Finite Element Analysis of the Maintenance Robot with Charged Used in Substation

Xu Dong*, Jianxiang Li, Jian Li, Qiang Chen, Jizhi Liu and Tao Li
State Grid Intelligence Technology Co., Ltd., Jinan, Shandong, 250101, China
*dxengineer@163.com

Abstract. The Maintenance Robot with Charged Used in Substation is mainly used for the maintenance tasks with hot-line in 220kV substation. It is mainly composed of the mobile chassis and insulated lifting arm. The end of insulated lifting arm is matched with different working tools to achieve different tasks. The robot needs to maintain the stability of the mechanical body during working, so the dynamic characteristics of the robot cannot be ignored. The finite element structure analysis of the robot body under working conditions is carried out, and the stress distribution and structural deformation diagram of the robot mechanical body under working conditions are obtained in this paper. The qualitative analysis of the material concentration in the stress concentration part is carried out due to the calculation results. The low-order vibration frequency of the robot and the corresponding mode shape are obtained by preload modal analysis. The dynamic characteristics of the robot during the operation are analyzed based on the preload modal analysis results.

1. Introduction
The maintenance robot with charged used in substation mainly carries out the post-insulator cleaning operation in the equipment area of the substation, and the foreign body removal work in the substation can be carried out under the rated speed of the hydraulic mechanical arm equipped at the end of the insulated lifting arm [1]. In the process of carrying out the robot's live working, the robot body needs to maintain a certain stability and provide support for live working. The vibration characteristics of the robot are related to its own structure. Under different working conditions, the boundary conditions are different, and the vibration characteristics are also different. The moving chassis of the robot is driven by a motor. The vibration frequency of the rated speed of the motor is about 93.3 Hz. The structure of the robot should be designed to avoid various operating conditions of the robot, especially under the working conditions. The structural frequency of the robot should be avoided at the same or similar to the vibration frequency of the drive motor to avoid resonance and then affects the safety of the robot.

The legs of the robot are opened, the insulation lifting arms are raised, and the end of working platform is equipped with different operational tools when the robot is working. The model of the robot under the working conditions is shown in Figure 1. The finite element analysis of the robot is carried out under the load of the robot chassis and the tool load of working platform, and the stress distribution and stress concentration part of the robot are obtained to conduct qualitative analysis. The deformation of the robot under external load conditions can also be obtained at the same time. The low-order vibration frequency and mode shape of the robot are obtained through the finite element preload modal analysis, and the modal analysis results are compared with the motor vibration frequency to analyze the stability of the robot under working conditions.
2. Theoretical Basis
The theoretical basis of the finite element modal analysis of the robot is structural dynamics. The general structural dynamics equation is as follows:

\[ [M] \ddot{u} + [C] \dot{u} + [K] u = \{F(t)\} \]  

(1)

In the equation, \([M]\) is the mass matrix of the structure, \([C]\) is the damping matrix of the structure, and \([K]\) is the stiffness matrix of the structure, \(\{\ddot{u}\}, \{\dot{u}\}, \{u\}\) are the acceleration vector, the velocity vector and the displacement vector of the structure, \(\{F(t)\}\) is the vector of load. \[2\]

The robot's system is mainly based on rigid connections, so the influence of damping characteristics on the structure is not considered at present. Therefore, the finite element analysis equation under preload is:

\[ [M] \ddot{u} + [K] u = \{F(t)\} \]  

(2)

3. Establishment of the finite element model
The robot's finite element model is discretized on the basis of the 3D model. The model of the insulation lifting arm is mainly composed of the rotary platform, the main arm, the upper arm and the telescopic arm, which simplifies the structure of the rotary support and integrates the bolts of the connecting part. The finite element model of the robot is shown in Fig. 2.

The material properties of the robot are mainly composed of three types: the Q345 steel, the rubber, and an insulating arm with FRP material properties. The material properties of Q345 have an elastic modulus of 206 GPa, a Poisson's ratio of 0.28, a density of \(7.85 \times 10^3\) kg/cm\(^3\). The material properties of rubber have an elastic modulus of 7.84 MPa, a Poisson's ratio of 0.47, a density of \(1.3 \times 10^3\) kg/cm\(^3\). The
material properties of FRP have an elastic modulus of 20 GPa, a Poisson's ratio of 0.22, a density of $1.7 \times 10^3$ kg/cm$^3$.

4. Meshing
The meshing is divided into tetrahedron and hexahedron. The division method adopts free division. The grid correlation is selected as Fine+0 according to the size of the model and the accuracy of the calculation. Local adjustment is performed on the mesh with large distortion, and localized encryption processing is performed to reduce the distortion. The number of nodes is 146,414, and the number of cells is 69,341 after meshing. The meshing of the robot is shown in Figure 3.

5. Boundary Conditions
The boundary conditions of the robot are divided into mechanical boundary conditions and displacement boundary conditions. The mechanical boundary conditions are mainly composed of three parts. The mounting plate of motor applies 3000N equal force to simulate the force of the motor and hydraulic tank. An equivalent force of 3000N is applied to position of the battery package to simulate the force of the battery package. An equivalent force of 2000N is applied to the end of the telescopic arm of the insulated lift arm to simulate the force of the load. The displacement boundary condition is that the contact surface between the leg and the ground is fully constrained by using Fixed, and then the DOFs of displacement is limited to simulate the actual working condition. The Bonded constraint is adopted at the contact part of the component, and the Bonded constraint is a linear constraint, so that the contact surface does not have tangential sliding and normal separation, and then no large separation deformation occurs between the components during the calculation process. The boundary conditions of the robot are shown in Figure 4.

6. Static Analysis
After the model processing, meshing and boundary constraints are applied to the finite element model of the robot, the solution calculation and post-processing operations are performed to obtain the static simulation deformation of the robot (Fig. 5) and the stress distribution of the robot(Fig. 6).
It can be seen from the static simulation deformation of the robot under working condition that the maximum deformation occurs on the end of the telescopic arm of the insulating lifting arm, and the maximum deformation is about 87.85 mm. It can be seen from the stress distribution of the robot that the overall stress distribution of the robot is uniform, and the material structure generally meets the design requirements. The stress concentration occurs at the joint between the main arm and the upper arm, and the maximum stress is 203.33 MPa, as shown in Fig. 7. The material of the joint between the main arm and the upper arm is Q345, and its yield strength is 345 MPa. The calculated maximum stress is much smaller than the yield strength. And then the structural design and material properties are all meet the working requirements.

7. Modal Analysis with Prestress
Prestressed modal analysis of the robot based on static analysis. The finite element model, mesh and boundary conditions of the robot are unchanged. The robot is solved and post-processed after proper pre-processing. The first mode to sixth mode are extracted in the solution process. The low-order vibration frequency is shown in Table 1, and the corresponding vibration modes are shown in Fig. 8.

| Modal Order | Vibration Frequency (Hz) |
|-------------|--------------------------|
| 1           | 5.96                     |
| 2           | 10.57                    |
| 3           | 13.06                    |
| 4           | 15.21                    |
| 5           | 24.25                    |
| 6           | 29.33                    |

Figure 5. The static simulation deformation of the robot

Figure 6. The stress distribution of the robot

Figure 7. The stress concentration part
Figure 8. The corresponding vibration modes

It can be seen from the Table 1 and Figure 8:

The first order vibration frequency is 0.51 Hz. The vibration performance is rotating vibration and pitching vibration before and after around the horizontal axis of the robot. The telescopic arm end of the insulated lifting arm is the largest vibration part.

The second-order vibration frequency is 0.61 Hz. The vibration performance is rotating vibration left and right around the horizontal axis of the robot. The telescopic arm end of the insulated lifting arm is the largest vibration part.

The third-order vibration frequency is 1.49 Hz. The vibration performance is rotating vibration left and right around the vertical axis of the robot. The front leg contacted with the ground is the largest vibration part.

The fourth-order vibration frequency is 1.73 Hz. The vibration performance is the insulating lifting arm swings to the left and right around the vertical axis of the rotating platform. The telescopic arm end of the insulated lifting arm has the maximum vibration displacement.

The fifth-order vibration frequency is 1.84 Hz. The vibration performance is the upper arm of the insulating lift arm and the telescopic arm pitching vibration up and down. The end of the telescopic arm of the insulating lifting arm has the maximum vibration displacement.

The sixth-order vibration frequency is 4.83 Hz. The vibration performance is the insulating lifting arm swings to the left and right around the vertical axis of the rotating platform. The ear plate of the telescopic arm of insulated lifting arm is the largest vibration part.
It can be seen from the preload modal analysis that the low-order vibration frequency of the robot is between 0.51 Hz and 4.83 Hz. The main vibration is the vibration of the insulated lifting arm. The vibration frequency of the driving motor is 93.3 Hz, which is much larger than the low-order vibration frequency of the robot. The vibration of the drive motor has little effect on the dynamic characteristics of the robot under working conditions, and the robot has good stability during operation.

8. Conclusions
The finite element analysis of the robot under working conditions is conducted to obtain the stress distribution and stress concentration part of the robot in this paper. By comparing the maximum stress part of the robot with the material properties, the conclusion that the material performance meets the requirements is obtained. And the rationality of the robot structure design is verified. The vibration of the robot under the working condition shows the vibration performances are most the main body of the robot. The maximum position of the vibration is mostly the end of the telescopic arm of the insulated lifting arm. The comparison of the low-order vibration frequency of the robot and the vibration of the driving motor shows that the robot has good dynamic characteristics under the action of the drive motor.

Acknowledgments
This work from the project of Technology Research and Demonstration Application of Live Working Robot for Substation Equipment is supported by the Key Research and Development Plan of Shandong Province in 2017(2017CXGC0918).

References
[1] X Zhang, Rh Huang, etc.(2017). Development of the Maintenance Robot with Electrification Used in Substation. In International Conference on Mechanical, Control and Computer Engineering. Harbin, pp.30-33.
[2] Z Pan(2004). Finite Element Analysis and Applications. Tsinghua University Press, Beijing.
[3] X Dong, Jj Su, etc(2016). Finite element analysis and vibration control of the Substation Equipment Water Washing Robot with Hot-line. International Conference on Applied Robotics for the Power Industry. Jinan pp:1-4.
[4] X Dong, Zc Zheng, etc(2014). Modal Analysis of the Line Inspection Robot's Guide Platform, Applied Mechanics and Materials, Vol.685, pp 265-270, 2014
[5] X Zhang, Rh Huang, etc(2016). Finite Element Analysis and Vibration Control of the Substation Charged Maintenance Robot. International Conference on Applied Robotics for the Power Industry, Jinan pp:13-16.
[6] Sg L, X Zhang, R Huang etc(2018). Optimization Design of the Maintenance Robot with Charged Used in Substation, Huhhot pp:141-144.
[7] X Dong, Jx Li, etc(2019). Finite Element Analysis of Mobile Chassis for the Maintenance Robot with Charged Used in Substation under Idle Condition, IOP Conference Series Earth and Environmental Science, Taiwan, Volume 233 pp:1-5