Finite Element Analysis Based on Virtual Material and Experimental of Vacuum Chamber

Yongling Fu¹,a*, Zeqi Wang¹,b, Wanguo Li¹,c

¹School of Mechanical Engineering and Automation, Beihang University, Beijing, China
*aemail: fuyongling@buaa.edu.cn, bemail: wangzeqi505@buaa.edu.cn, cemail: lwg@buaa.edu.cn

Abstract: Electron beam imaging system plays an important role in chip defect detection, so optimizing its dynamic performance is crucial. To understand the vibration characteristics of the electron beam imaging system, a reasonable finite element model is established. The simulation results show that the natural frequencies of the model adding virtual material layer are more accurate than bounded, but the local mode caused by the virtual material layer needs to be eliminated. The error of this method is within 10%, which verifies the accuracy of virtual materials in large assemblies. Our research promotes the development of the chip inspection technology.

1. Introduction

The electron beam imaging system is one of the core systems of the high-precision chip inspection workbench, and external vibration interference directly affects the working reliability and detection accuracy of the chip inspection workbench. The main structure of the electron beam imaging system is a vacuum chamber. In order to explore its vibration characteristics, modal analysis is required.

Modal analysis can evaluate the dynamic characteristics of existing structures in practical engineering applications and provide design guidance for avoiding resonance[1]. With the development of computer technology, digital simulation based on the finite element analysis has gradually matured, and modal analysis based on finite element has also become an important method of modal analysis[2].

The joint refers to the whole of the mating parts and their contact surfaces in the mechanical structure[3]. The error of the joint model is also the main source of the error of the mechanical structure model[4]. Establishing a suitable joint model for finite element simulation calculation has become a research hotspot. The finite element model of the joint based on equivalent virtual materials is high-precision and convenient for computer simulation calculation. So, it has been widely used in finite element modal analysis in recent years.

We use the equivalent transversely isotropic virtual material to model the bolted joints in the vacuum chamber, so as to obtain the finite element model of the vacuum chamber. In particular, removing the local mode caused by the virtual material layer is required. The correctness of the model is finally verified by the results of experimental modal analysis. This paper provides a basis for reducing the vibration interference of the electron beam imaging system and improving its imaging accuracy. It can also verify the accuracy of the virtual material in complex assemblies.
2. Finite element modal analysis of vacuum chamber

We use SolidWorks to build a three-dimensional model of the vacuum chamber, and then import the model into ANSYS Workbench for finite element simulation modal analysis. We establish two finite element models for modal analysis. One with virtual material, which needs to add a 1 mm virtual material layer to the two key surfaces, as shown in Figure 1, and the other without virtual material, whose contact surface is bonded. In equivalent transversely isotropic virtual material, the Poisson ratio in each direction is 0. Different mating surface junction models are determined by four variables: the elastic modulus of the isotropic axis $(x$ and $y)$ $E_{x/y}$, the elastic modulus of the symmetry $(z)$ $E_z$, shear modulus $G$ and density $\rho$ [5].

![Figure 1 The virtual material layer](image1)

In the simulation, the mesh size is limited to not more than 5 mm. The model with virtual material layer is divided into 112486 nodes and 57083 elements. And the model without virtual material layer is divided into 107708 nodes and 56668 elements. The meshing result is shown in Figure 2.

![Figure 2 Meshing result of the vacuum chamber](image2)

Virtual material for modeling is equivalent to reducing the stiffness of the model, therefore the natural frequencies of each mode are lower. The specific results are shown in detail in Table 2 below.

In the finite element simulation, the virtual material can better reflect the stiffness characteristics of the contact surface, but the geometry that does not exist in the physical model emerges when adding virtual material. Due to the large area and thin thickness of the virtual material layer, it is very easy to produce local modes during finite element simulation. Figure 3 shows the second order bending mode results with the virtual material layer. The vibration on the vacuum chamber of these two modes is basically the same, and both are the second order bending of the vacuum chamber cover, which is caused by the local modal generated at the virtual material layer. It is necessary to compare with the finite element model without virtual material, retain the mode with the same mode shape and lower natural frequency, and eliminate the false mode caused by the virtual material layer.
3. Experimental modal analysis of vacuum chamber

The test equipment used in the modal experiment is shown in Table 1. The force hammer is used for excitation, the three-way acceleration sensor is used to pick up the response signal, and the four corners of the vacuum chamber are supported by four passive isolators, which can be approximated as a free state. Choose 60 positions to be measured on the outer surface to describe the general shape of the vacuum chamber.

| Equipment       | Brand | Model       |
|-----------------|-------|-------------|
| Data collector  | LMS   | SCADAS      |
| Force hammer    | B&K   | B&K 8848   |
| Accelerometer   | PCB   | 356A16      |

Calculate the Sum function and modal indicator function (MIF), and obtain the corresponding modal pole steady state diagram. Obtain the first four natural frequencies and mode shapes of the vacuum chamber.

The modal assurance criterion (MAC) evaluates the correlation between two modal vectors. The MAC value usually evaluates the quality of the experimental results. The lower MAC value means the irrelevant between two vectors. It can be seen from Figure 5 that the MAC values on the diagonal are all 100%, and the values on the off diagonal are all less than 20%. This result indicates the modes are independent of each other and the experimental results are reliable.
From the data in Table 2, there is a large error between the experimental and simulation results in the low-order modes when the contact surface is bonded. When adding virtual material to the key joints, the error can be greatly reduced to 10% or less.

Table 2 Experiment and simulation natural frequencies

| Order | Experiment natural frequencies/Hz | Bounded connection natural frequencies/Hz | Bounded connection errors | Virtual material natural frequencies /Hz | Virtual material errors |
|-------|-----------------------------------|-------------------------------------------|--------------------------|-----------------------------------------|------------------------|
| Mode 1 | 323.38 | 484.85 | 49.9% | 348.47 | 7.8% |
| Mode 2 | 488.73 | 683.73 | 39.9% | 506.67 | 3.7% |
| Mode 3 | 636.98 | 706.77 | 10.9% | 573.42 | -9.9% |
| Mode 4 | 809.87 | 802.45 | 0.9% | 776.07 | -4.2% |

The comparison of the modes of each order is shown in Table 3. The first mode is the first order bending of the vacuum chamber cover; the second mode is the second order bending along the short side; the third mode is the second bending along the long side; The fourth order mode is the first order bending of the entire vacuum chamber. The corresponding relationship of each mode shape can be clearly obtained through several relatively large points in the wireframe. Intuitively, the simulation modal shapes correspond well to the experimental results.

Table 3 Comparison of models’ mode shapes

| Order | The experimental mode shapes | The theoretical mode shapes |
|-------|------------------------------|-----------------------------|
| Mode 1 | ![Mode 1 experimental shape](image) | ![Mode 1 theoretical shape](image) |
4. Conclusion
In this paper, we carry out the finite element modeling of the vacuum chamber of the electron beam imaging system and compare the difference between whether to add the virtual material to model the fixed joint surface. Then we perform experimental modal analysis on the vacuum chamber by the LMS Test.lab vibration test system. Through the comparison of the experimental results and the simulation results, we find that the finite element model of the virtual material will produce some local modes, but the error of the first four natural frequencies does not exceed 10%. To a certain extent, the accuracy of using the equivalent transversely isotropic virtual material to model large assemblies is also verified. This result provides a basis for reducing the vibration of the electron beam imaging system and improving the accuracy of the system.

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