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Introduction

1.1 ORIGIN OF THE PROBLEM

Since last three decades, research in the field of robot kinematics has gained great interest among numerous researchers worldwide this is mainly due to the extensive use of the robotic manipulators in various challenging fields of engineering and science such as mining, medical, nuclear, aerospace, manufacturing, search and rescue, military, fire fighting, agriculture etc. to execute the functions like assembling, space exploration, painting, spraying, grinding etc. A robotic manipulator is a robot arm which can be considered as an electronically controlled mechanism consisting of a series of links and joints providing relative motion between the links and performing tasks by interacting with its working environment. The robots which are utilized for the tasks involving forceful interactions with the environment are rapidly increasing in machining and assembling; in tele-operation and tele-manipulation; in search and rescue tasks; in cooperative tasks; in manipulation; in humanoid robots, e.g. walking. Traditionally, robot manipulators have been designed by considering all members as rigid bodies and hence the dynamic equations for rigid body model have been thoroughly derived to demonstrate its performance by many researchers. Earlier the robots have been designed and fabricated for maximizing the stiffness in order to reduce the end point residual vibrations to realise good position accuracy using high stiffness in links and actuator. As a result, the conventional robots lead to bulky design, high power consumption, lower speed and smaller workspace. But for last decade, in a quest to enhance the productivity and speed of industrial robotic manipulator, researchers have focused their attention towards the reduction of the weight of robotic components and hence flexible manipulators have come into existence due to their practical relevance.

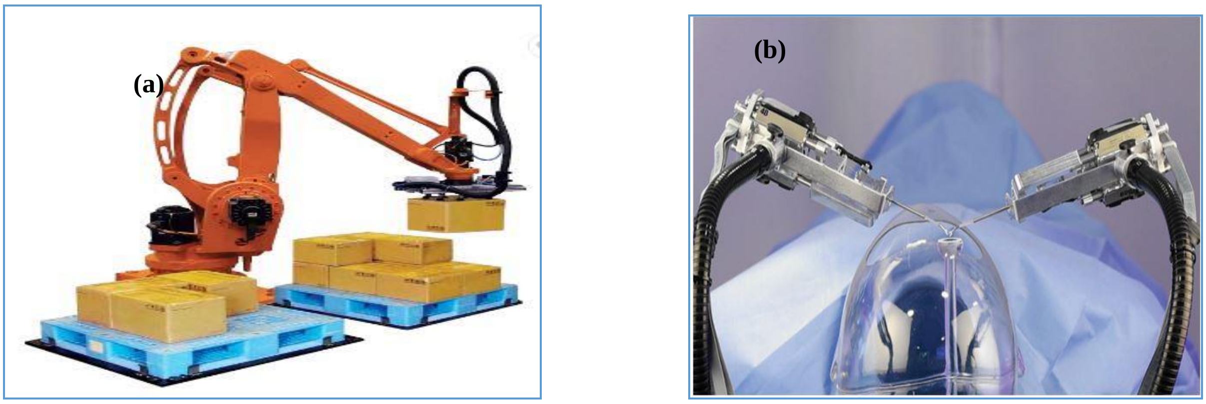

Fig. 1.1: (a) Robot palletizer machine and (b) Axsis robot.

The heavy and bulky industrial robot manipulators have been assigned to move an object from one position to another to perform pick and drop operations involving various objects for example robot palletizer machine (https://ikvrobot.en.alibaba.com) shown in Fig. 1.1. It is used for the transportation of boxes, woven bags, and bulk palletizing in construction, fertilizer and general industrial purposes. The controls can be operated from the controller touch screen and it only needs the positioning of the system for pick-up point and placing point. For industrial purpose, there has been a constant pursuit to have low power consumption, high speed, and light weight manipulator in order to boost the productivity. In case of space applications, the reduction in the payload of spacecraft is very essential to minimize the fuel cost. Also shown in Fig. 1.1 is an application where robot manipulator is used in waterproof operations such as disaster management and offshore plant construction. A Hydraulic Robot Arm – Underwater (http://www.knrsys.com/portfolio/hydraulic-based-robot-3/) is a heavy-load manipulator used for underwater explorations.

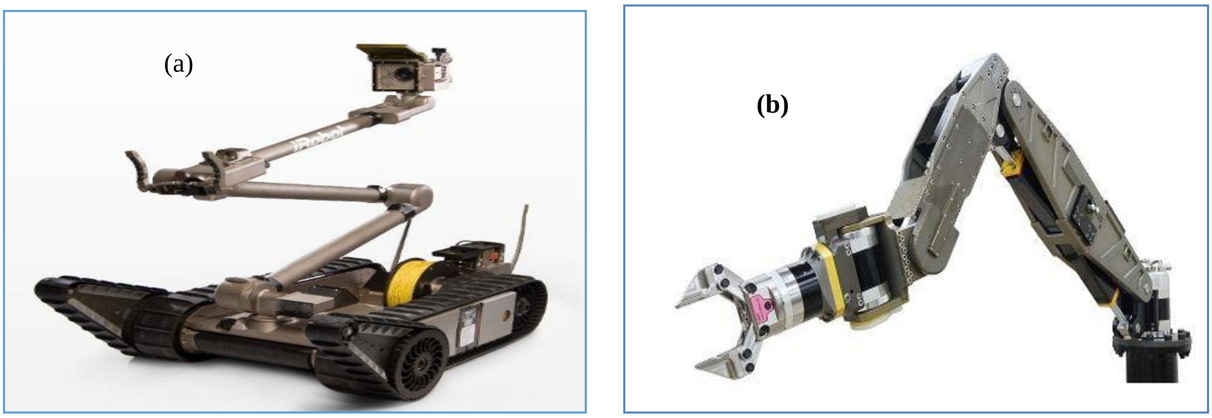

Fig. 1.2: (a) IRobot 510 PackBot and (b) Hydraulic Robot Arm – Underwater.

In today's military conflicts, detecting the improvised explosive devices and mines is one of the greatest challenges faced by ground armies. The deployment of robot manipulators for humanitarian demining and IED detections has increased tremendously due to its safe operation and speed of detection. In Fig. 1.2, a flexible iRobot 510 PackBot (https://www.army-technology.com/features/featuredetect-and-diffuse-the-top-5-military-robots-for-explosive-ordnance-disposal-4372678) has been shown which can perform surveillance and reconnaissance, biological, radiological, chemical and nuclear detection along with route clearance and IED detection. Based on the necessity of operator's mission, it can be configured accordingly. Low weight and flexibility of the links are the major advantages for researchers which have resulted in faster movement of the manipulators, which, in turn, has reduced the operating costs of the system, better transportability, and safer operation significantly. In medical industry robots are being employed to accomplish tedious and intricate surgical tasks where the accuracy is of main concern. On the right side of Fig. 1.2, the remotely operated Axsis robot (https://www.cambridgeconsultants.com/case-studies/axsis-medical-robotic-concept) for the cataract surgery has been shown. The robots involved in surgical operations require controlling the movement of the end-effector to avoid the damage to the human body due to the flexibility in the manipulator. The adequately controlled flexible robot manipulators can filter the tremor the hands of surgeon, saving time, speeding the workflow, and holding the tools in place without movement for the extended period along with achieving more precession than a human hand.

1.2 SIGNIFICANCE OF THE PRESENT WORK

The modelling and control problems for flexible robotic system have been a major centre of attention in recent years on the grounds that robots are widely used in modern industrial operations, medical utilities, agricultural production, defence tasks and space exploration. The disadvantages of high power consumption and low speed associated with rigid link manipulators has been minimized by introducing structural flexibilities in the links as well as the joints, especially for the long reach-manipulator which have in turn contributed to substantial residual vibrations. These residual vibrations originating due to the use of flexible link and actuator often lead to the delay in subsequent operations. Moreover, flexible long reach manipulators are often employed in various modern industrial operations to restrict the human interactions with the working environment conditions. Many such robotic systems are usually delineated and designed based on the theory of deformable bodies. Thus, a step towards designing and developing flexible robotic system must be characterized by accounting for the flexibility in the links and joints accurately.

In order to perform hazardous operations where human reach is not possible, for example in nuclear industry, long reach robotic manipulators are being used effectively. In pick and drop operations the manipulator is supposed to move on a planar surface to reach the required location and then perform the requisite tasks. Flexible robot manipulator with a prismatic and revolute motions are functioning in many engineering applications such as industrial robots, telescopic members attached to loading vehicles, spacecraft antenna, magnetic tape-drivers, printers, band saws, and weaving mechanisms. Many movements of the human arms are recreated by robotic manipulator, not only the conventional side-to-side and up-and-down motion, but also a full 360-degree circular motion at joint. The robot manipulator may experience inadmissible vibrations when the motion of the joints or the external forces becomes equal or nearly equal to the system natural frequencies and may damage the entire system. Hence it becomes pertinent to appropriately model and study the modal parameters along with the nonlinear vibrations characteristics of multi-link robotic manipulators having both prismatic and revolute motions.

In comparison with single-link manipulator, due to their long reach manoeuvrability and larger workspace, long reach flexible manipulators are more suitable especially in industrial purpose, aerospace, nuclear plant, military, defence, agriculture, and many other fields,. These manipulators are used to carry out numerous functions which involve holding a payload of an arbitrary shape and size carrying out operation in variety of environments, which makes it important to study the dynamic behavior of manipulators with such an end-effector. The presence of payload has a significant effect on the dynamic behavior of the manipulator because it exerts the inertial force and moment which are a function of the deformation of the manipulator. The payload cannot be assumed to be a point mass, as in reality the centre of gravity of the end-effector will not coincide with the point of attachment with the beam hence shall consists of inertia, weight along with offset and its centre of gravity may have some orientation. Moreover, the type of resonance conditions arising in the manipulator system with a generic payload also depends on the orientation of the excitation force acting on the payload. Thus, a sizeable payload not only influence modal characteristics but also the nonlinear response of a system under forcing conditions and hence the appropriate modelling of manipulators involved in holding/gripping arbitrarily shaped payloads becomes necessary for their efficient control.

Manipulators are designed to be operated in a natural and intuitive manner by utilizing the force information by the unspecified pressure, turning or twisting and tensile action applied to the robot during human-robot interaction. In industrial applications like drilling, reaming, routing, counter-boring, grinding, bending, chipping, fettling etc. the robot arm has to move continuously over the surface holding the tool with contact forces acting on the tool tip. In this category, many day-to-day activities performed by an amputee using prosthesis basically any task involving the use of a tool can also be included. In aircraft and space industry, automated drilling, fastening robots that crawl along the fuselage and train explorations involve interactive forces between the surface and manipulator. In microsurgeries such as retinal surgery, endo-microscopy etc. the end-effector forces has to be determined. In the nuclear industry, manipulators are required to perform decommissioning tasks, such as cutting or scabbling, involving contact forces at the end-effector. In these applications, unwanted vibrations may originate due to the time varying force exerted on the end-effector by the surface of interactions or by the work piece. The forced/parametric excitations induced due to these contact forces may cause catastrophic failure of the system and hence the system requires proper active or passive control to attenuate the undesirable vibrations.

For the position accuracy of the end-point, the joint control of elastic robots and avoidance of its link oscillations are some of the major concerns in the new generation of flexible robots employed in precision industries. However, various control strategies have been developed in order to ameliorate or avoid the undesirable vibrations and thereby achieving the required precession in the applications involved especially in aerospace, medical and nuclear industries. Viscous damping can be used as one of the passive vibration control strategies to attenuate the vibration of the system by storing the energy and dissipating it in the form of heat. Also, passive control of the system can be achieved through an appropriate modification of the dynamics of the underdamped structure by altering the configurations of the system. A viscoelastic material for the links, tuned-mass dampers and piezoceramic dampers can also be used to passively control the unwanted vibrations. In active vibration control, sliding mode, modern controllers such as proportional, proportional derivative (PD), and proportional integral derivative (PID) controller can be used as feedback control schemes. The piezoelectric and magneto-elastic material in presence of electric and magnetic fields, respectively, produce body forces that oppose the elastic deformation of the link and thus reducing the vibrations.

In previous studies, researchers have confined their attention to the modeling and nonlinear analysis of single-link manipulators with point payload and hence, results obtained in those researches depicted an insufficient representation of the actual payload carried by the end-effector. Moreover in nonlinear analysis, the authors have confined their investigation to demonstrate the effect of point payload on frequency characteristics due to the lack of proper admissible function. The studies demonstrate only the influence of parametric variations of system attributes on the modal characteristics, nonlinear dynamics and vibration characteristics of the single-link manipulator.

The dynamic modeling of a vibratory system can be accomplished by using Newton-Euler, D' Alembert's principle or using energy methods like Lagrange principle or extended Hamilton's principle. Also, the literature regarding modeling of manipulators based on the finite element method and lumped parameter method has also been reported. The primary disadvantage in the Newton-Euler formulation is that, a great deal of physical insight is required while developing the equations of motion as well as the boundary conditions by balancing the force and moment terms especially in the case of flexible-multi-body systems. Whereas, the implementation of energy methods it is relatively easy to derive the equations of motion. The governing equations of motions derived by Lagrange's formulation and Hamilton's principle are similar. However, for the flexible-multi-body systems, the derivation of boundary conditions by Hamilton's principle is significantly easier due to its straight-forward approach as compared to Lagrange's formulation where a great understanding of the generalised coordinates is required. In present work, the extended Hamilton's principle has been exploited to dynamically model the single as well as the multi-link manipulators because of the advantage of obtaining governing equations of motions along with the respective boundary conditions for any distributed system. The kinetic and potential energies have been expressed in terms of generalized coordinates by assigning global and local coordinate system to the links. Further, the Galerkin's method has been used to discretize the governing equations of motion into nonlinear temporal equations of the motion.

The adequate knowledge of the eigenfrequencies and vibratory characteristics of a system enhances the capability of a design engineer to detect, locate and quantify the extent of damages in system. The eigenfrequencies may vary significantly with the system parameters, which is sufficient to challenge the robustness of a designed controller. The design process of the robot manipulators needs to balance how the modifications in key design parameters for various purposes alter the modal properties and impact dynamic response of the system. The calculation of modal parameters is an essential and basic requirement prior to nonlinear dynamic analysis and control of the manipulator system. Parametric study of modal analysis also indicates the way of improving and optimizing the dynamic characteristics of flexible manipulators. Identification of eigenfrequencies and corresponding mode shapes renders the information about the deflection shape of vibration to the design engineer when one of the natural frequencies matches with the external frequency called as resonance. In reported works, the multi-link manipulators have been modelled considering the predefined boundary condition which is insufficient to calculate the modal parameters. As the type of joint motions along with the size and shape of payload also play a significant role in manipulator dynamics and hence, should be envisaged while modeling the flexible manipulators. Moreover, study of the influence of system parameters on the eigenspectrums of multi-link manipulators is found to be trivial in the existing studies.

A system is reduced to the parametrically excited system when time varying hub motions or external forces is applied to the manipulator as the governing equations of motion of the links contain time-dependent excitation terms. When the force is applied along with the axis of the link, the resonance occurs when the forcing frequency becomes nearly equal to or twice of the natural frequency of the link. But in case of hub motions at the joints, the resonance may occur when the hub frequency becomes equal or in combination of the natural frequencies of the links which are known as principal resonance or combination resonance, respectively. Moreover, internal resonance has been observed between the links of the manipulator due to the linear as well as nonlinear coupling of the dynamics of the links. The system may experience either the combination of internal resonance or parametric resonance depending on the forcing or hub frequencies. The nonlinear large and small transverse deformation model of the manipulator have been considered in the present work and the stability of steady-state solutions for system has been investigated for simple, subharmonic and super-harmonic and combination resonance conditions.

Different types of nonlinearities arise in a manipulator system such as inertial, geometric, damping, material and physical nonlinearities. Inertial nonlinearities such as centripetal and Coriolis accelerations can be observed in nonlinear equations of motion of the links which arise due to the rotary and complex motion of the links. These nonlinearities occur due the nonlinear terms in the velocities of the links which are expressed in terms of generalized coordinates. The geometric nonlinearities arise in the potential/strain energy terms of manipulator for inextensible, large deformation or nonlinear curvature conditions of the links. Both the conditions give rise to the cubic nonlinear terms in the equation of the motion which in turn causes the bending of the frequency response curves exhibiting spring softening or spring hardening effect. Coulombs friction due to nonlinear interactions between two surfaces induces the nonlinear terms in the system through damping. The nonlinear stress-strain relationship related to the inelastic behavior of a component or system has a substantial effect on the structural effect on the response of the system e.g. Piezo-electric materials. In the context of present study, the influence of inertial and geometric nonlinearities on the system response has been studied thoroughly for the parametric variation of system attributes which has remained absent in the literature. In the author’s view, the nonlinear response under external or parametric loading for multi-link manipulator has not been reported so far and hence, the frequency response of multi-link manipulators has been studied comprehensively through time responses, phase portraits and FFTs.

As mentioned earlier, the modern flexible robot manipulators demonstrate superiority over rigid robots due to their low weight, lower power consumption, smaller actuators, higher payload to manipulator weight ratio along with larger manoeuvrability and transportability. However, flexibilities in the links and joints make their control to achieve and maintain accurate positioning and trajectory tracking poses a major challenge. The dynamics of the flexible manipulator are significantly more complex by virtue of the flexible nature of the system. The simulation of the developed model subjected to specified input command is essential to form the basis for design and development of suitable control strategies for the systems. Subsequently, the designer of vibration controller is confronted by the parametric sensitivity of the manipulator dynamics, particularly to payload characteristics and configurations which may vary during operation undertaken by robotic system or depending upon the applications of the manipulator. The available literature indicates that there has been significant works regarding the trajectory tracking and control of single and two-link flexible manipulators but the influence of changing the configuration and system variables of manipulator on the system input-output parameters such as time response, settling time, rise time, input torques etc. has remained elusive from the researcher’s attention. As the robot manipulator of various capacities and configurations are being used in different industrial operations for different applications where the end point control is the major concern, it becomes inevitable to study the system performance under parametric variations. Hence, a step towards the graphical comprehension of system responses in time domain for the parametric variation of system attributes of a two-link flexible manipulator has also been taken in present study which can be further extended to the multi-link manipulators.

1.3 OBJECTIVES

Considering the development potential of flexible link robotic manipulators in various industries, which offer several advantages over the rigid manipulators, the detailed study of such manipulators becomes imperative for safer and cheaper operation of the system. This work focuses on the issues of modeling, modal analysis, nonlinear dynamics and trajectory tracking of flexible link manipulators. In order to reach the main objectives, the development of mathematical and analytical dynamic model of flexible manipulators using generalized coordinates based kinematic formulations following the Hamiltonian formalization to obtain the governing equations has been attempted. Further, the use of Galerkin's principle and method of multiple scales to obtain the second order nonlinear temporal equations of the motions has been accomplished. The closed form of solutions has been further obtained using second order method of multiple scales as one of the powerful perturbation techniques. The reduced governing equations of amplitude and phase have been derived and subsequently, the frequency response curves obtained for the steady-state conditions have been plotted to illustrate the influence of system parameters on the stability of the steady-state solutions. The analytical results have been validated numerically within the permissible error limit for the structures under study. Different models have been analyzed in space, frequency and time domain to comprehend the parametric influence of system attributes on the system responses. The main aims of this work are bulleted as follows:

a) Mathematical dynamic formulations of nonlinear governing equations of motion and coupled boundary conditions in transverse and longitudinal directions of single and multi-link manipulators using generalised coordinate system and Hamilton's principle is accomplished. The links have been modelled as Euler-Bernoulli beam element neglecting the shear deformation and rotary inertia arising due to rotation of the cross-section of the links, i.e., the cross-section remain perpendicular to the neutral axis even after the deformation. Planar harmonic prismatic and revolute motion at the joints and actuator of manipulator along with point payload or generic payload at the terminal end has been considered.
b) The normalized modal parameters, i.e., eigenfrequency and eigenfunctions have been numerically calculated and tabulated for the single and multi-link manipulators. The influence of the system parameters such as payload and hub attributes, flexibiltiy of links, beam mass density of links etc. on the eigenparameters has been demonstrated graphically.
c) Nondimensionalized temporal equations of motion have been derived using Galerkin's method with further demonstration of nonlinear phenomena for external and parametric excitations using method of multiple scales as one of the perturbation method. The multiple steady-state solutions and jump phenomena due to the existence of geometric nonlinearities has been noticed and graphically illustrated.The investigation of the parametric instability regions along with qualitative and quantitative effect of system parameters on the frequency response curve has been accomplished.
d) The simulation of closed form of computationally efficient matrix composed of the rigid and flexible motions of the manipulator is accomplished to analyse the influence of system attributes on the system responses such as angular tip position, modal deflections and angular accelerations. Smooth sinusoidal torque input has been imparted at the

joint of the manipulator to inspect the obtained trajectories through forward dynamic technique.

e) The exact reproduction of desired smooth joint trajectory based on the input-output inversion technique in conjunction with state feedback control law for flexible manipulator has been accomplished. The simulation results exhibiting the significant effect of system parameters on the control parameters have been demonstrated.

1.4 OUTLINE AND METHODOLOGY

This thesis is composed of seven chapters. The present chapter provides the introduction of thesis along with the objectives thus accomplished. The chapter 2 deals with the detailed literature review and recent developments in the field of flexible robots. A thorough discussion on the single-link, two-link and multi-link manipulator with reference to the modeling, free vibration, forced vibration and control has been presented. Chapter 3 is dedicated to the dynamic modeling, modal analysis, nonlinear behavior, and vibration characteristics of the single-link manipulator driven by revolute or prismatic joints with generic payload. In chapter 4, the detailed mathematical modeling, eigenanalysis and behavior under external excitations of two-link manipulator with or without generic payload driven by combination of revolute and prismatic joints have been illustrated. In addition, in order to facilitate the effective control, the parametric variations of dynamic responses of manipulator under externally applied torque are graphically studied. Chapter 5 deals with the development of dynamic model of the multi-link manipulator with time dependent bi-directional motion and subsequent study of modal parameters and forced vibration characteristics of 3R manipulator. Chapter 6 includes the conclusion and recommendations for the future study. Finally, in Chapter 6, the bibliography containing the references of the previously authored works has been provided.