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NEW PROCEDURE OF VIBRATION ANALYSIS USING STATISTICAL ENERGY ANALYSIS : CASE OF BOX-LIKE STRUCTURE

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This paper describes a new procedure for SEA model construction (estimation of loss factors) and the finite element analysis aided for SEA approach. In the construction of SEA model, the power flow between subsystems are directly measured using the structural intensity measurement. To predict the vibration energy distribution in a subsystem, we use FE analysis of the objective subsystem. These approach is applied a box-like structure to predict the vibration energy levels and the energy distributions of subsystems. The constructed SEA model gives the energy level predictions with reasonable precision, and the FE analysis of subsystems give the proper prediction of the distributions.

1. INTRODUCTION

Statistical Energy Analysis(SEA)[1] is a very useful tool for analyzing the structure-borne noise in machinery. In SEA, the vibration response of subsystem is described by the vibration energy, which is a mean value in space and frequency. It is an attractive method for the vibration of high frequency range mainly because of the simplicity of the governing power flow equations. For SEA model construction, the high precious estimation of parameters presenting power flow is required. The parameters can be estimated theoretically if the shapes of substructures are simple. However, it is generally difficult to evaluate them in most machinery. Then, experimental approach for estimating the parameters is employed. The experimental construction of SEA model was proposed by Hamid and Bies[2] in 1980, which is named as the Power Injection Method. And the practical method with approximation was introduced by Lalor[3]. These methods require a large number of power injections. In this paper, we take a new procedure in a series of analysis using SEA. The construction method of SEA model is presented. This method uses the structural intensity measurement to evaluate the transmitted power between subsystems. The method are applied to a box-like structure numerically.

It is possible to predict the energy of each subsystem if the SEA model is constructed. In noise control, however, we sometimes need more detailed information for subsystems. In this paper, it is also shown that the vibration energy distribution inside a subsystem is predicted using the finite element analysis of the subsystem. This procedure is applied to predict the energy distribution of a box-like structure numerically.

2. NEW PROCEDURE FOR SEA MODEL CONSTRUCTION[4]

In constructing SEA model, the estimation of internal and coupling loss factors is important. In this chapter, the procedure for estimating these factors based on the intensity measurement is introduced.

In SEA, we must divide the system into some subsystems. For example, if the system is a box-like structure, the subsystems are plates. The power transmitted to a subsystem can be measured by the structural intensity measurement around the boundary lines dividing into subsystems. It is because the intensity expresses the power flow per unit area of section on structures.

If two subsystem are joined with one boundary line, the power is the transmitted power in SEA. Therefore, the coupling loss factor (CLF) and the internal loss factor (ILF) are determined from the following equations, respectively.

$$\eta_{ij} = \frac{\Pi_{ij}}{\omega n_i \left(E_i/n_i - E_j/n_j \right)} \qquad (1) \qquad\qquad \eta_i = \frac{P_i - \Pi_{ij}}{\omega n_i E_i} \qquad (2)$$

Where, η_{ij} :CLF between subsystem i and j, P_i :input power into subsystem i, Π_{ij} :transmitted power from subsystem i to j measured by the intensity, n_i :modal count of subsystem i, E_i :vibration energy of subsystem i, ω :center angular frequency.

In case more than three subsystems are joined with one boundary line, we can not use Eq.(1) to determine CLFs. It is because the power estimated by the intensity is the net power that is expressed the summation of the transferred powers from the neighbor subsystems. Then, we introduced the following treatment in order to enable the estimation in that case. In case N subsystems are joined with one boundary line, we regard the system composed of N subsystems as two groups of one subsystem and (N-1) subsystems. The power transmitted from (N-1) subsystems to one subsystem Π_{one} is measured by the intensity measurement, and CLFs are determined using the constant φ_{one} from the following equations.

$$\varphi_{one} = \frac{-\Pi_{one}}{\omega n_i \left(E_i/n_i - \sum_{k \neq i} E_k/n_k \right)} \qquad (3) \qquad\qquad \eta_{ij} = \frac{n_j}{n_i} \varphi_{one} \qquad (4)$$

In that case, ILFs are determined as well as Eq.(2) from

$$\eta_i = \frac{P_i + \Pi_{one}}{\omega n_i E_i} \qquad (5).$$

In some case studies as for the validity of such treatment, we confirmed that the loss factors estimated by the above procedure are sufficient to predict the vibration energy if ILFs are smaller than CLFs.

3. PREDICTION OF ENERGY DISTRIBUTION USING FEM

The finite element method (FEM) is a powerful tool to calculate the vibration energy of structures. If the structure is large and complex, it is difficult to analyze the vibration response in high frequencies using a full FE model (full model calculation). However, the analysis of only a part of the structure is possible (sub model calculation).

The SEA result is given as the vibration energy of subsystems and it is impossible to know the distribution of energy inside a subsystem. The knowledge is useful to take a step to reduce the vibration level. Therefore, we think the FE analysis aided SEA approach applicable to predict the vibration energy distributions inside subsystems that can not be analyzed by SEA. To enable the prediction, there are some problems how the boundary condition is set in making the FE model of a subsystem subtracted from a structure, and how the excitation condition is set in FE calculation. We discuss these problems in this paper.

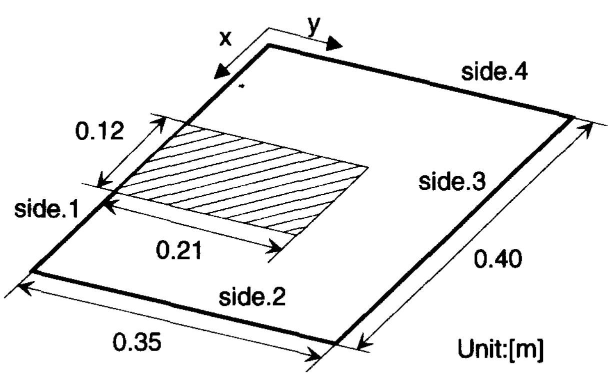
3.1 Procedure of FE calculation

A rectangular plate model shown in Fig.1 is used. The FE model has 400 isoparametric square elements (QUAD4) in the FEM code MSC/NASTRAN, and the direct solution method was used. The objective frequency band is 500 and 1kHz octave band. The vibration energies were summed within the band. The following results are presented as the value normalized by the input power.

3.2 Excitation condition

We discuss how to employ the condition of excitation. There are many excitation conditions applicable to the plate. In the aim of this paper, it is desired that the excitation condition is general for SEA approach.By some investigations, we concluded that it is reasonable to average the responses in each excitation by a point force.

As for the number of excitations, 4 excitations assure the SEA assumptions which all modes of the subsystem are equally excited. Table.1 and Fig.2 show the comparison of the energy levels and the distributions between the average of 4 excitations and that of 10 under the boundary condition that side.1 is free and the others are fixed.



Material:Steel, t=0.002m

Material damping:0.0 except for hatching area (0.1)

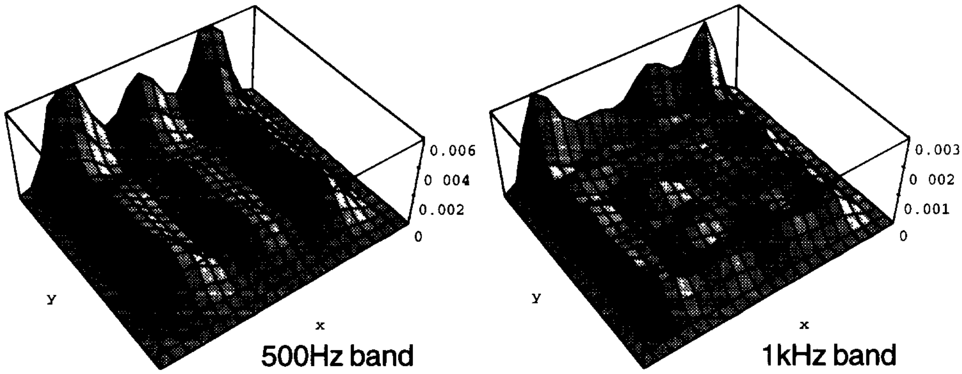
Fig.1 Calculation object

3.3 Boundary condition

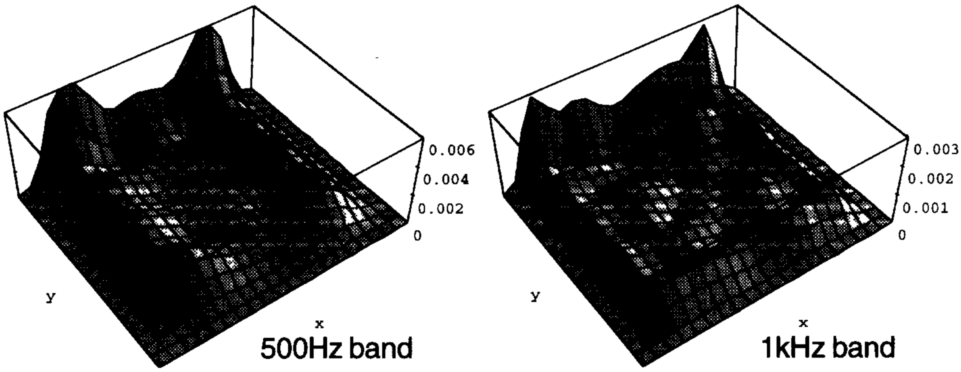
The effect of boundary condition is next discussed. In case that the side.1 in Fig.1 is free and the others are simply supported or fixed, we compared the energy levels and distributions. The difference of boundary

Table.1 Energy levels due to the difference of the considered number of excitations[J/W]

No. of excitations	500Hz band	1kHz band
4	0.0151	0.0094
10	0.0150	0.0095

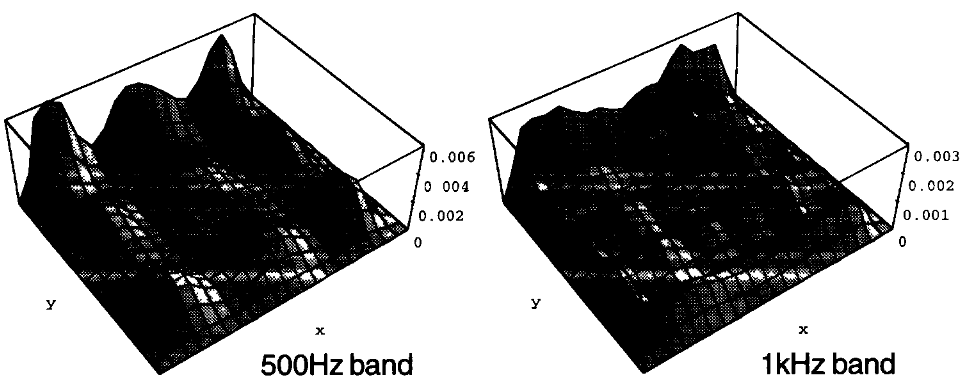


(a) Average of 4 excitations

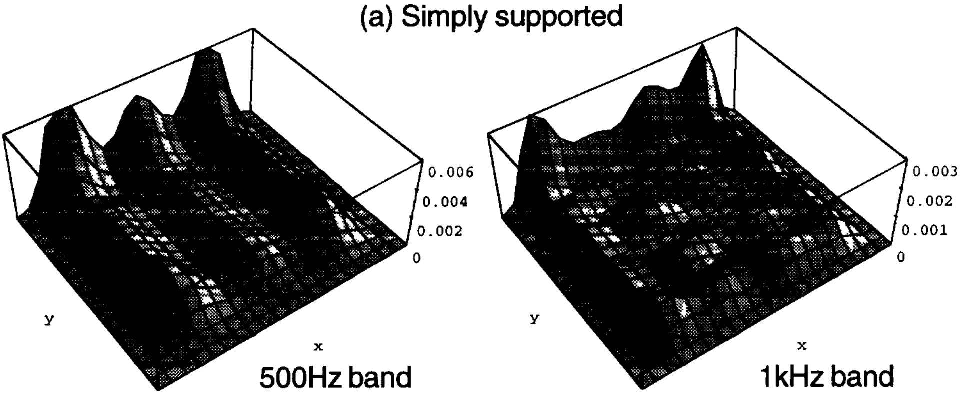


(b) Average of 10 excitations

Fig.2 The difference of distribution due to the considered number of excitations



(a) Simply supported



(b) Fixed

Fig.3 The difference of distribution due to boundary condition conditions makes little influence in the levels as Table.2. And, the distributions of square velocity of each condition are also similar as shown in Fig.3.

Table.2 Energy levels due to the difference of boundary condition[J/W]

Boundary condition	500Hz band	1kHz band
Supported	0.0151	0.0094
Fixed	0.0148	0.0084

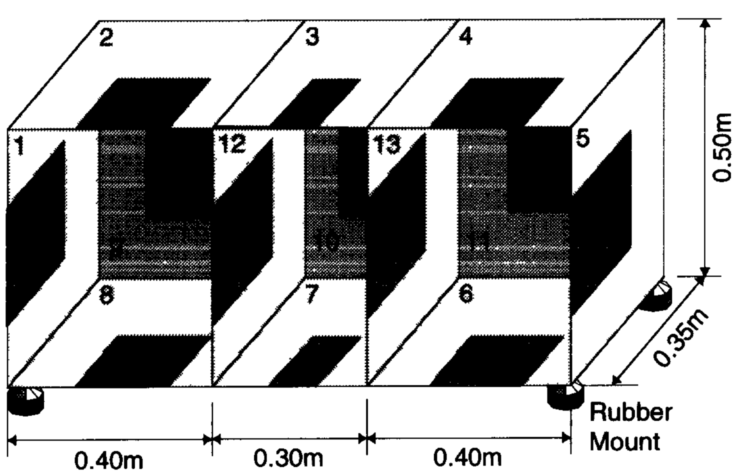
Therefore, the procedure to predict the energy distribution inside a subsystem as a further information of SEA approach is as follows. We have only to make the FE model of the only subsystem with the boundary condition of supported or fixed. Then four excitation positions of a point force are selected suitably, and the responses are calculated at resonance frequencies of it in each excitation. The energy levels and distributions in each excitation are averaged. The application will be presented in next chapter.

4. APPLICATION TO BOX-LIKE STRUCTURE

The procedure described in chapter 2 and 3 are numerically applied to a box-like structure, which has 13 plate subsystems as shown in Fig.4. The SEA model is constructed by the method shown in chapter 2 using full model calculationiunder the condition that one plate is excited. To verify the constructed SEA model, the predicted energy levels of 13 plates are compared with the directly calculated levels using full model calculation in case another plate is excited. Moreover, the energy distributions of plates are also predicted using the procedure shown in chapter 3. The FE model of this structure has 5616 nodes and 5575 elements. The element size is 0.02×0.0175m.

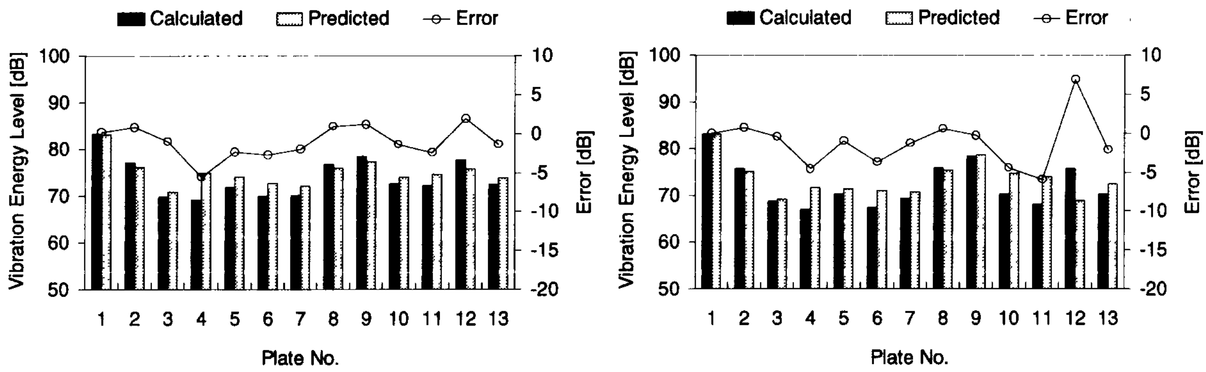
4.1 Construction of SEA model

At first, to construct the SEA model, the response of the structure was calculated in full model calculation under the condition that the plate 9 is excited by a point force. The vibration responses of 4 excitation sets were averaged. The transmitted powers were estimated by the intensity along the junctions between plates. The vibration energy of each plate was evaluated by the displacements at all nodes included in the plate. The SEA model has 13 ILFs, 48 CLFs estimated by Eq.(2) and 12 CLFs by Eq.(4). After the construction of the SEA model, the energy level of each plate under the plate 1 excitation is predicted. The results are shown in Fig.5 with the calculated one by full model calculation. The figure indicates that the energy levels predicted by SEA are in good agreement with those calculated by full model calculation.



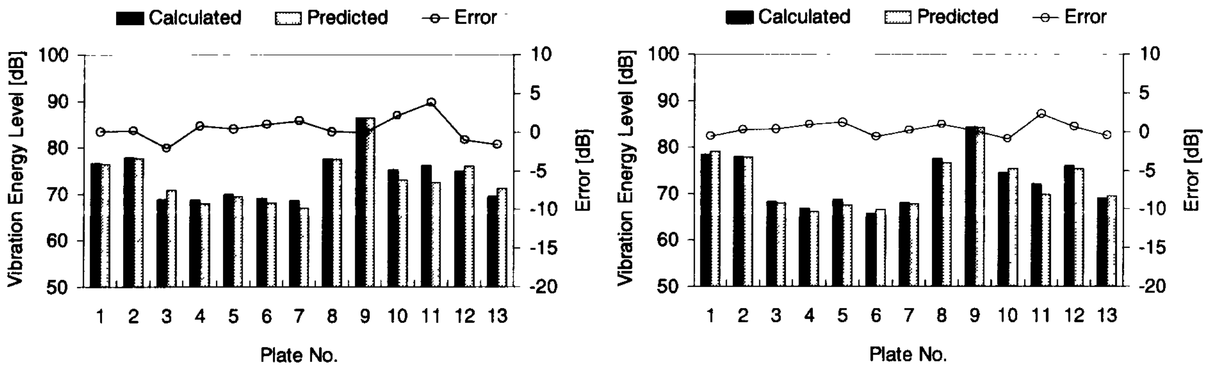
Material : Steel plate $t = 2$ mm
Material damping:0.0 except for hatching area (0.1)
Fig.4 Box-like structure

Moreover, we compared the predicted levels and the calculated levels under another condition.



(a) 500Hz (b) 1kHz

Fig.5 Vibration energy levels in case the plate.1 is excited



(a) 500Hz (b) 1kHz

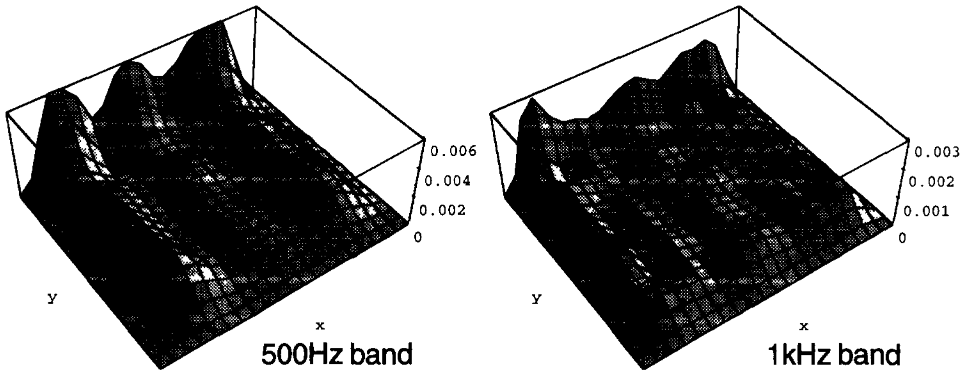
Fig.6 Vibration energy levels in case the plate.9 is excited

That is to say that the SEA model constructed under the plate 1 excitation was used to predict the levels in case the plate 9 was excited. Figure 6 shows the result of the comparison between the predicted and the calculated energy levels. The constructed SEA model gives the high precious prediction of the level.

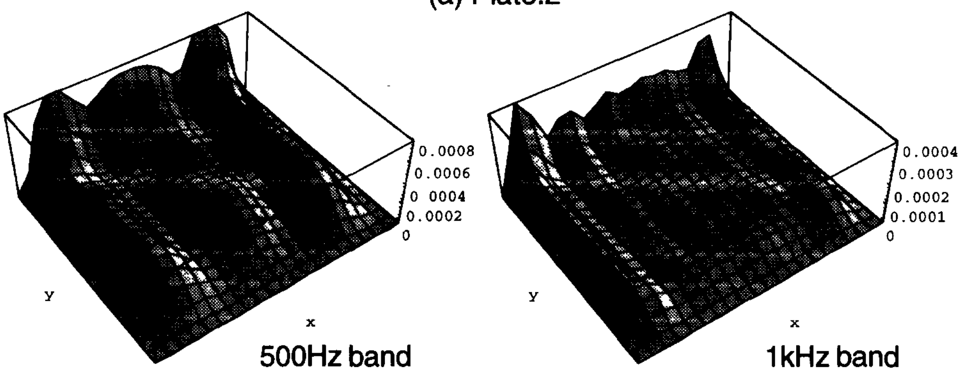
4.2 Prediction of energy distribution

In this section, we discuss the vibration energy levels and the distributions between the results in the full model calculation and those in the sub model calculation. To predict the absolute energy level by sub model calculation, we must know the transmitted power into the subsystem in full model calculation. The power can be easily estimated from the dissipated power or the transmitted power from the neighbor subsystems to the subsystem if the SEA model of the total system is constructed. Therefore, the analysis of the sub model calculation provides the energy level and the distribution per unit input power. And, the level is determined from the multiplication by the dissipated power to predict the absolute energy level in full model. Here, the dissipated power is estimated from the internal loss factor and the calculated energy level, and the loss factor was determined by the method described in chapter 2.

The energy levels and distributions of the plate 2 and 4 are calculated in case the plate 1 is excited. The results are shown in Table.3 and Fig.7. And, the levels and distributions are calculated as shown in Table.4 and Fig.8 in the case the plate 9 is excited. The comparison between Fig.7 and Fig.8 presents that the difference of the excited plate makes large influence to the

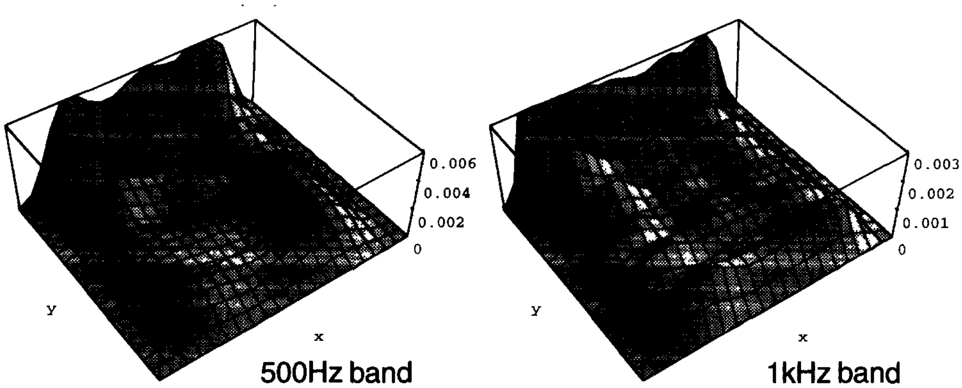


(a) Plate.2

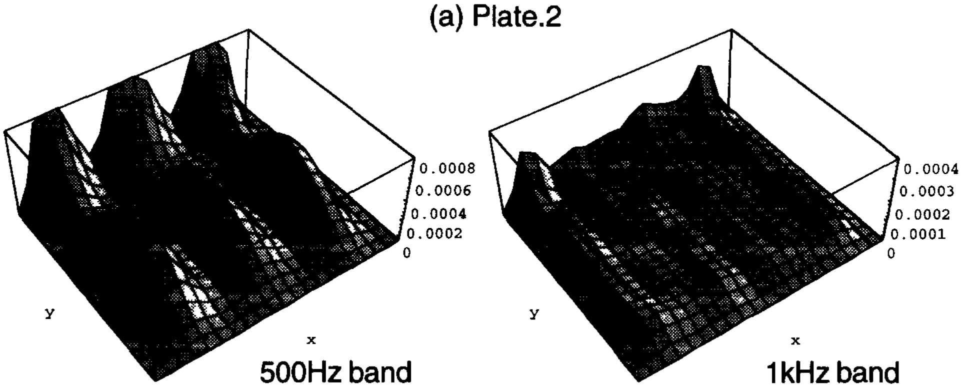


(b) Plate.4

Fig.7 Calculate energy distribution under plate.1 is excited



(a) Plate.2



(b) Plate.4

Fig.8 Calculate energy distribution under plate.9 is excited

Table.3 Comparison of energy levels between by Full and by Sub model under plate.1 is excited

Unit: [J/W]

	Plate.2		Plate.4	
	500Hz band	1kHz band	500Hz band	1kHz band
Full model	0.0013	0.00056	0.00021	0.000074
Sub model(supported)	0.0011	0.00059	0.00018	0.000079
Sub model(fixed)	0.0011	0.00053	0.00018	0.000071

Table.4 Comparison of energy levels between by Full and by Sub model under plate.9 is excited

Unit: [J/W]

	Plate.2		Plate.4	
	500Hz band	1kHz band	500Hz band	1kHz band
Full model	0.0013	0.00086	0.00022	0.000055
Sub model(supported)	0.0011	0.00091	0.00019	0.000059
Sub model(fixed)	0.0011	0.00081	0.00018	0.000052

distribution of the plate 2, and a little influence to that of the plate 4. We think that the excitation location affects strongly in the plate which neighbors on the excited plate.

The sub models of the plate 2 and 4 are same, and the energy levels and the dictributions of the sub models are calculated according to chapter 3. The energy levels are predicted as shown in Tables.3 and 4. These levels are in good agreement with those by full model calculation shown in Table.4 independent of boundary conditions. On the other hand, the predicted distributions have been shown in Fig.3. As for the plate 4, we can recognize the similarity between Figs.7(b), 8(b) calculated by full model and Fig.3(b) calculated by sub model. In case of the plate 2, however, it is difficult to recognize the similarity between Figs.7(a), 8(a) and Figs.3(a),(b). It is because the distribution of the plate which neighbors on the excited plate is affected strongly on the location of excitation. Therefore, we would have to consider the influence of excitation in full model furthermore.

5. CONCLUDING REMARKS

In this paper, we discussed procedures of SEA numerically. Contents are summarized as follows.

(1) The procedure of SEA model construction was proposed and the validity was confirmed.

(2) As for FE analysis aided for SEA, the comparison between full model calculation and sub model calculation is discussed.

(3) To predict the energy distribution inside a subsystem, the finite element analysis of only the subsystem is effective.

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