International Journal of Control and Automation
Vol.7, No.8 (2014), pp. 317-324
http://dx.doi.org/10.14257/ijca.2014.7.8.29

Study on the Junction Surface Method of Heavy Machine Tool based on Similarity Theory

Ren Sheng-le*, Cheng Tian-yu and Dai Ye

School of Mechanical & Power Engineering, Harbin University of Science and Technology, Heilongjiang Harbin 150080, China
**renshengle@163.com*

Abstract

Junction surface characteristics is one of the many factors influencing the performance of machine tool. It is also a major source of machine tool contact stiffness and damping. Study on the junction surface characteristics of this machine is very important to improve the performance of the machine and the machine structure optimization. According to the similarity theory, this paper will small guide rails are used as scale model, research on small rail junction surface characteristics and combining the conclusion extended to heavy machine tool surface. This paper from the geometric similarity and dynamic similarity surface on the comparative analysis of the small rail and heavy machine tool guide rail with two aspects of similarity theory, after verification, proof of small guide surface and heavy machine tool guide surface similarity.

Keywords: *junction surface; similarity theory; heavy machine tool; characteristic analysis*

1. Introduction

Rails is an affordable, fixed, guide mobile device. Longitudinal grooves or ridges on the surface of the rails, for guidance, fixed machine parts and so on. At the same time, guides can assume a certain level of torque and achieve high precision linear motion in the case of heavy load.

Guide joint surface are important factors affect the performance of machine tool, the guide rail is used to support and guide the moving parts, according to the given direction do reciprocating linear motion. The continuous expansion of power industry, automotive and other industries, the demand for linear guide will be rapid growth. Linear guide industry has huge development potential in the future, thus guide rail performance good and bad quality directly influence the development of relevant industries [1].

Linear guide has two basic components: one fixed component is responsible for guiding and the other is a mobile device. Various function module assembly into linear guide. Through the combination of fixed or relative motion, these components implement function of position, walking and carrying capacity. In engineering, rail joint surface simple static design and experience have been unable to meet the actual requirements. Only consider the basis of vibration reduction cannot accurately reflect the dynamic response of integration under the effect of vibration. Modal analysis is an effective method for the structure dynamic characteristics [2]. Modal analysis can get all orders of main modal parameters in the frequency range, predict the guide rail junction in the actual vibration response under the action of the various source and guide the guide rail structure optimization design.

Because of heavy machine tool has the characteristics of large size, heavy load and partial load large, experiments were conducted in a real machine to get the data becomes very

ISSN: 2005-4297 IJCA

difficult and long time. By using the combination of similarity theory, this paper proposes a heavy duty machine scale model, also known as small linear guide, are analyzed. The method is extended to the heavy duty machine tool and draw the following conclusion.

We get the static stiffness, the top five bands of the natural frequency and damping ratio of small linear guide surface by using test methods. Through the analysis of dynamic performance of rails, simulation of junction surface characteristics, we can understand the impact of junction surface characteristics on the overall structure of the component. Finally, small rails analysis of the results compare with experimental results to verify the validity and accuracy of the analysis method.

2. Theoretical Study on Joint Surface

2.1. Contact Theory

The contact asperity by elastic deformation of the elastic strain energy stored produce joint stiffness [3]. These micro convex body has the characteristics of self affine type [4]. Majumdar and Bhushan [5] put forward the famous MB contact model. The contact relation is simplified as a rigid plane and a plane contact with numerous micro convex body.

Guide joint surface is a typical mechanical structure. Guide rail and slide block has the quality and elasticity, so the surface will produce vibration in the work. The vibration state can be composed of parameter mathematical model to calculate the expression. One of the most important parameter is the vibration damping of structures. Vibration damping coefficient equation for [6]:

$$\ddot{x} + 2\left(\frac{c}{2m}\right)\dot{x} + \frac{k}{m}x = 0 \tag{1}$$

Because of the existence of joint surface, the continuous physical machine structure change to a complex discontinuous structure with damping parameters. Related research shows that the contact rigidity of joint surface accounts for 60% to 80% [7] of overall stiffness of machine tool. And the contact damping results from contact surfaces accounts for more than 90% [8, 9] of the whole machine tool. So the contact rigidity and contact damping simultaneously exist in joint surface, and the two characteristics had a tremendous impact on the machine performance. References 1 simplifies contact relationship of joint surface to a kind of contact between micro convex body and plane, and presents the dimensionless stiffness model of the joint surface.

$$K_n^* = \frac{2}{\sqrt{\pi}} g_1(D)\varphi^{\left(\frac{2-D}{2}\right)^2} A_r^{*\frac{D}{2}} \square \left[\left(\frac{2-D}{D}\right)^{\frac{1-D}{2}} - a_c^{*\frac{1-D}{2}}\right] \tag{2}$$

2.2. Similarity Theory

Similarity theory is the theory method described works of similar phenomena. The relationship between the theory through the study of similar engineering problems, such as the model and the calculation expression. Similar theory use similarity relation mathematical model to determine the unknown with the known data.

Fixed structure in the elastic range according to the structural types and materials given damping ratio. The value given is the viscous damping ratio of equivalent structure. The loss factor of the same material is the same [10]. The damping ratio of structural damping and critical damping coefficient. So the damping ratio is dimensionless [11]. From the theory, structure similar structural materials of the same damping ratio as constant and similar approximation for $S_\zeta=1$.

In the research on dynamic characteristics of structure, mainly to keep the elastic restoring force and inertia force of the similarity, and obey the similarity criterion:

$$S_t^2 = S_l^2 S_\rho / S_E \tag{3}$$

Where S_t represents the two models at the time of the similarity coefficient, S_l represents the geometric similarity coefficient, S_ρ and S_E represent the density and elastic modulus of the material. If using the same material at the same time range of similar structure, their dynamic similarity relation depends entirely on the geometric similarity[12]. The similarity relation about conclusions of test model can deduce to heavy machine tool combining surface.

According to the mentioned dimension analysis method, the relationship between various physical quantities can be obtained structural dynamic problems involved:

$$f(\sigma, l, E, \rho, t, u, v, a, g, w) = 0 \tag{4}$$

l, E, ρ respectively represent the physical size, the elastic modulus and density of materials. u, v, a, w respectively represent the dynamic parameters of displacement, velocity, acceleration and angular frequency, g for the acceleration of gravity, σ for structure dynamic stress.

We choose the physical quantity of three independent dimensional structure of l, E, ρ, which the elastic modulus of E with the same stress σ dimension $E/\rho l$. has accelerated the dimension. Dimension of other physical quantities can be obtained according to the mathematical transformation of these three independent between physical quantity. According to the similarity of second law:

$$f\left(\frac{\sigma}{E}, \frac{t}{l\sqrt{\rho/E}}, \frac{u}{l}, \frac{v}{\sqrt{E/\rho}}, \frac{a}{E/\rho l}, \frac{g}{E/\rho l}, \frac{\omega}{l^{-1}E^{0.5}\rho^{-0.5}}\right) = 0 \tag{5}$$

Let C be a similar proportion of the various physical quantities can obtain the relationship between dynamic function similar to each of the similar constant C:

$$C_\sigma = C_E, C_t = C_l C_E^{-1/2} C_\rho^{1/2}, C_u = C_l, C_v = C_E^{1/2} C_\rho^{1/2} \tag{6}$$

$$C_a = C_E C_\rho^{-1} C_l^{-1} = C_g, C_\omega = C_E^{1/2} C_\rho^{-1/2} C_l^{-1} \tag{7}$$

If the test track materials and heavy machine tool guide surface made of the same material will make $C_l=1$,it is difficult to study the dynamic do complete similarity by using the similarity theory[13]. There is, according to the characteristics of dynamic analysis:

$$Cauchy\ value = \frac{\rho v^2}{E} \tag{8}$$

$$Froude\ value = \frac{v^2}{gl} \tag{9}$$

Cauchy and Froude maintain consistency in kinetic analysis model and real structure. Rail materials used in this experiment is GCr15. Its density is about 7.8e3 kg/m3. The heavy machine tool guideway density is about 7.4e3 kg/m3. The two almost equal can ensure consistent Cauchy constant. When the stress caused by the gravity effect than the inertial force generated stress is much less time, effect of Froude inconsistency brought too small. Therefore this paper ignore gravity effect, is not considering the effect of the Froude constant to complete the simulation of the heavy machine tool surface.

3. Experimental Study on Surface Characteristics

The static stiffness of the rail surface is an important parameter which directly impact on work performance and accuracy of machine tools. Joint surfaces often subjected to face pressure loads on the job, so the key of measurement is compressive stiffness of the joint surfaces. Experimental project specific as follows: Exert force on the slider guide assembly; Changing the power output force and measurement the downward displacement of joint surfaces; Record results and calculate to get the equivalent stiffness of joint surfaces. Figure 1 is required for the static stiffness test equipment.

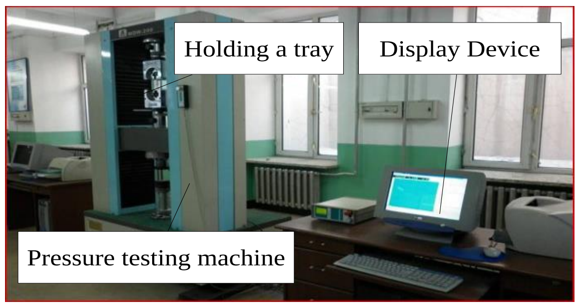


Figure 1. Pressure Testing Machine

This experiment adopts the method of frequency response function. According to the mechanical structure of the relationship between the input and output response to identify modal parameters. The principle is to impose an incentive for mechanical structure and measure the response of the structure at a point, and then use the frequency response analysis software analysis relevant data, through the modal parameters is obtained by modal parameter identification method.

Table 1. Melting Points and Elemental Analyses

Normal pressure/ KN	20	22	24	26	28	30	32	34
Measuring displacement/ mm	0.10	0.12	0.13	0.14	0.16	0.17	0.18	0.19

The experiment support at the bottom of the guide rail component and fixed position of slider, using the modal analysis test chamber, data acquisition and the modal analysis software. Place where the slider test acceleration sensor to measure the structural response. Acceleration sensor measured signal after filtering charge enlarged transmitted to the computer terminal, and the installed inside a computer terminal of the modal analysis software to calculate the modal parameters of the system structure. Laboratory equipment as shown in Figure 2.

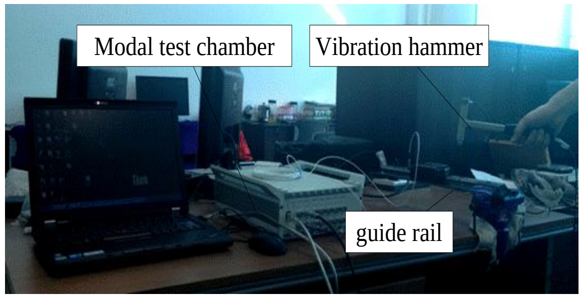


Figure 2. Modal Instruments

Table 2. Guide the First Five Steps Inherent Frequency

steps	1	2	3	4	5
Frequency/Hz	1540.3	2401.6	3875.3	4052.3	4311.7
damping ratio %	1.45	1.59	1.01	1.37	1.71

The location of the workbench has certain effects on dynamic characteristics of structure. Slider work in different position of the model is set up to reflect guide in the actual work condition. This is consistent with the guide role conditions in the work load and the biased load.

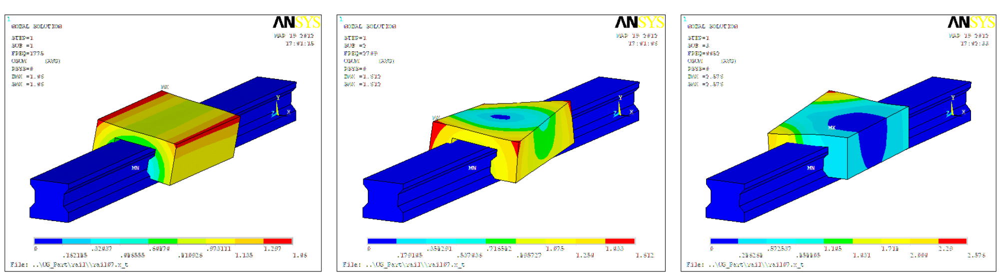
When dealing with rails models, guide rail and slide block selected mesh with 10 grid nodes tetrahedron element. The unit of ten nodes have along the x, y, z direction of the degrees of freedom. Tetrahedron unit is perfect for dividing irregular 3 d model because it has the displacement characteristics of quadratic function.

Mesh model is done. The displacement constraints imposed on one end of the model according to the guide rail slider component test installation. Enter the solving module and select damping method. Then solve the parameter setting and extract the structure of the top 5 steps modal.

Table 3. Results of the Top 5 Steps Modal in the Middle

steps	1	2	3	4	5
Frequency/Hz	1763.4	2692.3	4439.9	4694.2	4898.2

When the slider in the middle position, the first five order modal shape as shown in Figure 3:



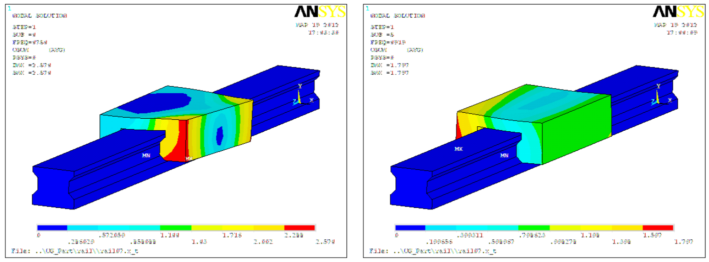


Figure 3. The Slide in the Middle Position Corresponding to the First Five Modes

Modify the relative guide rail sliding block position expression to update the model in a CAD system. We can get the slider on the edge of the geometric model, and the model is imported into ANSYS again. The new model use macro command to mesh subdivision.

Modify Z-axis coordinate parameters in the macro command to the edge slide position of the model parameters [14]. Follow the same process for modal analysis of the model and get the top five steps mode as shown in Table 4.

Table 4. Results of the Top 5 Steps Modal in the Edge

steps	1	2	3	4	5
Frequency/Hz	1676	2508.7	3933	4154.3	4478

When the slider at the edge position, the first five order modal shape as shown in Figure 4:

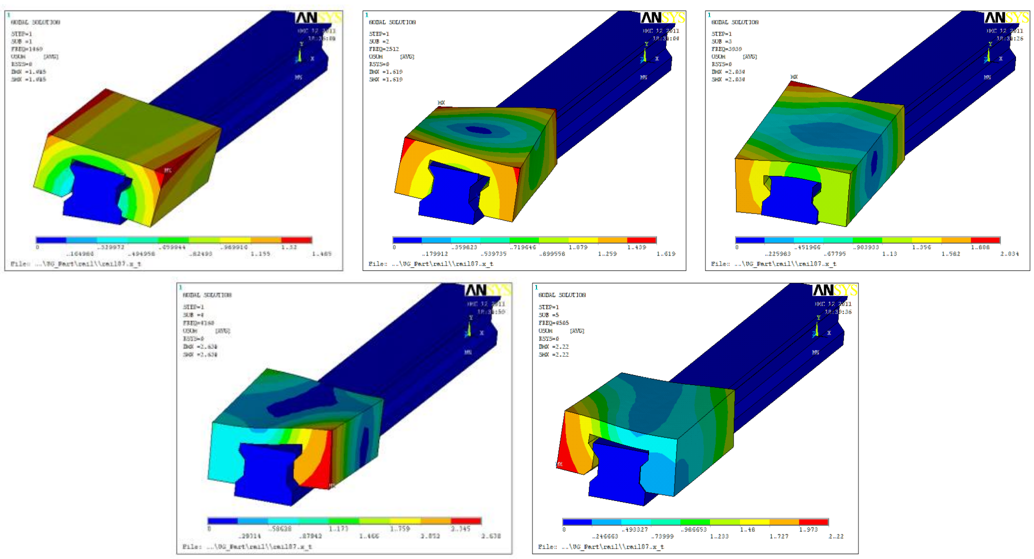


Figure 4. The First Five Modes Corresponding to the Slider in the Edge

4. Theoretical and Experimental Comparison

Compare twice of theoretical analysis to get the frequency values and the experimental analysis of frequency values.

Table 5. When the Slider at the Middle Position, Comparing the Theoretical Results with the Experimental Results

Steps	test frequency/Hz	Simulation of the middle frequencies/Hz	Test and intermediate position error%
1	1540.3	1763.4	12.65
2	2401.6	2692.3	10.80
3	3875.3	4439.9	12.72
4	4052.3	4694.2	13.67
5	4311.7	4898.2	11.97

Table 6. When the Slider at the Edge Position, Comparing the Theoretical Results with the Experimental Results

Steps	test frequency/Hz	Simulation of edge frequencies/Hz	Test and edge position error%
1	1540.3	1676	8.10
2	2401.6	2508.7	4.27
3	3875.3	3875.3	4.01
4	4052.3	4154.3	2.46
5	4311.7	4478	3.71

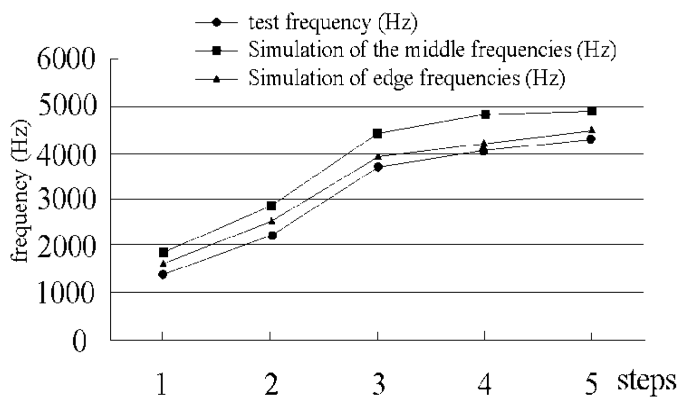


Figure 5. Comparison of Test Results and the Two Simulation Results

We can see from Table 5, there are certain error analysis results with the experimental results. But the error value is stable, the results of two kinds of trend are also the same. According to the relative error formula:

$$\varepsilon = \frac{|\Delta x_1|}{x_0} \times 100\ \% = \frac{|x_1 - x_0|}{x_0} \times 100\ \% \tag{10}$$

The overall error of the average percentage is 10.80%~13.67%. While the table 6, the results of simulation and experiment result error maintained at 2.46%~ 8.10%. The modal test of guide joint surface is a direct means of verifying finite element modeling and modal analysis accuracy. Theoretical calculation results and the dynamic testing results are basically identical, so the guide joint surface model is reliable.

5. Conclusion

We regard the small guide as a scale model of heavy machine tool. Combination with the similarity theory from the geometric similarity comparative and analyze the small rail and heavy machine tool. When large and small linear guide rail joint surface morphology consistent, the small guide surface with large binding in the geometry are similar. The small rail and heavy machine tool guideway have slightly difference in material density and elastic modulus. When gravity and material micro differences is neglected, the scale model and heavy machine tool satisfy the similarity conditions in kinetics. Based on the similarity of two guide rails, the analysis process and method of small guide surface characteristics are fit for heavy machine combining surface. So the method can be used for heavy machine tool combining surface characteristics analysis and prediction. The guide joint surface correctly established provides a reliable basis analysis of dynamic characteristics of composite structures. This article has carried on the small guide modal stiffness test. The actual work of junction surface also has the load characteristics such as high torque and overturning force. Then you can design related experimental to simulate these special working load.

Acknowledgements

The research is supported by National Natural Science Foundation Project (51105120), Key Project Fund of Ministry of Education (210058), Post-doctoral funding projects in Heilongjiang province (LBH-210115).

References

[1] S. Jiang, Y. Zheng and H. Zhu, “A Contact Stiffness Model of Machined Plane Joint Based on Fractal Theory”, Journal of Tribology, vol. 1, no. 132, **(2010)**.
[2] Y. Jinmin, “Fractal Model for Normal Dynamic Parameters of Joint Surfaces. Journal of Xi’an Jiaotong University, vol. 9, no. 43, **(2009)**.
[3] A. Majumdar and B. Bhushan, “Fractal model of elastic-plastic contact between rough surfaces”, ASME Journal of Tribology, vol. 1, **(1991)**, pp. 1-11.
[4] A. Majumdar and B. Bhushan, “Role of fractal geometry in roughness characterization and contact mechanics of surfaces”, ASME Journal of Tribology, vol. 2, **(1990)**, pp. 205-216.
[5] M. dalenbring, “Damping function estimation based on measured vibration frequency responses and finite-element displacement modes”, MSSP, vol. 4, no. 13, **(2012)**.
[6] C. Shuqian, “Vibration modal analysis of structures”, Tianjin University Press, Tianjin, vol. 3, **(2011)**, pp. 107-111.
[7] K. F. Moustafa, “Shaking table testing and analysis of two-column bents”, 13WCEE, Canada, **(2004)**.
[8] J. Crawford, “Create a hardpoint on an area using existing keypoints”, **(2009)**.
[9] B. Nour Omid and R. W.Clough, “Dynamic analysis of structures using Lanczos co-ordinates Earthquake Engineering and Structural Dynamics”, vol. 12, **(1984)**, pp. 565-577.
[10] Z. Ping, “Defines of Element Attributes in Building Computer Models in ANSYS”, Modern Electronic Technique, **(2003)**.
[11] Z. Zhaohui, “ANSYS 8.0 structure analysis and Example analysis”, Machinery Industry Press, vol. 3, **(2005)**.
[12] U. Zwiers, “First Steps in Vibration Analysis Using ANSYS, **(2007)**.
[13] S. Moaveni, “Finite element analysis: theory and application with ANSYS”, Beijing Publishing House of Electronics Industry, **(2011)**.
[14] ANSYS INC. Release 11 documentation for ANSYS, commands reference, **(2007)**.

