Research on Structural Dynamic Characteristics of Construction Machinery Arm System

Chunming Chen *, Yang Yang
Hebei Normal University of Science & Technology, Hebei, China

Abstract — Objective: This paper studies the application of construction mechanical arm system in dynamics of multibody system. Method: Several dynamic theoretical equations and methods of establishing the mechanical arm model are introduced in the paper. Process: This paper introduced the concept of manipulator system structure and dynamics of multibody system, and introduced the research status in this area at home and abroad, then expounded the establishment method of dynamic model of the manipulator arm system based on Lagrange equation. Result & Analysis: The paper used the powerful NASTRAN to establish the viscous damping simulation model of the manipulator arm system and analyzed data of the structure of the manipulator arm. Result: For the application of manipulator arm system, it’s very necessary to do more study about the characteristics of the dynamics of multibody system.

Keywords - Construction mechanical arm; Multibody system; Dynamics

I. INTRODUCTION

The mechanical arm is considered as a multi body system. At present, the mechanical arm of the ground and the water is used, and its arm is rigid. The space-remote manipulator used in the US space shuttle has been quite flexible. With the needs of light and high-speed robot arm, especially the development needs of the space environment of space robot, the mechanical-arm engineering has become an important field of engineering to promote the multi-rigid flexible multibody system. To develop the space station, we must solve the space docking and assembly technology, because of the huge scale; we must assemble the space rendezvous and docking. Therefore, the development of space robot arm has been the only road. The US space shuttle has equipped the space robot arm. According to the Russian experts on the Mir space station's docking and assembly process is achieved by using horizontal space manipulator, the specific approach is to achieve vertical docking, then the manipulator will move cabin on the transverse to the docking interface. In recent years, scholars have done a lot of research work in this field, the research focuses on how to set up a convenient and simple dynamic model, and how to improve calculation efficiency and shorten the time of calculation, to facilitate real-time control. Lindberg and Longman first proposed the dynamic model of the manipulator mounted on the carrier, and studied the problem of the motion of the manipulator and the movement of the carrier. Vafa and Dubowsky proposed the concept of virtual manipulator to simplify the dynamics problem of space manipulator. Umetani and Yoshida proposed the generalized Jacobi matrix of space manipulator, and it's used in the discuss of inverse dynamics of the space manipulator.

Since the end of the 80's, the domestic researchers have begun to do research in this area. Zhao Ping researched on the modelling of flexible chain multibody system composed of base flexible connecting rod and end load, and did numerical simulation about the 3D mechanical arm system in space composed of load with a rigid rod, two flexible and rigid rod, using Gear algorithm. Jifeng Guo gived out a linear model of the inverse dynamics of a space flexible robot, and with the method proposed by him, the 2D plane motion of a flexible robot is extended to 3D space [1].Fig 1(a) - (d) shows several kinds of mature mechanical arm.
II. DYNAMIC MODEL OF THE MANIPULATOR

A. Brief Introduction of the Second Kind of Lagrange Equation

Analytical mechanics is an important branch of general mechanics, and it holds the basic position in mechanics. It analyzes the general rule of low speed of mechanical movement in macro world, in summary, it is to study the description method, the general principle of the dynamic system and the establishment of the differential equations of motion. Analytical mechanics is different from Newtonian mechanics. Newton mechanics bases on force, velocity and acceleration, etc., and solves with the application of Euclidean geometry method. The geometrical intuition is strong, and the mechanical problem with less complexity can be obtained simply and satisfied. But it is very difficult to rely on the method of geometric method. Analytical mechanics is focused on energy, and is used to analyze the dynamics of a particle system. Because there is a high degree of generality in the method, and it has more abstract features in concept, it is convenient to solve the dynamic problem of non-free particle system. Along with the development of engineering technology and the wide range of analytical mechanics, its principle and method are more and more applied to the space engineering, mechanical engineering, robot, etc.. In 1755,19 year old Lagrange wrote and published in 1788, the immortal masterpiece "analysis of mechanics", and laid the foundation stone for the analysis mechanics. Lagrange puts forward the generalized coordinates, and combines the mechanics principle and the mathematical analysis method, and proposed a general method for establishing the differential equations of motion of a non free particle system [1]. The other ones who make a significant contribution to the analysis of mechanics are Gauss, Jacobi, Appell, Hamilton et al, they perfected the analytical mechanics system. The second kind of Lagrange equation is the most important kinetic equation in the analysis of mechanics, it gives a general, simple and unified solution to the dynamic problem. Lagrange equation is the source of the development of analytical mechanics. The title of the second kind of Lagrange equation is relative to the Lagrange equation. The first kind of Lagrange equation is a multiplier method in the application of mathematical analysis. A set of dynamic equations are established by using the universal equation and constraint equation in the form of rectangular coordinates. Because of the number of equations, it is difficult to solve, so in a period, its application value is far less than the second kind of Lagrange equation [2].

B. Study on the Dynamics of the Manipulator under Viscous Drag

When a particle is moving in a medium, it is often subject to the action of the medium. The size of the drag is generally related to the speed and the coordinates, and its direction is in the opposite direction of speed. We lead in Rayleigh dissipation function without reduction:

\[ F = \frac{1}{2} \sum_{i=1}^{n} (k_x x_i^2 + k_y y_i^2 + k_z z_i^2) \]  

In the formula, \( F \) represents resistance; \( x_i, y_i \) and \( z_i \) are coordinates of three directions; \( k_x, k_y \) and \( k_z \) represent the components of velocity in the three directions respectively. Then we can get the Lagrange equation with Rayleigh dissipation function:

\[
\frac{d}{dt} \frac{\partial T}{\partial \dot{q}_s} - \frac{\partial T}{\partial q_s} = \frac{\partial F}{\partial q_s} + Q, \quad (s = 1, 2, ..., n)
\]
In the formula, $q^s$ is generalized coordinates; $q_s$ is generalized velocity; $T$ is the kinetic energy presented by them; $Q_s$ is the generalized force corresponding to $q_s$; $N$ is the number of complete constraint equation. Also, we introduce the Luliye dissipation function without derivation:

$$
\Phi = \sum_{m} k_i \int_0^1 f_i(u) du \quad (3)
$$

Where $\Phi$ is a positive function; $k_i$ is proportional coefficient, which is related to the dissipation force; $f_i(u)$ is a function of the generalized velocity. And we get the Lagrange equation with dissipation function Luliye:

$$
\frac{d}{dt} \frac{\partial T}{\partial \dot{q}_s} - \frac{\partial T}{\partial q_s} = \frac{\partial \Phi}{\partial q_s} + Q_s \quad (s = 1, 2, ..., n) \quad (4)
$$

Comparison of Rayleigh dissipation function and Luliye dissipation function makes it not difficult for us to find out that, Rayleigh dissipation function is quadratic function of generalized homogeneous velocity, in mechanics, it belongs to linear damping property [4]. While the Luliye dissipation function is a more general situation, it considers the nonlinear damping. Rayleigh dissipation function is a special case of Luliye dissipation function. Because of the slow motion of the manipulator in the fluid, Rayleigh dissipation function is chose to describe the motion of an object under viscous damping. The number of viscous resistance is 10-3 or 10-4, and the influence of the mechanical arm can be neglected. The reason for this phenomenon is that the water is very small, which is 1.002×10^{-3}Ns/m² at 20 degrees Celsius. The simulation result of the viscous damping of the arm is shown in Figure 2. On the other hand, the viscous resistance is proportional to the third square of the length. Therefore, the increase in the length of the manipulator will greatly increase the viscous resistance of the manipulator. In summary, in the mechanical arm dynamic analysis, when the length of the arm is in a certain range, the mechanical arm viscous resistance is negligible [5].

![Viscous drag torque](image)

**Figure 2. Simulation results of viscous damping.**

### III. STATUS OF RESEARCH ON THE STRUCTURE DYNAMICS AND CHARACTERISTICS OF CONSTRUCTION MACHINERY ARM SYSTEM

#### A. Research Status of Multibody System Dynamics at Home and Abroad

Construction machinery arm system is a typical multibody system. Firstly, the research status of multibody system dynamics is introduced. The physical model of the multibody system is defined by the elements of the object, the hinge, the force element and the external force, and has a certain topological structure. Multibody system dynamics is a science to study the law of motion of the multibody system. Multibody system dynamics includes multibody system dynamics and multibody system dynamics. The relationship between multi flexible body system and multi-rigid body system can be expressed by graph. The research contents of multi-body system dynamics include rigid, flexible body dynamics modeling theory and its calculation method, numerical solution of differential equations, computational efficiency, mechanism analysis, flexible effect, control theory, optimization method, real-time simulation virtual prototyping technology, parallel computing and reliability, etc. At present, the multi-body dynamics has formed a systematic analysis and modeling method [6]. Fig.3 shows the relationship between the multi-rigid body system and the multi flexible body system.
For the research of multibody system, the domestic and foreign scholars have carried out a lot of research. In the rigid body dynamics, Fichter drives the drive rod as an ideal two-force bar to handle ignoring the quality of the connecting rod and the hinge, and derived the dynamic equation of the Stewart platform according to the force and moment balance equation of the dynamic platform. DAE model of flexible multi-body dynamics was studied by RBetsch; Codourey introduces a method of dynamic model of Lagrange equation and virtual work equation based on parallel mechanism. Song Yu analysised and simulated vehicle suspension using Lagrange method of multi-rigid body system dynamics. Shuiguang Tong, et al. used Kane-Huston method to establish the multi-body dynamics model of the axial piston system [7].Dailey et al. used Lagrange's equations to establish rigid motion differential equations of the four sections of the arm of the concrete system, and adopted the method of numerical solution to analyze the angle and the end of each arm. At present, there are many references: RBetsch studied the solution method of DAE for flexible multi-body dynamics; On the basis of deep research on the flexible damping system of multibody system dynamics, R.G. langfois made dynamic modeling of the two unit system with six degrees of freedom using Kaine equation; P. shi studied the application of the Euler beam of flexible multi-body dynamics. In China, Youfang Lu and so on, deeply studied the system dynamics of the multi flexible body system. The dynamic differential equations of the flexible arm of the concrete pump truck are established by using the theory of robot and Lagrange equation by Dameng Guo et al. And the inverse dynamics problem is solved based on the flexible generalized coordinates. Guoguang Jin established the flexible multi-body dynamics model of complex spacecraft with space stretching mechanism, analysed the theory of equality based on flexible multi-body dynamics, and established multibody dynamics model of space robot with rigid flexible coupling, with overall consideration dynamics of space robot joints and flexible connecting rod. Shiji Sun, et al. established the flexible multi-body dynamics model of the crank link mechanism of the internal combustion engine[8].Through the domestic and foreign literature data, we can find that, the research on the dynamics of rigid body system is quite mature, however, the research on the dynamics of flexible multibody systems is still in the stage of exploration. There are still many problems in multibody system of multi-degree of freedom or joint and multi-node arms, in particular, in the modeling and solving of flexible system with complex structures. At the same time, especially the multi-body system dynamics model of flexible multibody system is highly nonlinear and rigid flexible coupling, also contains more reference variables. The accuracy of the equation is also a very challenging task for the researchers in the relevant field. Although many research achievements have been made in the present multibody system dynamics and flexible multi-body dynamics, but most of the research is aimed at simple mechanical systems analysis. For complex structure and long-arm rod system such as mechanical arm, there is no mature modeling method. So research on the multibody system dynamics and flexible multi-body dynamics of construction machinery still needs a lot of work to do for further study[9].

B. Modal Analysis and Structural Dynamic Optimization of the Structure of the Manipulator

Dynamic characteristics of mechanical structure is expressed with the structure of vibration modal parameters. The so-called modal parameters are the frequency, damping and mode shapes of the structure vibration, by these modal parameters, the dynamic characteristics of the structure can be judged. Through modal analysis of the structure of the robot arm, the analysis of the natural frequencies and mode shapes of the arm frame structure system are obtained by analyzing the frequency and mode of the system, this provides the basis for the design and structure optimization of the structure of the manipulator [10].The vibration modes of concrete-pump truck boom under different working conditions are analyzed by Lixin Guo et al. The finite element modal analysis of the crane boom is carried out to obtain the frequency and mode shapes of the crane by
Hongqi Jiang et al. The danger area in the vibration of the boom is to provide a theoretical basis for the structural modification of the boom; Zhong Fei, et al use ANSYS Workbench to establish the finite element model of hydraulic excavator working device. The mode analysis of three kinds of working conditions of the working device of the excavator type hammer is carried out, to obtain the natural frequencies and vibration modes of the working device. For arm frame structure of construction machinery, it is necessary to carry out dynamic optimization design, its natural frequency, vibration mode and vibration response are calculated, in order to select the reasonable kinematic and dynamic parameters, and ensure the best performance of its performance [11].

Dynamic optimization design theory and content is very wide, including structural dynamics, mechanism dynamics, mechanical system dynamics, dynamic strength theory, fatigue reliability theory, etc. Shuiguang Tong, et al, study on the arm frame of the strong arm, and the structural strength and stiffness are analyzed by using the NASTRAN, the stress and displacement maps are obtained by using the stress and displacement maps, and the weak parts of the dangerous area and the stiffness are obtained. Under the condition of satisfying the stress and displacement, a structural optimization model and optimization of the structure of a variety of ground point from the moment of lifting and decoupling are made. This makes the stress and displacement distribution of the boom more uniform, weight is lighter, and structure is more reasonable [12]. Chengfeng Zhang, et al, calculate the structure design of the boom structure, use BP neural network algorithm to simulate the optimization design variables of the boom structure and the mapping relationship between the force of arm structure and the displacement. In order to make the weight of the boom is the most light, the structure of the arm is optimized, which reduce the material consumption and manufacturing costs effectively. The structure modal analysis technology of the arm frame mainly used experimental modal technology, assisted by the finite element modal analysis. The sensitivity of key factors affecting the dynamic characteristics of the boom structure is analyzed by using experimental modal analysis method. Some regularities of dynamic sensitivity of structure parameters are obtained, this provides important reference value for the dynamic design of boom structure; Application of finite element analysis software to analyze the various modes of the boom. The important mode parameters, such as natural frequency, total amplitude, main mode and so on, are calculated. The research results provide the basis for the analysis of the vibration characteristics of the boom system as well as the dynamic characteristics of the structure [13].

IV. DYNAMIC OPTIMIZATION OF THE WORKING DEVICE
STRUCTURE BASED ON FINITE ELEMENT ANALYSIS

NASTRAN has a strong and efficient optimization design capability, it can optimize staticforce, modal, buckling, transient response, frequency response and flutter analysis. In the process of structural optimization using NASTRAN, it allows the use of multiple responses to define the optimization force, velocity, displacement, acceleration, stress, strain, frequency, volume and the combination of them. The constraints of design variables can be 1D,2D,3D constraints and model constraints[14]. Choose the maximum second order natural frequency \( f_2 \) as dynamic optimization objective, that is:

\[
\min F(X) = \frac{1}{f_2}.
\]

In the formula, \( F(X) \) is the maximum bending stiffness of steel frame; According to the above optimization model, the optimization module of the finite element analysis software is used, to set objective function, design variables and constraint conditions, etc. The main evaluation parameters of comparison before and after the optimization of the pre-order natural frequency of the structure system is shown in Table I.

| TABLE I THE FIRST TEN ORDER NATURAL FREQUENCY COMPARISON BEFORE AND AFTER DYNAMIC OPTIMIZATION FOR WORKING DEVICE |
|---|---|---|---|---|---|---|---|---|---|---|
| Before Optimization | 3.792 | 8.626 | 12.696 | 27.182 | 32.585 | 42.924 | 52.521 | 62.941 | 65.428 | 70.506 |
| After Optimization | 3.641 | 10.733 | 13.172 | 28.881 | 32.627 | 44.555 | 50.756 | 65.962 | 64.054 | 69.307 |
| Change rate\% | -3.98 | 24.42 | 3.75 | 6.25 | 0.13 | 3.8 | -3.36 | -0.48 | -2.1 | -1.7 |

From the data in the table, we can know that the second order frequency of the dynamic performance of the working device is increased by 24.42% compared with the original design, the bending degree decreased obviously; The second order frequency is also improved by different degrees, and the mechanical rigidity is enhanced; The first order and the 7th-10th order frequency decreased slightly, that is, the torsional rigidity and bending rigidity of the structure are decreased slightly.

V. CONCLUSION

Construction machinery arm frame system is a typical multibody system, multibody system dynamics is a science to study the law of motion of the multibody system. Many researches have been carried out in the aspects of dynamics and modeling of the kinematics, the structural modal analysis, the structural dynamic optimization techniques, etc. at home and abroad, and achieved fruitful results, to some extent, improved the dynamic performance of construction machinery boom structure. In particular, the research and application of the engineering mechanical arm dynamics in China have achieved a great development. But we also need to do more research to improve the application in the field.

REFERENCES


