2.03m/s	1.98m/s
Y_2	0.13m	0.14m	2.03m/s	1.98m/s
Y_4	0.18m	0.19m	1.34m/s	1.16m/s
β	1.43e-15rad	1.87e-14rad	1.20e-13rad/s	5.23e-14rad/s

V. CONCLUSION

In conclusion, investigations into the design, modeling and simulation of transmission line inspection robot using mass-spring-damper concept has been presented. The dynamic equations of the model were derived using the Newton's second law of motion. MATLAB simulations results of the dynamic equations have been performed to study the dynamic behavior of the system. The vibration analyses of the robot subjected to a pulse input signal demonstrated that the results will provide useful information for the selection of appropriate control strategy for an efficient control of the transmission line robot.

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