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OPTIMIZATION METHOD AND TEST VALIDATION OF LOAD MAPPING BASED ON LOCAL RESPONSE APPROXIMATION

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Abstract. *Load mapping describes the relationship of input load between operation mechanics environment and test mechanics environment, while the responses of a structure in these two environments are equivalent. This paper considered the response equivalent as response approximation, and the load mapping is understood as load optimization. Shell structure numerical simulation of multi-operation condition based on local response approximation is given, and genetic algorithm (GA) is used as optimization arithmetic. The simulation results indicate the rationality of load mapping optimization method, and the mapping error could be reduced when more kinds of load supplied in test environment. Finally, experiment of plate structure is performed; the experiment result shows the validity and effectiveness of load mapping optimization method.*

1 INTRODUCTION

Environment experiment is considered as an important and necessary mean to check the reliability and durability of production. The key problem of environment experiment is exhibiting what the production/structure suffered in operation environment as factually as possible, the environment discussed in this paper is mechanics environment in which the load the structure suffered is vibrate and impact. Traditional environment experiment focused on the simulation of the load in operation environment, it is the load equivalence essentially, but mainly because of the difference of boundary condition, the experiment environment and operation environment are different, even the experiment environment could simulate the load in operation environment perfectly, the performance inspection of production maybe inadequately.

In fact, what people concerned ultimately is structure response equivalence between two environments, the new concept of load mapping proposed in this paper described the input load relationship of two environments, while the response of a same structure in these two environments are equivalent. There are few literatures about this research; Cao [1] considered earth shake as harmonic excitation based on structure response equivalent; Zhu and Li [2] made a pilot study of simulating practical flying environment in laboratory with the principle of response power spectrum equivalence.

Practically, the ultimately concerned is the response equivalence of local structure (such as key component), with a view to universality significance, this paper considerate response equivalence as response approximation, and understand load mapping standing at the point of load optimization, when the difference of structure response between test environment and operation environment less than the default tolerance, it also achieves the objective of response equivalence. The rationality and validity of load optimization are confirmed by numerical simulation and experiment. The purpose of this research is providing theoretic foundation for applying load rationally in vibration environmental test.

2 RESPONSE EQUIVALENCE OF LOAD MAPPING

The models discussed in this paper are established with finite element method. The structure dynamic equation of mechanics environment I (operation environment) is list as follow:

$$(M_0 + M_{b1})\ddot{x}_1(t) + (C_0 + C_{b1})\dot{x}_1(t) + (K_0 + K_{b1})x_1(t) = f_1(t) \tag{1}$$

In equation(1), M_0, C_0 and K_0 corresponding to the mass, damping and kinetic matrix of structure; M_{b1}, C_{b1} and K_{b1} corresponding to the boundary mass, damping and kinetic matrix of mechanics environment I; $x_1(t)$ and $f_1(t)$ corresponding to the displacement response and load of mechanics environment I.

In the same way, the dynamic equation of the same structure in mechanics environment II (experiment environment) could be described as:

$$(M_0 + M_{b2})\ddot{x}_2(t) + (C_0 + C_{b2})\dot{x}_2(t) + (K_0 + K_{b2})x_2(t) = f_2(t) \tag{2}$$

In equation(2), M_{b2}, C_{b2} and K_{b2} corresponding to the boundary mass, damping and kinetic matrix of mechanics environment II; $x_2(t)$ and $f_2(t)$ corresponding to the displacement response and load of mechanics environment II.

Carrying Fourier transform to equation(1) and (2), their dynamic equations in frequency domain are:

$$[(K_0 + K_{b1}) - \omega^2(M_0 + M_{b1}) + i\omega(C_0 + C_{b1})]X_1(\omega) = F_1(\omega) \tag{3}$$

$$[(K_0 + K_{b2}) - \omega^2(M_0 + M_{b2}) + i\omega(C_0 + C_{b2})]X_2(\omega) = F_2(\omega) \tag{4}$$

In equation (3) and (4), $F_1(\omega)$and $X_1(\omega)$ corresponding to the load spectrum and displacement response spectrum in mechanics I; $F_2(\omega)$ and $X_2(\omega)$ corresponding to the load spectrum and displacement response spectrum in mechanics II. Define mapping error ε as:

$$\varepsilon = \sum_{i=1}^{n_c} norm(X_{a1,i}(\omega) - X_{a2,i}(\omega)) \tag{5}$$

$X_{a1}(\omega)$ and $X_{a2}(\omega)$ corresponding to the displacement response spectrum of concerned local DOFs in mechanics environment I and II; n_c is the number of concerned local DOFs.

This paper considered mapping load spectrum F_2 (ω) as optimization object, the optimization purpose is the minimum of ε, the less numerical value of ε means the less error of concerned local structure response spectrum in these two environments, and the better approximation of response spectrum. The optimization arithmetic used in this paper is GA.

3 NUMERICAL SIMULATION

3.1 Two different mechanics environments

Fig.1 is the finite element model of a column shell, the model is established in Ansys software, the bottom of the shell connects with the free end of four cantilever beams. There are 12 additional centralized masses on the plate in mechanics environment I, the weight of each mass element is 0.1kg.

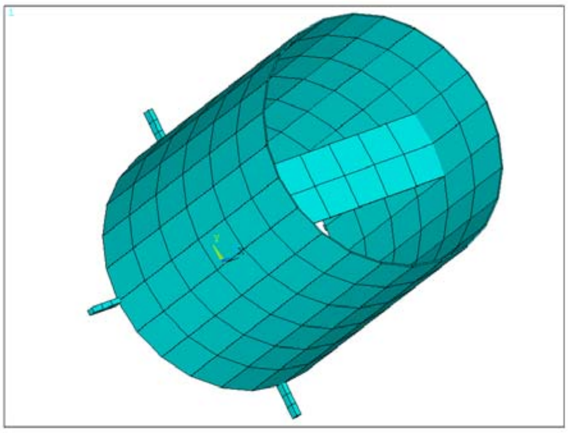

Fig.1 Finite element model of column shell

The structure parameters are listed in table 1.

	Mechanics environment I	Mechanics environment II
Shell diameter(mm)	600	600
Shell thickness(mm)	3	3
Shell height(mm)	750	750
Plate thickness(mm)	3	3
Plate width(mm)	155.3	155.3
Beam height(mm)	20	20
Beam width(mm)	12	12
Beam length(mm)	100	80
Additional mass weight(kg)	0.1	0

Table 1. Structure parameters comparison of two mechanics environments

According to the result of modal analysis, comparison of the first 10 nature frequency of two environments is listed in table 2.

Order	Mechanics environment I(Hz)	Mechanics environment II(Hz)
1	33.08	44.25
2	33.09	45.27
3	33.98	45.29
4	52.30	52.38
5	66.53	68.22
6	72.80	101.04
7	78.48	104.11
8	94.68	109.98
9	102.40	123.69
10	103.60	125.87

Table 2. Comparison of the first 10 nature frequencies of two mechanics environments

3.2 Load in two mechanics environments

Force load in mechanics environment I is applied on the top nodes along the Z direction (parallel to generatrix) of column shell, the load of each node is the same, and the load curve is shown in fig 2. Load in mechanics environment II is base acceleration excitation, and applied on the fixed end of cantilever. The chosen concerned objective is the Z direction displacement response of 12 nodes also located on the plate. The optimization purpose is to obtain the base acceleration spectrum value to make the mapping error as small as possible.

Considering the base excitation is produced by shaking table, and maybe more than one shaking tables are supplied, numerical simulation include three operation conditions as follow:

a) Four fixed ends of cantilever beam mounted on one shaking table.
b) Four fixed ends of cantilever beam mounted on two shaking tables.
c) Four fixed ends of cantilever beam mounted on four shaking tables.

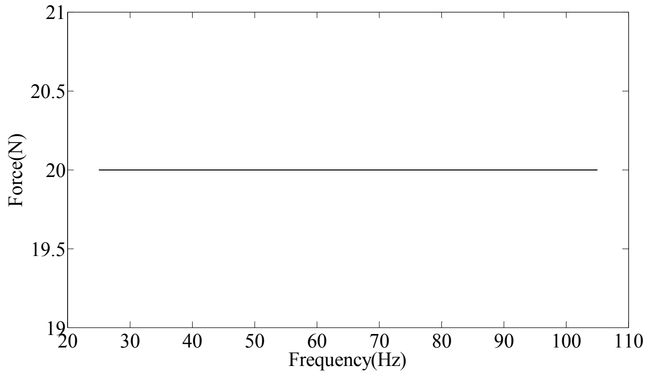

Fig 2. Load in mechanics environment I

3.3 Numerical simulation result

In operation condition a), the mapping load curve in mechanics environment II is shown in fig.3, and the mapping error is ε=0.0129.

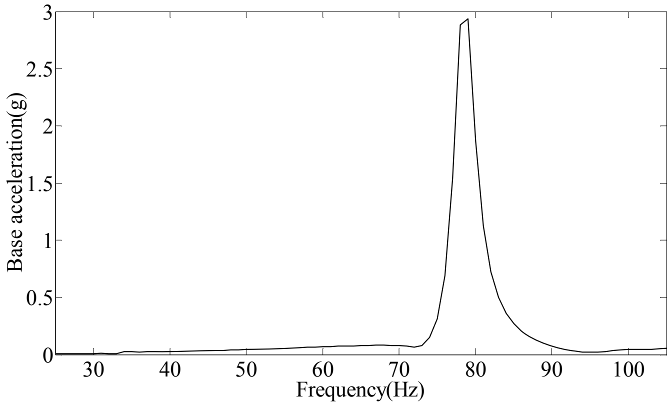

Fig.3 Mapping load in mechanics environment II

Take the displacement of two concerned nodes as example, their response comparison in two mechanics environments is shown in fig 4.

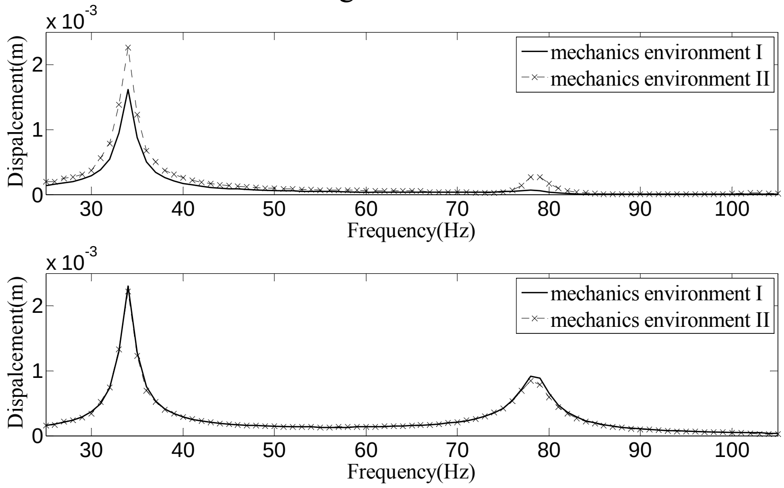

Fig.4 Response comparison in two mechanics environments

In operation condition b, two shaking tables are supplied, every two fixed ends of cantilever beam are mounted at a shaking table. Two mapping load curves in mechanics environment II are shown in fig.5, and the mapping error is ε=0.0029.

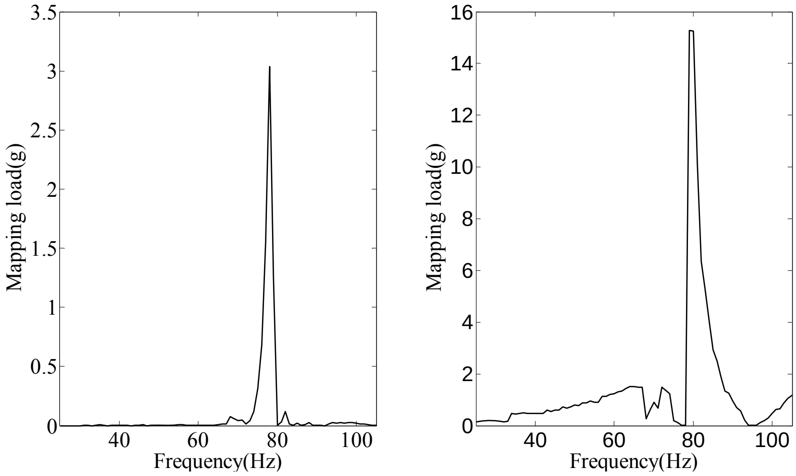

Fig.5 Mapping load in mechanics environment II

The response comparison of two chosen nodes (the same number with operation condition a) in two mechanics environments are shown in fig 6.

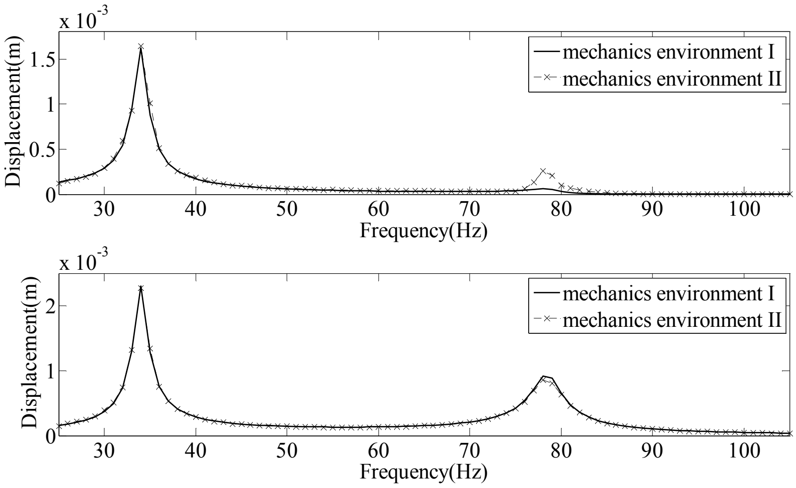

Fig.6 Response comparison in two mechanics environments

In operation condition c, four shaking tables are supplied, the mapping load curve in mechanics environment II is shown in fig.7, and the mapping error is ε=0.0024.

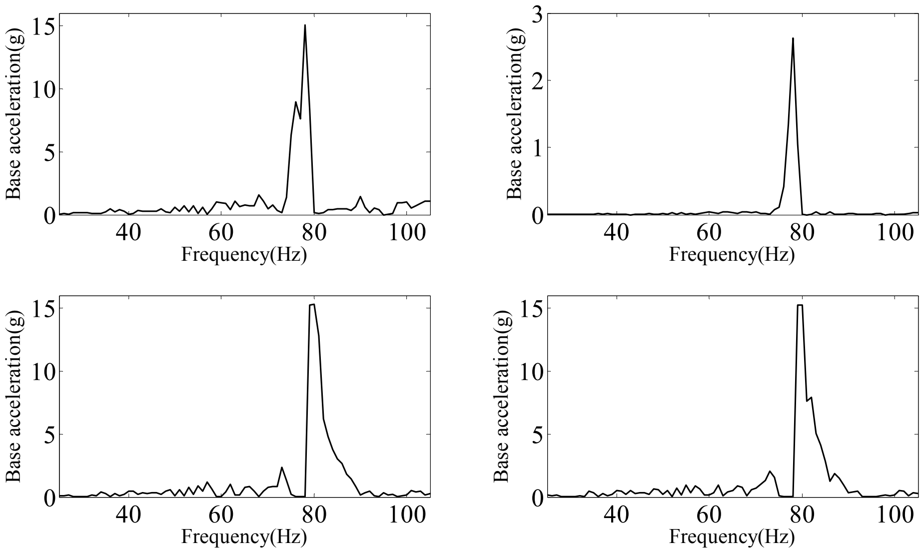

Fig.7 Mapping load in mechanics environment II

Take the displacement of two concerned nodes as example, their response comparison in two mechanics environments is shown in fig 8.

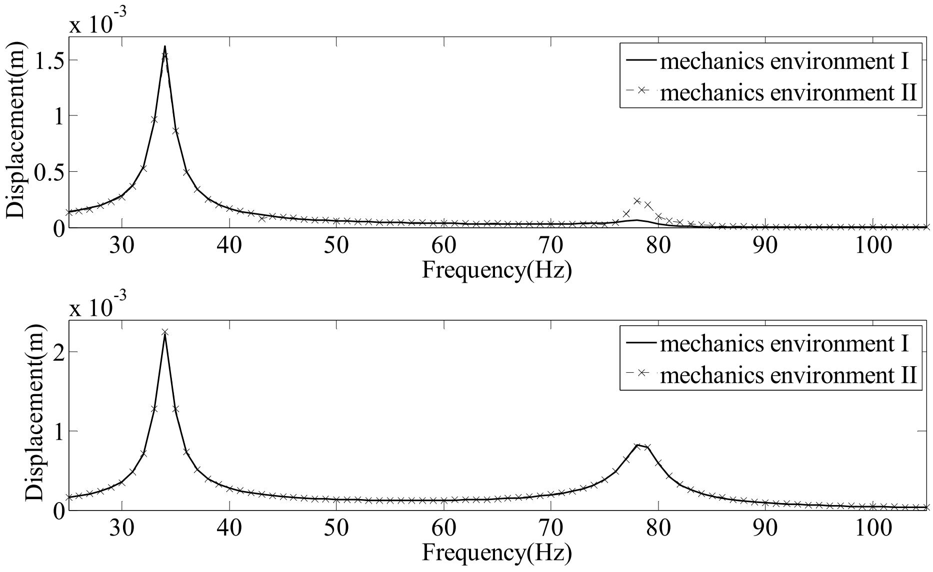

Fig.8 Response comparison in two mechanics environments

The numerical simulation result indicates that the mapping error is decreasing with the increasing of shaking table, it means more kinds of load provided in mechanics environment II, better approximate response between two mechanics environments.

4 EXPERIMENT VALIDITY

4.1 Plate Parameters

Load mapping experiment of plate was carried, cause of the limitation of equipments, the experiment was carried with only one shaking table. The structure used in experiment is a plate, its structure parameters is listed in Table 3.

Length (mm)	Width (mm)	Thickness (mm)	Young`s Modulus (Mpa)	Density (kg/m^3)	Possion ratio
332	332	3mm	71e3	2700	0.3

Table 3. Parameters of Plate

4.2 Two Different Mechanic Environments

The boundary condition of plate is shown in Fig.9.The four corner of plate are connected with the free end of four cantilever beams, the fix end of cantilever beams are fixed on the shaking table. The differences of two mechanic environments are:

a) The geometry parameters of cantilever beam in two mechanic environments are different, these parameters are listed in Table 4.
b) There are four mass blocks laid on plate in mechanic environment I. The nodes which four mass blocks located are shown in Fig.10.

Cantilever Beam	Mechanic Environment I	Mechanic Environment II
Cross Height(mm)	20	20
Cross Thickness(mm)	5	5
Length(mm)	73.8	124.8
Density(kg/m^3)	7800	7800
Young`s Modulus(Mpa)	210e3	210e3
Possion Ratio	0.3	0.3
Mass Block(g)	25.1	0

Table 4. Parameters Comparison of Cantilever Beam and Mass Block

Figure.9.a Distribution of boundary condition   Figure.9.b Detail of boundary condition
Figure.9 Boundary Condition of Plate

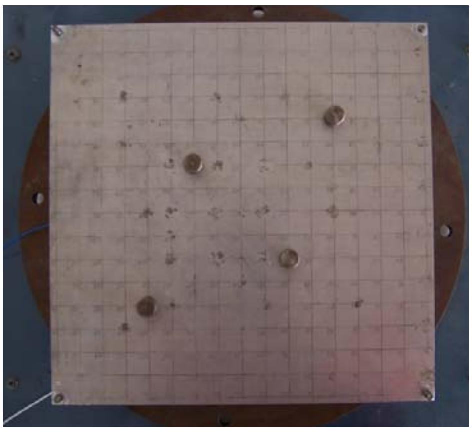

Figure.10 Mass location in mechanic environment I

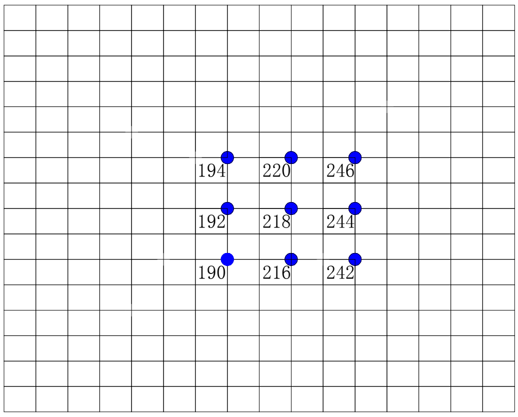

Figure.11 Location of nine acceleration sensors

Nine acceleration sensors installed on nodes marked in Fig.11 to measure the transverse acceleration response signal.

4.3 Test flow

The Load of two mechanic environments is base acceleration produced by shaking table. It should be mentioned out that what need to be provided in mechanic environment I is the measured response data of cared DOFs, the purpose of test is to obtain certain load to reproduce the measured response of mechanic environment I, so the model veracity of mechanic environment II is very important to guarantee the reliability of load mapping. The comparison of modal test result of mechanic environment II and its modal analysis result of finite element model is listed in Tab.4.

Table.4 Result comparison of modal test and simulation

Mode order	Simulation value(Hz)	Test value(Hz)	Error(%)	Mode damp ratio
1	76.04	76.21	0.22	0.59
2	145.92	141.37	3.12	0.22
3	145.92	145.15	0.53	0.20
4	173.83	173.51	0.18	0.15
5	277.05	284.67	2.75	0.09
6	321.03	314.53	2.02	0.04
7	329.52	319.92	2.91	0.08
8	392.65	388.79	0.98	0.08

The comparison result of Tab.4 indicated the FEM accuracy of mechanic environment II.

4.4 Load mapping test of random excitation

In mechanical environment I, the base acceleration PSD curve in PUMA input control system is shown in Fig.12.

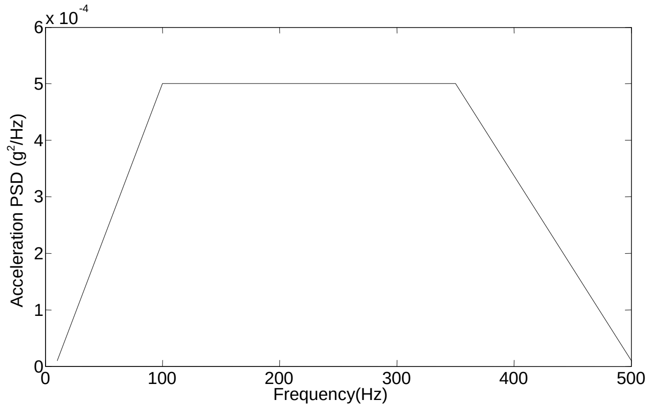

Fig.12 Input acceleration PSD of mechanical environment I

The acceleration response spectra $X(\omega)_1$ of 9 cared local DOFs in mechanical environment I are measured. The mapping base acceleration PSD of mechanical environment II obtained by optimization calculation is shown in Fig.13.

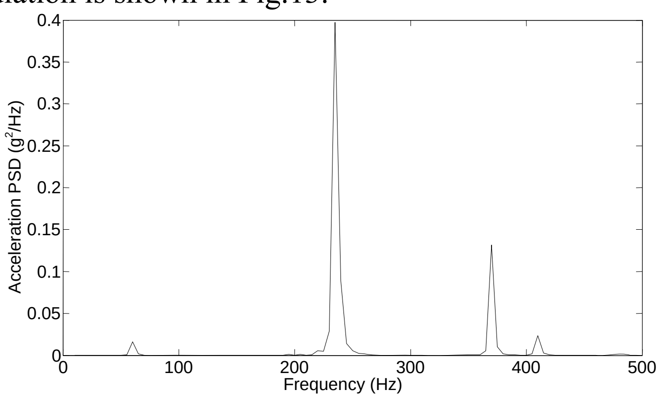

Fig.13 Mapping base acceleration PSD of mechanical environment II

The excitation of Fig.13 is applied in mechanical environment II, acceleration response spectra $X(\omega)_2$ of the same 9 cared local DOFs are measured, the comparison of $X(\omega)_1$ and $X(\omega)_2$ are shown in Fig.14(a)~(b) with the example of node 194 and 218.

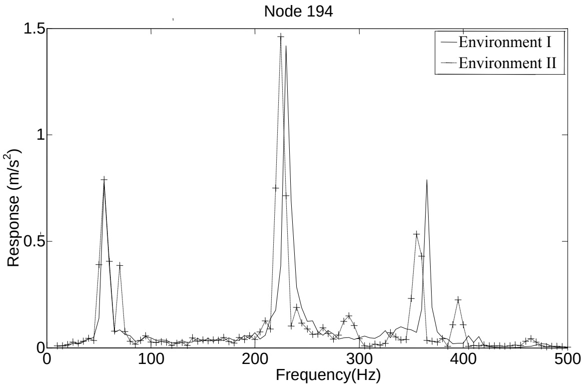

Fig 13.a Response comparison of node 194

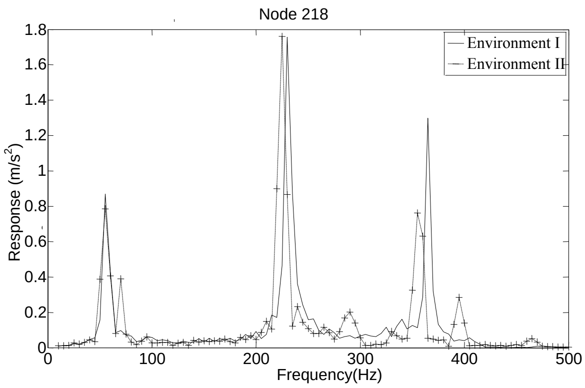

Fig 13.b Response comparison of node 218

Fig.13 Response comparison in two mechanics environments of node 194 and 218

It could be concluded from Fig.13 that these spectra are rather close in certain degree, and achieved the purpose of local equivalent. The error of acceleration response spectra is caused mainly by following reasons.

a) The output excitation of shaking table is different from the set input load in control system, the comparison of setting input excitation of Fig.13 and the practical output of shaking table is shown in Fig.14

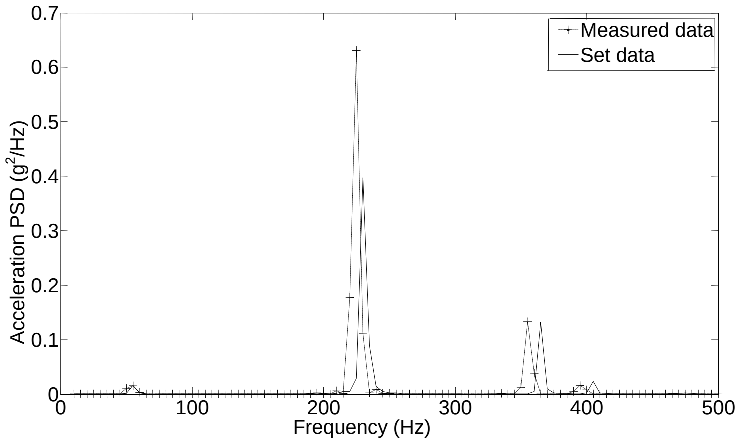

Fig.14 Comparison of setting excitation and practical output of shaking table

There is obviously difference between the two spectrum curves in Fig.14, it means the input equipment didn`t actualize the setting input excitation.

b) The mapping load is obtained by optimization calculation, the objective is making the response error of 9 cared DOFs between two mechanical environments as small as possible, and the error cannot be zero.

5 CONCLUSIONS

This paper studied the load mapping method based on the local equivalence with the universality significance. Numerical simulation result indicated the validity and effectiveness of load mapping obtained by optimization method; the mapping error could be decreased when more kinds of load applied in test environment. Single operation condition load mapping experiment (include sinusoid and random excitation) obtained satisfaction result, the acceleration response of selected load DOFs are considerably equivalent. These works of this paper provide the method guidance and theoretic foundation for environment test based on response control.

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