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Research Article

Guideway Joint Surface Properties of Heavy Machine Tools Based on the Theory of Similarity

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Abstract: In the process of Heavy NC machine tool design, the combination of static, dynamic characteristics directly determines and influences stiffness, damping, machining precision and work efficiency, Therefore the research on the combination of the characteristics become extremely important to the success of machine tool design. This study mainly studies the dynamic and static characteristic parameters of heavy machine tool guide way joint. And put forward a practical machine tool combining surface analysis method according to the experimental verification. How to obtain the analysis and test of the dynamic parameters to the combination is introduced. It is presented that small linear guide as a scale model based on similarity theory. And make a research on the static and dynamic characteristics of small guide joint and the conclusion extended to heavy machine set of faces. And the conclusion is extended to the heavy machine set of faces. It is introduced the spring damping unit of combined surface characteristics simulation during a small test about guide way dynamic performance analysis. Thus it can more effective simulate influence of combination of surface characteristics to components of the overall structure. The study analyze the dynamic performance of machine tool bed rail section by the verification and treat extraction of the first five modes as the analysis and forecast of the models of guide-way joint dynamic performance. The results can be used as reference data about structure and design of the machine tool due to the similarity principle and error range.

Keywords: Characteristic parameters, guide way joint surface, similarity theory, spring damping unit

INTRODUCTION

Heavy machine tool is called the "machine tools" of manufacturing industry, not only reflects the ability and level of manufacturing in China, but also concerning national economic security and national defense as industrial base (Bai, 2011). At present, the projects that china has begun, without exception, are dependent on heavy equipment, such as the large hydropower station, the nuclear power plant project, the "big aircraft" project, the space exploration project and so on. So the performance quality of heavy machine directly influences the related industrial development.

Combined interface of machine tool is one of the most important factors which influence the performance of heavy machine tools. Like the other machine tools, heavy machine tools are assembled by all sorts of function module. These components or component complete orientation, walk and carrying function by mutually assembling between fixed or combined interface in relative motion. These fixed combined interface or in relative motion have significant effect on the performance of mechanical equipment. And the immense existence of combined interface in large heavy equipment is owing to its own characteristics. Heavy machine is characterized by large- dimension, high self-weight, great loading capability and big inertia, especially the larger size and its own weight make its own structure special (Dalenbring, 1999).

Because the size of the heavy machine tools is larger and prototype manufacturing has high costs, it becomes very difficult even cannot be implemented to do related characteristics analysis test in the actual equipment directly. So based on similarity theory, we choose small linear guide rail as the scale model of large joint surface and this study puts forward a kind of simulation analysis method applied to the joint surface of heavy machine tools and use the test data of the small linear guide rail to verify the validity of the method.

THE CHARACTERISTIC PARAMETERS OF JOINT SURFACE

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% (Zhang

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and Shuhua, 2003) of overall stiffness of machine tool. And the contact damping results from contact surfaces accounts for more than 90% (Wang *et al.*, 2004; Su *et al.*, 2011) 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:

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

Type (1-1)

$$K_n^* = \frac{K_n}{E\sqrt{A_a}}$$

$$g(D) = \frac{D^{\frac{2-D}{2}} (2-D)^{\frac{D}{2}}}{1-D}$$

$$A_r^* = \frac{A_r}{A_a} \quad a_c^* = \frac{a_c}{A_a} = \frac{G^{*2}}{(k\varphi/2)^{\frac{2}{D-1}}}$$

$$G^* = \frac{G}{\sqrt{A_a}}$$

Including, Aa for contact area, Ar* for dimensionless real contact area, Ar for real contact area, ac Ji (2010) for critical contact area, G* for lengthwise characteristic parameter. Because the stiffness model which the literature proposed introduces the influence of the distribution domain expansion factor, this model is more close to the truth.

Like the mass distribution of the mechanical structure and elastic properties, damping, a kind of energy dissipate mechanism when mechanical structure vibrate, influences the vibration characteristics of mechanical structure. In general, damping mechanism between joint surfaces can be regarded as the microscopic slip between surface and micro deformation energy storage, etc. The damping caused by surfaces has a great influence on the dynamic performance of machine structure. Since there were no scholars put forward joint surface damping's accurate calculation formula, its acquisition method is from testing.

Characterized by large- dimension, high self-weight, great loading capability and big inertia, especially the larger size and its own weight make its own structure special.

Because the size of the heavy machine tools is larger and prototype manufacturing has high costs, it becomes very difficult even cannot be implemented to do related characteristics analysis test in the actual equipment directly. So based on similarity theory, we choose small linear guide rail as the scale model of large joint surface and this study puts forward a kind of simulation analysis method applied to the joint surface of heavy machine tools and use the test data of the small linear guide rail to verify the validity of the method.

THE APPLICATION OF SIMILARITY THEORY AND THE SELECTION OF SCALE MODEL

This study use similarity theory to guide the model test, to determine the similar degree between "model" and the "prototype". We adopt the equation analysis in the static stiffness of the joint surface. Contact stiffness's expression of contact plane micro convex body can be got by the elastic modulus, spheres radius and displacement which describe its stiffness, the concrete expression for:

$$k_n = 2ER^{\frac{1}{2}}\delta^{\frac{1}{2}} \tag{2}$$

When E_1, E_2 is for modulus of elasticity of two combined part, R_1, R_2 is for radius and δ_1, δ_2 is for displacement, the similarity coefficient of the elastic modulus is for SE = 1, similarity coefficient of slightly convex body's radius is for $S_R = 1$, similarity coefficient of displacement is for $S_\delta = 1$. Take all similar coefficient into the Eq. (3), we can get:

$$K_{n1} = S_E S_R S_\delta * 2E_1 R_1^{\frac{1}{2}} S_1^{\frac{1}{2}} \tag{3}$$

Obviously when the slide rail fringe of heavy machine and experimental guide use the same material, SE = 1 and when surface roughness of the two combine part in the microstructure is the same, $S_R = 1$ and when assume the micro normal displacement δ are equal, stiffness of the two combine part are similar, that is similar index. According to the above equation analysis, the conclusion is that the stiffness characteristics of heavy machine slide rail joint surface and small guide joint surface is similar on the assumption that the microstructure is the same. So when choose the model, we should guarantee the material properties of model is approximate to the material performance of heavy machine tools guide as far as possible.

As to the dynamic performance of joint surface, we can get the relationship between the various physical quantities what common structure dynamics problems relate in the application of the dimension analysis of the second law of similarity theory (Lin, 1958):

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

Including, l, E, ρ is representing the physical size of structure, elastic modulus and density of the materials, u, v, a, w is representing dynamic parameter of the structure, displacement, velocity, acceleration and circular frequency, g for gravity acceleration and σ for structural dynamic stress.

Choose the three independent dimension physical quantities that related to structure, l, E, ρ, elastic modulus of the E is the same to dimension of stress, $E/\rho l$ has accelerated dimension and other dimension of physical quantities can get from the mathematical transformation between the three independent physical quantities. According to the second law of similar:

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

According to the type, If C represents similar percentage of physical quantities and making dynamic function similar, the relationship between each constant C should be:

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

It can be seen from type (6) that $C_E C^{-1}_{p} C^{l-}_{1}$ =1 for gravity acceleration cannot be artificial selection, making the three variables can't be freely chosen. But if the material of test guide rail is consistent with joint surface material of heavy machine tools guide, it will force C l = 1. So it is difficult to make things completely similar using similar methods in researching the dynamics of joint surface. According to the characteristics of dynamic analysis (Chi, 2004):

$$Cauchy\ value = \frac{\rho v^2}{E} \tag{7}$$

$$Froude\ value = \frac{v^2}{gl} \tag{8}$$

Literature [vi] points out that we should guarantee Cauchy and Froude remain consistent between the model and the real structure in the analysis of dynamics.

To sum up, this study selects small linear guide rail (type HGH 35HA) for the experiment. Its material is Cr15 and density is about 7.8 e3 kg/m^3 that is about the same constant as HT200 materials (density is about 7.4 e3 kg/m^3) of heavy machine slide rail of integral casting. We can guarantee the Cauchy constant consistent, but hard to ensure Froude constant consistent. But when the stress caused by gravitational effects much smaller than the stress that the inertial force produced, the impact that inconsistent of Froude constant brings is small (Ji, 2010). Therefore we ignore the gravitational effects, that is to say, we don't consider the impact of Froude constant, thus completing the characteristic simulation of the heavy machine tool joint surface.

Table 1: First five natural frequency result

Steps	1	2	3	4	5
Natural frequency (Hz)	1774.7	2709.3	4452.1	4754.2	4919.2

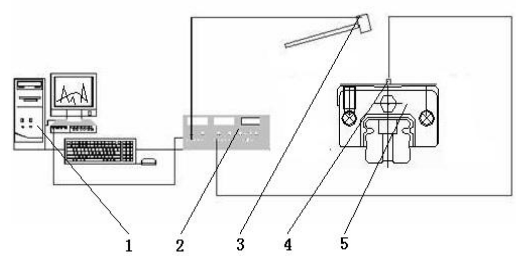


Fig. 1: Experimental program of modal test
1. Computer, 2.Charge Amplifier, 3. Force Sensor,
4. Acceleration Sensor, 5. Guide Rail

THE SIMULATION AND ANALYSIS OF A SCALE MODEL OF THE DYNAMIC PARAMETERS

In this study, the Combine14 cell array is connected with the two surfaces when we build digital model of small guide in the ANSYS environment, to simulate the combination surface simultaneously with the stiffness and damping properties. The corresponding hard point array is established on the side of the guide rail and the top surface and the corresponding surface of slide when modeling. Node are forced to generation in the corresponding position through the control of hard point coordinates, the Combin14 unit is defined by these nodes (Crawford, 1999). According to the spring parallel rigidity formula, Combin14unit stiffness is defined for the contact stiffness value of 1/24 provided by manufacturers which is 7.3N/m, unit of damping parameters are set for steel structure's damping ratio0.02. After applying the corresponding displacement constraint to the model, through Modal solution module, we can get the extraction results of the structure of the first five natural frequencies shown in Table 1.

The results will be used for comparison with experimental results to determine the validity of the simulation analysis method.

The test to obtain a scale model of the dynamic parameter: The dynamic performance of small linear guide which contains binding surface are embodied in the natural frequency of the distribution range and corresponding damping ratio, the study obtain the dynamic performance of small linear guide cantilever mounted with the modal experimental method (Chang and Junwu, 2009). In the test 40 excitation points of small linear guide are selected and numbered. We select a point as the vibration pt acceleration sensor in the vibration pickup point to change into a charge signal and

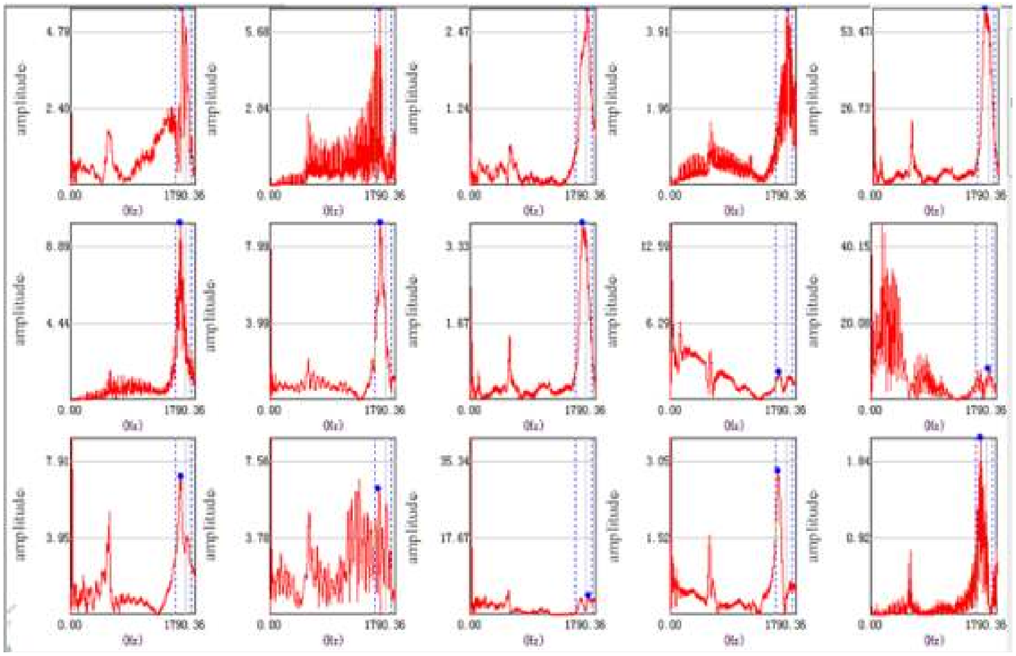


Fig. 2: The data of some monitoring points

Table 2: First five steps of natural frequency

Steps	1	2	3	4	5
Frequency (Hz)	1525.6	2383.9	3784.2	4088.3	4328.7
Damping ratio (%)	1.47	1.61	1.02	1.39	1.77

Table 3: Contrast between simulation result and test result

Steps	1	2	3	4	5
Test Frequency (Hz)	1525.6	2383.9	3784.2	4088.3	4328.7
Simulation F (Hz)	1774.7	2709.3	4452.1	4754.2	4919.2
Error ratio%	14.03	12.03	15	14.01	12.01

then it is input to the acquisition system. The hammer with a force sensor applied step excitation in various excitation points. The excitation signal is used to start the process of data collection and participate in the force measurement method modal. Test principle as shown in Fig. 1.

Strike various excitation point three times, the data is automatic linear average with analysis software, the data of some monitoring points is as shown in Fig. 2.

We can get a small guide rail structure for the first five natural frequencies and corresponding damping ratio by model analysis software for peak search and calculation of residues. The results are shown in Table 2. The experimental data and the simulation data results are compared in Table 3 From Table 3 and Fig. 3, we can see the analysis and the experimental results are obvious errors, the true model is simplified into finite element model ,and the difference of material properties and the simplify generated error, the second is the principle error ANSYS algorithm, but the error value is relatively stable, The trends of two kinds results are much the same, at the same time, the overall average error percentage is 13.42%<15%, so the analysis method in the error of no more than 15% of the required range is effective.

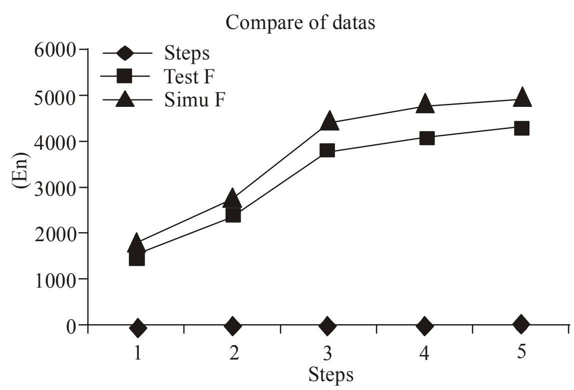


Fig. 3: Contrast between simulation result and test result

THE APPLICATION OF THE METHOD IN THE ANASIS OF HEAVY MACHINE TOOL'S COMBINATION

The simulation analysis method of the combination surface is valid within a certain range of error after the analysis and verification test, this method is applied to the XK2420series CNC boring and milling machine bed part of Lon gmen with the analysis of dynamic characteristics in the passage, thus it provide reference value on the heavy duty machine tool dynamic performance prediction and optimization design. The slide way of the machine tool and a work table surface is similar to a small rail interface; it belongs to the face to face contacting plane linear guide. Because of the Long men milling machine bed body part and Long men frame portion is mounted on a cement foundation, they are connected separately with the ground, so when we

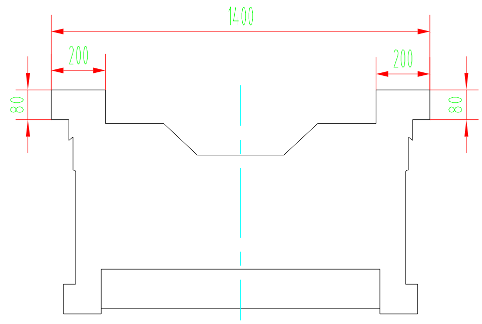


Fig. 4: Sketch of the machine body section

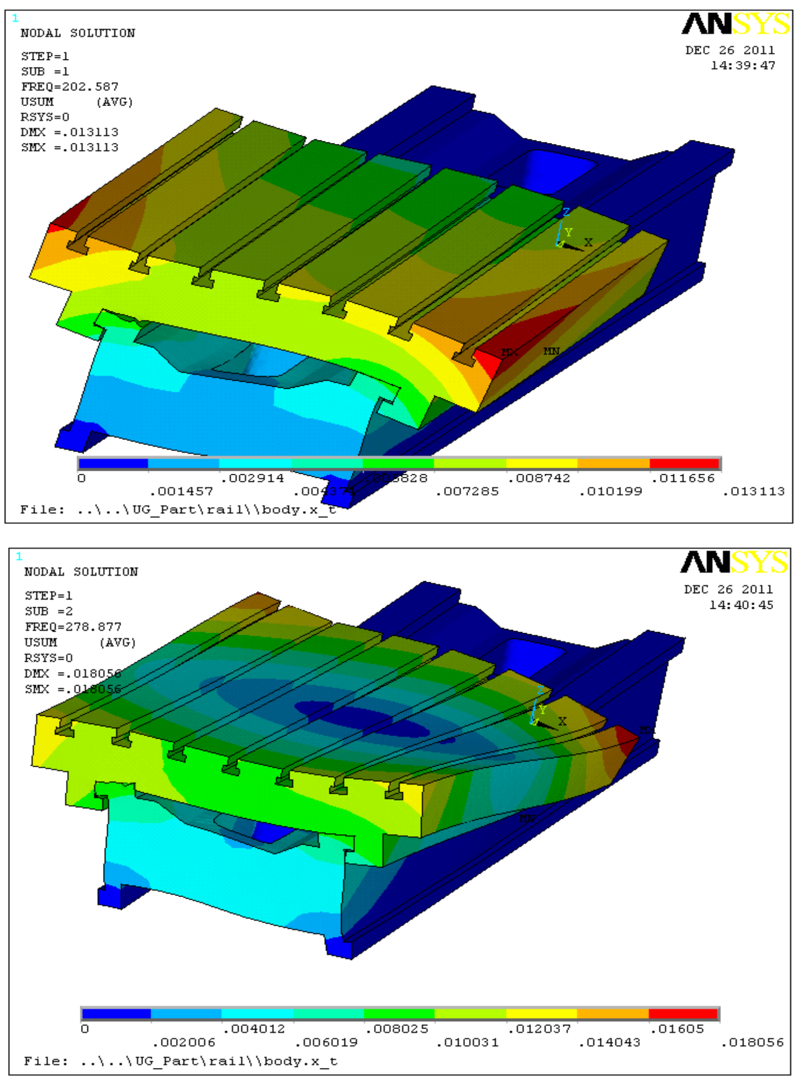
Table 4: First five natural frequency result of the heavy machine tool

Steps	1	2	3	4	5
Natural frequency (Hz)	202.59	278.88	315.75	329.47	367.77

analyze dynamic characteristics separately for bed portion, the influence Long men structure to its dynamic characteristics can be ignored. In the analysis, the fixed displacement constraint is applied to Long men frame and the bed portion of the contact to simulate the actual connection.

During the model building process, taking the follow-up network division and analysis of efficiency into account, regardless of the character that affect the overall kinetics characteristics a little. Reference chart of the size of model is shown in Fig. 4.

The analysis results are shown in Table 4. According to the conclusion of the linear guide test data and the simulation data, dynamic parameters and test data exists deviation with the simulation method in this study and the deviations is in the range of 15%, according to the theory of similarity, the deviation above between the data of the heavy machine tool simulation analysis and the actual outcome should be about 15%, so the allowable deviation in <15% range, the simulation results are valid. At the same time, the first five order modes of the machine tool bed portion is given as shown in Fig. 5.



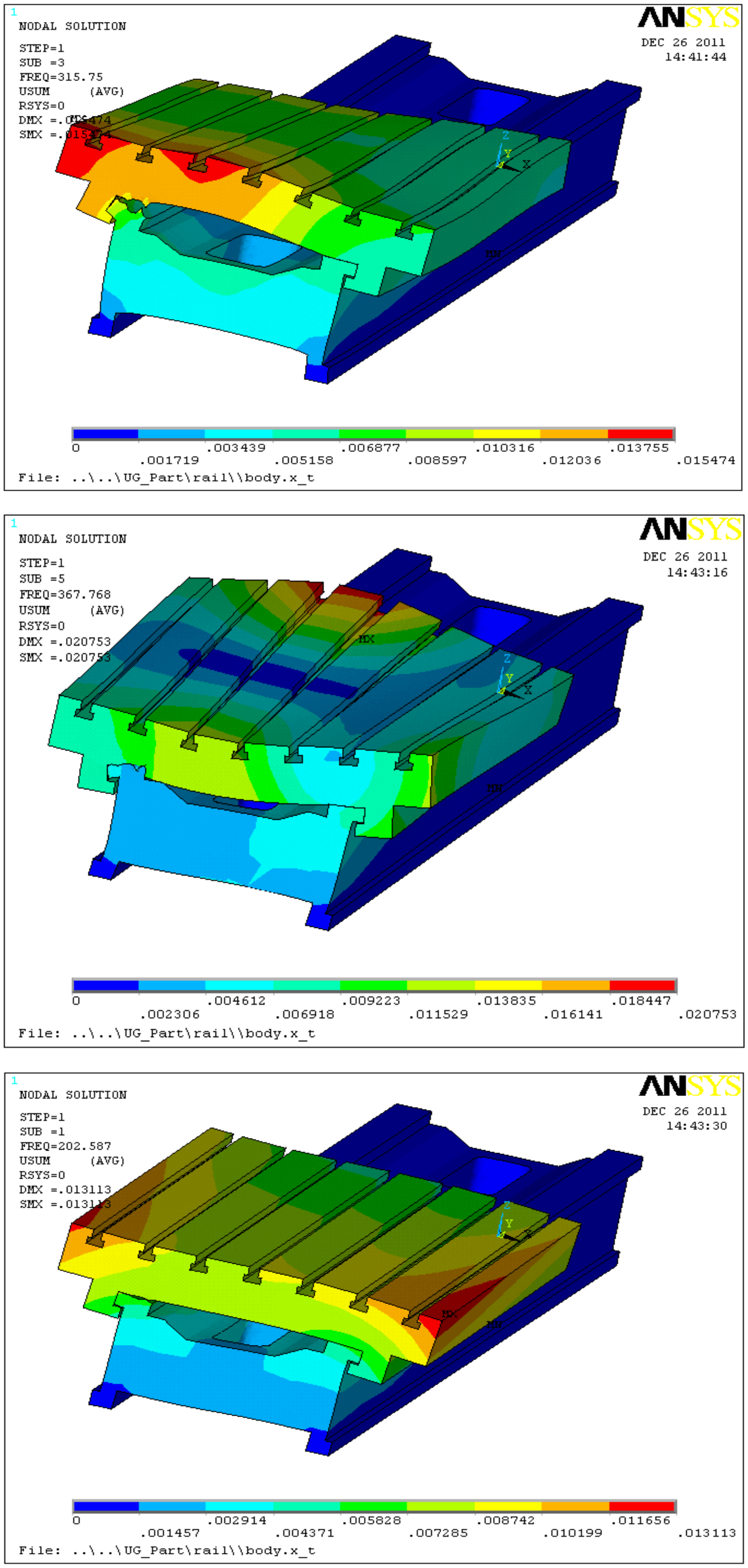


Fig. 5: First five vibration mode

In the study a small linear guide the scale model was select for simulation analysis from the similarity theory perspective according to the heavy machine tools joint dynamic parameter characteristics and simulation method was put forward that simulate the joint stiffness and damping characteristics with two combining surface of spring damping and the method of the reliability and deviation range is validated through the experiment, the result shows that the analysis method is effective in the case of allowable error is no more than 15%, thus we can simulate heavy machine tools joint dynamic characteristics by using the method and it offer reference value for performance prediction of heavy machine tool dynamic.

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