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Dynamic modeling and control of flexible manipulators: a review

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Abstract: In this paper a survey of flexible robotic manipulators has been carried out. The significance of flexible mechanical arms is considered compared with traditional robot arms .The applications of flexible mechanical arm are introduced. Papers are classified according to flexible manipulator modeling technology and flexible manipulators control method.

Key words: Flexible robotic manipulators, robot arms, multi-body system dynamics model, flexible manipulator control

1. Introduction

With the completion of the International Space Station and exploration of deep space, advanced aerospace technology is acquired. Mankind completed the first on track operation in 1973. Solar panels on the Sky lab space station were repaired successfully through the extravehicular activities [1].

However, astronauts cannot perform on-orbit operations accurately and effectively, restricted by physical conditions and the environment. Nowadays scientists are pursuing applications of space manipulator to complete a large number of difficult and dangerous tasks. Significant features of space maneuvering arm are large load capacity and high control requirements. Multi-degree freedom flexible mechanical arm has become popular considering the launch costs, space energy constraints, and space operations [2].

As a result, robotic arms are widely used in dangerous, monotonous and tedious repetitive applications. However, most robotic arms are traditional rigid manipulators. They are mostly designed from heavy-duty materials and built in a manner to maximize stiffness in an attempt to minimize the vibration of end-effectors to achieve desired position accuracy [3]. Typical examples of flexible structural systems are: large-size solar panels, light-arm robots, large parabolic expansion antennas, satellite whip antennas, and high-sensitivity radio telescope reflectors [4]. Flexible manipulators can improve production efficiency, reduce operating time and decrease consumption of resources. Elastic deformation and vibration are unavoidable in the operation of flexible manipulators.

Elastic deformation and vibration of flexible mechanical arm mainly occurs in joints and arms. The production and transmission power, location perception, mechanical connection are three tasks of joints, which is the key of the movement ability, movement precision, sport stability and motion safety of the manipulator. Motor, transmission, sports shaft and sensors are main components of joints. The joint flexibility is mainly determined by the two series of flexible components, torque sensor and harmonic reducer. Robotic arm is often made of lightweight materials, such as carbon fibers, which have the characteristics of low density, high rigidity and high strength [2]. Therefore, joint flexibility and arm flexibility must be considered in the dynamic modeling of manipulators, to ensure the control accuracy and system reliability, reduce the elastic vibration and decrease the life span of flexible mechanical arms.

Meanwhile, the space flexible manipulator and its rigid carrier form a set of typical rigid and soft fit multi-body system. It is necessary to research dynamics of the flexible multi-body system. In recent years, many scholars have done a lot of work on the modeling theory, calculation methods and experimental research of flexible multi-body systems. However, mechanisms of motion and elastic deformation between the rigid and soft in a large range are not fully understood [4].

In summary, the study of flexible arms can have a significant impact on the field of aerospace and also improve the efficiency of social production.

2. Flexible manipulator modeling technology

2.1 Research Status of Multi-body System Dynamics

Multi-body system dynamics includes multi-rigid body dynamics and flexible multi-body system dynamics. Multi-rigid body system dynamics has been studied by many scholars, the theory of multi-rigid body dynamics has been fully studied. The first multi-body dynamics monograph written by Wittenburg [5] illustrates the kinematics and dynamics of the multi-rigid body system very well. Graph theory was introduced into the dynamics of multi - body system, which laid a perfect foundation for later scholars' research on related fields. Kane [6] proposed Kane's method based on the analysis and comparison of various dynamical principles, to replace the generalized coordinates by selecting the generalized rate which has the advantages of both vector mechanics and analytical mechanics. Haug [7] proposed a computer modeling of the Cartesian method, which has application in business. Since then, scholars have made important contributions in this area such as Roberson [8], Nikravesh [9], Schiehlen [10], Huston [11] and so on. With the scholar's in-depth study of the multi-rigid body dynamics, the theories of multi-rigid body dynamics has been very mature, to produce many commercial software.

In the field of flexible multi-system dynamics, kineto-elastodynamics(KED) method [12] was firstly proposed to solve the related problems. The elastic deformation is obtained by finite element analysis, but not considering the interaction of the large-scale rigid motion and the structural elastic deformation in motion. Subsequently, some scholars proposed floating coordinate method. It is a way of combining the multi-rigid-body dynamics with the structural dynamic. It can take full advantage of modal technology and have a better computing efficiency and accuracy in small deformation and low-speed large-scale movement. It is the most extensive method in flexible multi-body system modeling[13].

In 1996, Shabana [14] proposed the absolute node coordinate method based on finite element and continuum mechanics theory. The modeling process does not need small deformation and local coordinate system assumptions, it can truly reflect the dynamic behavior of large deformation [2]. Berzeri proposed a simplified model for elasticity of one-dimensional beams based on different assumptions and made a comparison. Omar and Shabana proposed a classic plane strain shear beam element based on continuous dielectric mechanics theory, which leads to the bending strain and axial strain of the inconsistency and shear lock. This problem can be solved by redefining the bending strain by using the local tangent coordinate system of the element [15].

2.2 Multi-body system dynamics modeling

The multi-body system dynamics model is the basis of dynamic analysis. Kinetic equations are determined by different dynamic model. Newton-Euler method, Lagrange method, Kane method are the most widely used.

The Newton-Euler method is clearly in physical meaning, but the number of equations is large, which leads to low calculation efficiency. Lagrange method is suitable for relatively simple flexible multi-body system based on the kinetic energy and potential energy. It avoids the emergence of internal forces in the equation. Angular velocity and partial velocity are introduced by Kane's method, instead of the generalized rate of the generalized coordinates. It avoids the differential operation and is more suitable for the automatic derivation of the application computer [16].

In addition to the above three classical methods, the dynamic modeling method of the multi-body system also includes an optimization algorithm based on the principle of Gauss extreme value. Hamilton principle transmits the traditional Euclidean geometry to the symplectic geometry, the multi - body dynamics equation are solved by the symplectic mathematical framework[17].

2.3 Discrete Method

In the flexible multi-body system modeling, the discrete method can be divided into two categories: the discretization of the physical model and the discretization of the mathematical model. The purpose of the former is to discrete the actual engineering flexible multi-body system into physical model. The latter mainly chooses the appropriate expression to describe the flexible deformation of the object in the flexible multi-body system [18].

(1) Rayleigh-Ritz method

On the basis of satisfying the displacement compatibility condition and the complete condition, a hypothetical displacement field function is constructed, and the modal analysis vector and the corresponding modal coordinates are used to describe the displacement of the object in time. The method has high computational efficiency.

(2) Finite element method

The objects are divided into many simple shapes such as lines, triangular elements, tetrahedral elements, etc. The units are connected at the nodes, and the damping and stiffness of each unit are equally transplanted to the nodes, such as external loads, etc. Finite element method is suitable for dealing with complex boundary, shape and complex load under the problem.

(3) Modal analysis

The modal coordinate is used to describe the change of the component with time, and the modal synthesis and mode truncation are carried out to reduce the size of the solution. It can be used to consider the range of modal truncation according to the system prior parameters. The computational complexity is relatively small. However, this method cannot describe the rigid body motion in the system accurately, so it is not suitable for solving the dynamic problem with large rigid body displacement[16].

3. Flexible manipulators control

3.1 Difficulties of flexible manipulator control

Because of its light-weight and long arms, a series of problems will arise in the actual movement, it is difficult to make sure the accuracy and efficiency of the flexible robot arm control. At the same time, the flexible manipulator needs to track its trajectory during operation. In addition, unlike the rigid robotic arm, movements of the flexible manipulator and the platform are coupled to each other, which leads to higher control errors. Scholars have made a lot of research on the problem of flexible manipulator control, and proposed many mature control methods

3.2 **Classic control method**

(1). PID control

In the classical control method, PID feedback control methods are widely used . PID parameters can be adjusted according to the external disturbance and the system's own kinetic parameters to achieve the effect of a more fine PID control.

(2) Computational torque method

Computational torque method is a dynamic control method considering the dynamic model of the manipulator. It is also the most important and most widely used method in the tracking control of the manipulator. The basic idea is to introduce a model-based nonlinear compensation in the internal control loop, which makes the nonlinear coupling robot system realizing global linearization and decoupling, and then use the classical PD control to control the linear stationary system after decoupling[19].

3.3 Modern control method

(1). Adaptive control method

Adaptive control can adjust the parameters of the controller to adapt to the state change according to system process status data measured in real time. Lin Lih-Chang [20] and YehSy-Lin [21] have designed an adaptive control rule to identify the uncertainty parameters.

(2).Robust control method

Because the flexible manipulator model is discredited from the infinite dimension to the finite dynamic model, there are obvious uncertainties in the dynamic equation. Many scholars use the robust control method to solve this problem[22]. Jong-Guk [23] designed a recursive robust controller to eliminate the effects of uncertainties.

(3).Optimal control method

In the problems of the active control of the flexible manipulator, the optimal control quantity can be solved by using the optimal control theory in order to maximize the vibration suppression effect [24].

(4).Other control methods

The singular value perturbation control [25] divides the robotic arm system into fast-changing subsystems and slow-changing subsystem. Sliding mode control [26] has a good adaptability in a wide range of applications through the design of the sliding surface to switch the state of arm.

4. Conclusions

This review of flexible robotic manipulators indicates that in the field of automation and manufacturing, the dynamic analysis and control of flexible manipulators is an important research area. A large number of researches have been done to improve efficiency, accuracy and reliability. A series of problems elicited by flexible manipulators are also worth study, such as inhibition of flexible mechanical arm elastic vibration and deformation, rigid and flexible co-system system, flexible mechanical arm dynamics modeling. As to authenticate the theoretical modeling, more experiments are needed.

5. References

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