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A METHOD OF IDENTIFYING INTERFACE CHARACTERISTIC FOR MACHINE TOOLS DESIGN

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In order to develop the technology of calculating static and dynamic behavior of a new product during its design period without prototype, an identification method for calculating interface characteristic of mechanical structure system is presented. The paper discusses an optimum algorithm, in which the contact stiffness coefficients are taken as design variables, aiming at minimizing the sum of squares of eigenfrequency differences between finite element modes and their corresponding experimental modes, based on mode shape identification. The corresponding software has been developed. Using the identified parameters from an interface sample composed of one base and two columns, the eigenfrequency of mechanical structure system has been calculated and their accuracy has been verified by testing.

1. INTRODUCTION

In mechanical structure system, there exist contact stiffness and contact damp in the interface of two parts. They have a great effect on the behavior, especially on the dynamic behavior of the whole system. The interfaces often are the weakest chains in the whole mechanical structural system. Therefore, accurate identification of the interface characteristic is a prerequisite for accurately predicating the whole machine's behavior.

In the past decades, many researchers made a great deal of investigation on the functioning mechanism and the characteristic identification of interface [1–4]. Various methods of interface characteristic identification have been put forward, but the accuracy and the validity of the identified parameters are lacking verification, and the behavior of interface has not been fully grasped. In the paper authored by Yu Dejie *et al.* [2], through mode analysis to the mode test results made to the radial drilling machine of Z3025, the natural frequencies and corresponding mode shapes of the machine are obtained. The results show that the rocker arm is the possible part in which the failure occurs, and the weakest point is located in the interface between the rocker arm and the column of the drilling machine. Then, by combining FEM and experimental mode test, the interface characteristic is studied, but the validity of the identified parameters is not discussed.

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The behavior of interface is very difficult to be determined because of the complexity of the factors that affect the interface characteristic [4]. Experimental tests and theoretical analyses show that, in the case of fixed interface, the fundamental factors that affect interface characteristic can be classified into three types:

(1) The form and size of the structure, and the number and distribution of the fixing bolts used for joining two parts.
(2) The materials processing method, and the accuracy and roughness of the interface.
(3) The working status of the interface, such as the pressure distribution and the inter-medium between two joint surfaces.

Factor (1) does not reflect the essential property of the interface. However, the interface does not exist independently. It is very important to eliminate the influence of the joint structure on interface characteristic. The best method is to heighten the accuracy of the Finite Element model for the interface sample. Factor (2) illustrates the essential property of the interface. Factor (3) reveals the working condition of the interface. The last two factors depend on the enterprise production condition, manufacture and assembly status. Therefore, it is possible to make some interface samples according to the product design requirements, identify the characteristic parameters of these samples, and then apply the identified parameters in behavior prediction of the newly designed product.

According to the above viewpoints, using the identification method presented in this paper, six-degree-of-freedom (d.o.f.) contact stiffness on the interface sample are identified, and then being applied to predict the eigenfrequency of the whole structural system composed of one base and two columns. The errors of system eigenfrequency between the result from FEM analysis and that from experiment are very small, illustrating the correctness and practicability of the method discussed in this paper for product design and behavior prediction.

2. METHOD OF INTERFACE CHARACTERISTIC IDENTIFICATION

2.1. SET UP THE FEM MODEL OF THE INTERFACE SAMPLES

The definition of FEM model must accurately reflect the real condition of the structural system. According to the samples in this project, the thin shell and beam element types are used to make the model.

The interface between the samples was simulated by distributed springs and dampers. Because the focus of this research is on predicting the natural frequency of the structural system, and contact damp has little effect on natural frequency, dampers can be ignored safely. The interface elements were chosen at the fixing bolts. Six springs were used to simulate the contact stiffness on six degree of freedom for one interface element.

Because the boundary condition of FEM model must be in accordance with the free status of the sample system while performing impact testing, no boundary restraint was set to it. As a result, six rigid body movement modes exist in the results of FEM analysis and experiment testing.

2.2. SELECT THE INITIAL VALUES OF THE CONTACT STIFFNESS OF THE INTERFACE ELEMENTS AND PERFORM FINITE ELEMENT ANALYSIS TO SAMPLE MODEL

In order to accurately identify the interface characteristic parameters, output of 16–20 mode shapes and their corresponding natural frequencies were made.

2.3. MEASURE EXPERIMENT MODE SHAPES AND THEIR CORRESPONDING NATURAL FREQUENCIES OF THE INTERFACE SAMPLE MODEL

In this research, HP3562A was used as Dynamic Signal Analyzer, and uni-point impulse exciting method was used.

2.4. FIT FEM MODE SHAPES IN WITH EXPERIMENT MODE SHAPE

By regularizing mode shapes, find the corresponding mode shapes and natural frequencies between the experiment mode and the FEM mode.

2.5. CHOOSE THE CONTACT STIFFNESS COEFFICIENTS AS DESIGN VARIABLES

The purpose is to minimize the sum of squares of eigenfrequency differences between finite element modes and their corresponding experimental modes, based on fitted mode shape. Optimum algorithm is employed to search the value of the contact stiffness at the interface.

3. OPTIMUM ALGORITHM OF INTERFACE CONTACT STIFFNESS

3.1. DESIGN VARIABLES

Choose interface contact stiffness coefficients as design variables $\bar{x}_i (i = 1, 2, \ldots, n)$. Make scale transformation to $\bar{\mathbf{x}}_i$,

$$x_i = \frac{\bar{x}_i}{S} \tag{1}$$

take $S = \bar{x}_3^{(0)}$, where $\bar{x}_3^{(0)}$ is the initial value of contact stiffness in the direction perpendicular to the interface.

3.2. OBJECTIVE FUNCTION

$$\min f(x) = \left[\sum_{j=1}^{m} \left(\frac{\omega_j(x) - \bar{\omega}_j}{\bar{\omega}_j} \right)^2 \right] \cdot \beta^2 \quad x \in R^n, \tag{2}$$

where $\bar{\omega}_j$ is the jth natural frequency measured through testing, $\omega_j(x)$ is the jth natural frequency calculated from FEM, which is the function of design variables, m is the number of fitted modes, j is the mode order, and β is the scale transformation coefficient of the objective function.

3.3. METHOD OF OPTIMIZATION

In the non-constrained optimum problem [5], using quasi-Newtonian method, the searching direction $d^{(k)}$ of Kth iteration is determined by

$$B^{(k)} d^{(k)} = -\nabla f(x), \tag{3}$$

where $B^{(k)}$ is the approximation of the objective function's Hessian Matrix, and $\nabla f(x)$ is the gradient of the objective function.

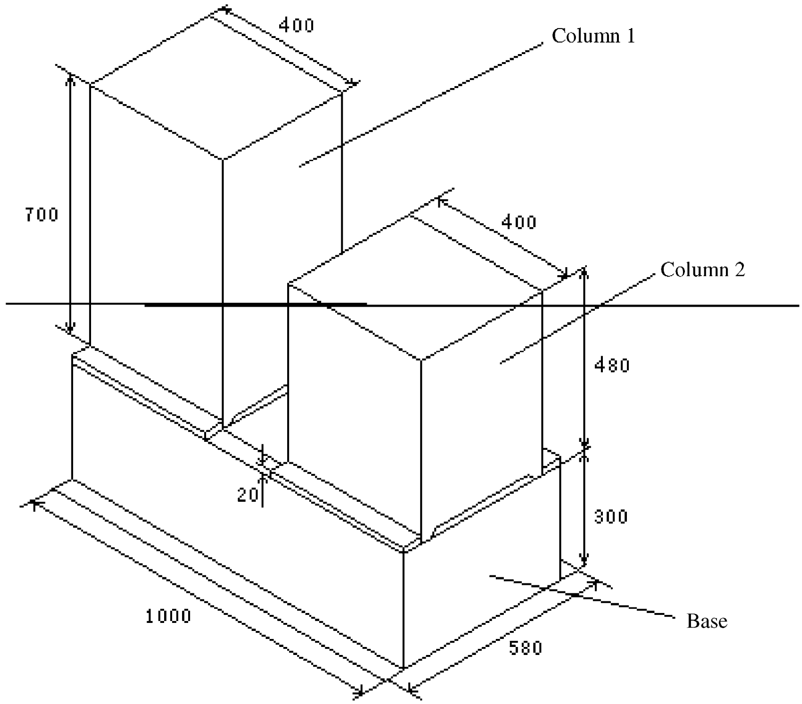

Figure 1. Schematic representation of the mechanical structural system used in this research.

From the FEM dynamic equation, the following simple gradient calculating formula of objective function can be obtained:

$$\nabla f(x) = \begin{bmatrix} \sum_{j=1}^{m} \frac{\beta^2 S}{\bar{\omega}_j}\left(\frac{1}{\bar{\omega}_j} - \frac{1}{\omega_j(x)}\right)\cdot (y_{j1_1} - y_{j1_2})^2 \\ \vdots \\ \sum_{j=1}^{m} \frac{\beta^2 S}{\overline{\omega_j}}\left(\frac{1}{\overline{\omega_j}} - \frac{1}{\omega_j(x)}\right)\cdot (y_{jn_1} - y_{jn_2})^2 \end{bmatrix}, \tag{4}$$

where (y_{ji_1}, y_{ji_2}) is a couple of deformation corresponding with χ_i in jth mode shape.

4. RESULTS AND DISCUSSION

A mechanical structural system composed of one base and two columns was designed, and its size and assembly status are illustrated as in Figure 1. There are two fixed interface planes. The characteristics of the interface are as follows:

interface materials: carbon steel;
interface flange thickness: 20 mm;
bolts distribution on the interface: along the two sides of the flange there are five evenly distributed M12 fixing bolts respectively;
interface processing method: precision mill;
interface roughness: Ra 3.2 μm;

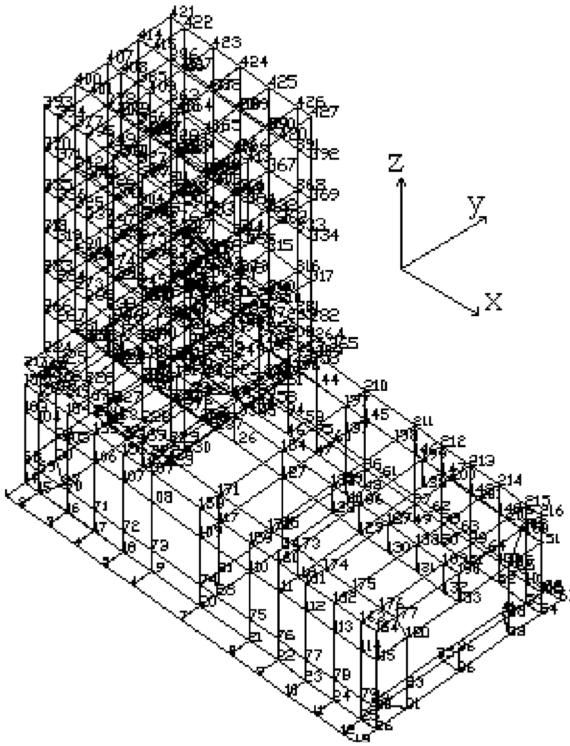

Figure 2. Finite element analysis model of the sample.

pressure between the interface: 6.3 N/mm^2;
interface inter-medium: dry surface.

(1) A interface sample is composed of base and column 1. The finite element model of the sample is shown in Figure 2. There are 427 nodes, 420 plate elements, 168 beam elements and 10 interface elements.
(2) Choose the initial value of the contact stiffness coefficients at 6 d.o.f. of every interface element. Translation stiffness coefficient is 1×10^4 N/mm, rotation stiffness coefficient is 1×10^4 N mm/rad.

Using FEM to analyze the above model, output 19 mode shapes and their corresponding natural frequencies. Ignore six rigid body modes, all other modes' natural frequencies can be obtained, as shown in Table 1.
(3) Measure every mode shapes and their corresponding natural frequencies. Ignore six rigid body modes in the sample and also list other modes' natural frequencies in Table 1.
(4) Fit the results from experiments in with those from FEM analysis to find the relations of natural frequencies between them, where the mode shapes were in accordance with each other. The results are shown in Table 1.
(5) Using optimum algorithm to calculate the interface contact stiffness. 6-d.o.f-contact stiffness coefficients of the interface are identified, as listed in Table 2.
(6) Apply interface contact stiffness coefficients shown in Table 2 to predict natural frequencies of the structural system as illustrated in Figure 1. The results from FEM analysis are listed in Table 3.

TABLE 1

The comparison of finite element analysis results and experiment mode test results of the interface sample

Experiment mode analysis		FEM analysis		Sum of squares of corresponding displacement differences
Modes	Natural frequencies (Hz)	Natural frequencies (Hz)	Modes	
1	106^{+3}_{-2}	89	2	0·659
2	123^{+3}_{-3}	130	3	0·126
3	152^{+3}_{-2}	—	—	—
4	176^{+2}_{-3}	—	—	—
5	250^{+3}_{-3}	256	4	0·184
6	330^{+3}_{-3}	327	5	> 1
7	511^{+3}_{-3}	478	10	0·434
8	626^{+3}_{-3}	645	12	0·341
9	773^{+3}_{-3}	790	15	0·526
10	838^{+3}_{-2}	803	16	> 1
11	858^{+3}_{-3}	886	17	> 1
12	877^{+3}_{-3}	922	18	0·241
13	891^{+3}_{-3}	930	19	> 1

TABLE 2

The identified interface contact stiffness coefficients (*interface pressure*: 6·3 N/mm^2)

D.o.f.	1	2	3
K_n (N/mm)	$2{\cdot}15 \times 10^5$	$2{\cdot}21 \times 10^5$	$1{\cdot}25 \times 10^5$
D.o.f.	4	5	6
K_s (N mm/rad)	$2{\cdot}01 \times 10^3$	$2{\cdot}00 \times 10^3$	$2{\cdot}01 \times 10^3$

(7) Table 3 also shows the natural frequencies of the system measured by HP3562A. The predicted frequencies and the measured frequencies are compared in Table 3. It shows that many modes can be fitted in, and the errors of the corresponding natural frequencies are very small.

5. CONCLUSIONS

1. By using interface sample to identify interface characteristic parameters, it is applicable to provide interface information for the prediction of product behavior during new product designing period. Thus, static and dynamic behavior of the whole machine can be predicted without making prototype.
2. If the processing method, manufacturing precision and working conditions of the interface sample are in accordance with the new product interface designing

TABLE 3

The results of the mode frequency analysis of structural system composed of one base and two columns

Modes	FEM predicted frequencies (Hz)	Experiment measured frequencies (Hz)	Modes	Errors of frequencies (%)
1	65·4	$62{\cdot}5^{+0{\cdot}5}_{-0{\cdot}5}$	1	4·6
2	112·4	$113{\cdot}7^{+0{\cdot}5}_{-1}$	2	1·1
3	148·7	$150^{+0{\cdot}5}_{-0{\cdot}5}$	3	0·8
4	155·4	$153{\cdot}7^{+0{\cdot}5}_{-0{\cdot}5}$	4	1·1
5	195·2	$180^{+1{\cdot}5}_{-0{\cdot}5}$	5	8·4
—	—	255^{+1}_{-1}	6	—
6	339·2	$350^{+1}_{-1{\cdot}5}$	7	3·1
7	411·4	$381{\cdot}2^{+1}_{-0{\cdot}5}$	8	7·9
8	420·1	$422{\cdot}5^{+0{\cdot}5}_{-0{\cdot}5}$	9	0·5
—	—	$450^{+0{\cdot}5}_{-1}$	10	—
9	475·7	$478{\cdot}7^{+0{\cdot}5}_{-0{\cdot}5}$	11	0·6
10	529·2	—	—	—
11	539·5	560^{+1}_{-5}	12	3·6
12	585·2	—	13	—
13	604·5	$605^{+0{\cdot}5}_{-1}$	14	0·08
14	610·8	$618{\cdot}7^{+0{\cdot}5}_{-1}$	15	1·2
15	623·5	—	—	—
16	626·1	—	—	—
17	718·2	$730^{+0{\cdot}5}_{-1}$	16	1·6

requirements, manufacturing conditions and assembling specifications, the method in this paper can be used to identify interface parameters accurately.

3. The method presented in this paper can identify the interface contact stiffness accurately.

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