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# Determining the boundary conditions by estimating RDOFs CMS for piping system

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**Abstract**

It is difficult to obtain boundary conditioners for air conditioner piping system by FE model. An estimating rotational degree of freedoms (RDOFs) component mode synthesis (CMS) method is presented and used to determine the boundary conditions. This paper presents the method to determine the boundary conditions of the piping system from experimental data. A piping system of the air conditioner is carried out as an example using MSC. Nastran, and the comparisons between the results and the experimental ones show the achievements.


*Keywords:* Estimating RDOFs CMS method; FE model; Experimental data; MSC.Nastran; Piping system

## 1. Introduction

Vibration and noise control is important for air conditioners. The piping system is the most important component in the air conditioner outdoor unit, and the FE models are widely used to analyze them. However, it is difficult to set up exact FE models for some components of the piping system because of their complexities, such as the heat exchanger, valve and compressor. Therefore experimental data will be used. Component mode synthesis (CMS) method can be used to describe these components as boundary conditions for the piping system in dynamic analysis. Free boundary CMS method is commonly used because of the easiness of carrying out the experiments (Fu [1]; Fu and Hua [2]; Zou et al. [3]).

CMS methods consist in performing the dynamic analysis of structures by a decomposition of the structure into substructures. The substructures are represented by their modes (in the sense of Ritz vectors), which include the vibration normal modes, the rigid body modes, the static modes, and the interface modes, etc. The CMS method was first used by Hurty [4] in 1960. The idea of decomposing a structure into substructures for dynamic analysis was also used by Gladwell [5] in his branch mode method. Several CMS methods have been developed since then, and all of them made use of the vibrational normal modes of the substructures. Depending on the boundary conditions applied to the substructure interfaces, the CMS methods can be classified into four groups: fixed interface methods; free interface methods; hybrid interface methods; loaded interface methods. The variant in each group differ from each other mainly in the choice of the supplementary Ritz vectors and the associated generalized coordinates, and in the coupling procedure. CMS methods have been reviewed by Tran [6], Meirovitch [7], Imbert [8], Craig [9], etc.

The free interface CMS methods are popular because of the convenience of experiments. Ever since Hou [10] presented the free interface CMS method in 1969, many methods have been developed to improve the couple accuracy. Among those the Craig–Chang [11] method is the most practiced and accurate.

Perfect in theory, there are no problems in applying CMS in full FE models; however there are problems when applied in experimental models. One of the major problems is the spatial incompleteness. The rotational degree of freedoms (RDOFs) are not included in the experiments;

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however, all of the above-mentioned methods are based on spatial completeness (with information of all DOFs, both translational and rotational DOFs). Spatial incompleteness is known to be a problem tracing back to 1972, as referred to the paper by Ewins and Sainsbury [12] and it is still a problem in many cases today. To solve the problem, the RDOFs must be included in the model. In practice, only translational DOFs (TDOFs) can be obtained easily in experiments. In the other hand, there is no such a problem when coupling two FE models with CMS method.

Duarte [13] has reviewed the history of researching on obtaining RDOFs from 1972 to 1997. Many methods have been used to get RDOFs (Quattro [14], Helderwerit [16], Avitabile [17,18], Yoon [19] study on the RDOFs estimation; Ziaei-Rad [15] measured RDOFs by laser Doppler vibrometer). Since the usual instruments are relatively large that it may not be practiced to use the direct measurements in experiments for the piping system. Hence indirect method, which estimates the RDOFs from TDOFs, is preferred. Silva et al. [20,21] have estimated the rotational frequency response functions (FRFs) using T-block and mass uncoupled method (MUM). They are mostly based on the close-accelerometers method to estimate RDOFs.

This paper focuses on determining the boundary conditions of the piping system, which are transformed from experimental results by the estimating RDOFs CMS method. The method is firstly to obtain the RDOFs from the experimental data and then apply in CMS method; furthermore the boundary conditions by stiffness, mass and damping matrixes are obtained from the experimental results. A piping system of air conditioner outdoor unit is studied as an example. The comparisons between the simulation and experimental results verify the boundary condition derived in this paper. Some aspects are discussed for the utility of the estimating RDOFs CMS method, and some conclusions are drawn.

## 2. Estimating RDOFs CMS method

### 2.1. Estimating the RDOFs from experimental TDOFs

In most situations, only force excitations can be applied to the structure, while the moment excitations are difficult to be applied. If we can measure the TDOFs and RDOFs FRFs with the force excitation, the full spatial DOFs modal parameters can be obtained (Quattro [14]).

Close accelerometers are used to estimate RDOFs. Two or three accelerometers are displaced closely in the same direction, which is shown in Fig. 1. Acceleration $y_1$, $y_2$, $y_3$, and the force excitation are in the same direction. If $y_1$, $y_2$ and $y_3$ are obtained, angle $\theta_3$ can be estimated by the closed accelerometers. For RDOF $\theta_3$:

$$\begin{Bmatrix} y_3 \\ \theta_3 \end{Bmatrix} = \left[T_{1f}\right]\begin{Bmatrix} y_2 \\ y_3 \end{Bmatrix} = \begin{bmatrix} 0 & 1 \\ 1/d & -1/d \end{bmatrix}\begin{Bmatrix} y_2 \\ y_3 \end{Bmatrix}. \quad (1)$$

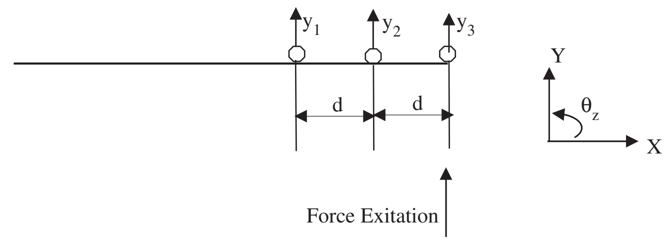

Fig. 1. Close-accelerometers method for RDOFs measurement.

The FRFs are

$$\begin{Bmatrix} H_3 \\ H_{\theta_3} \end{Bmatrix} = \left[T_{1f}\right]\begin{Bmatrix} H_2 \\ H_3 \end{Bmatrix}. \quad (2)$$

When the modal models are used to describe the experimental models, Eqs. (1) and (2) still agree with the modal vectors $\{\phi_j\}$ ($j = 1$, $N$; $N$ is the number of the modes).

There are still errors in the experiments, and the experimental results are not the real ones. Optimizations of estimations of the experimental results are very useful. Since the modal vectors are the modal shapes, RDOFs can be obtained by Spline and least-square errors method (LSEM) with the following assumptions [22].

(1) Modal shapes are continuous and have second derivative.
(2) Their experiments of the components can be obtained.

If test point $x$ and its vibration $y$ are known,

$$(x_i, y_i), \quad i = 1, 2, \ldots, M.$$

$y = f(x)$ is used to express the relationship between $x$ and $y$.

As $f(x)$ is polynomial,

$$y = a_0 + \sum_{k=1}^{N} a_k x^k. \quad (3)$$

Error function is defined as follows:

$$\mathrm{EER} = \sum_{j=1}^{M}\left(f(x_j) - y_j\right)^2. \quad (4)$$

The equation for LSEM is

$$\begin{bmatrix} M & \sum_{i=1}^{M} x_i & \cdots & \sum_{i=1}^{M} x_i^N \\ \sum_{i=1}^{M} x_i & \sum_{i=1}^{M} x_i^2 & \cdots & \sum_{i=1}^{M} x_i^{N+1} \\ \vdots & \vdots & & \vdots \\ \sum_{i=1}^{M} x_i^N & \sum_{i=1}^{M} x_i^{N+1} & \cdots & \sum_{i=1}^{M} x_i^{2N} \end{bmatrix}\begin{Bmatrix} a_0 \\ a_1 \\ \vdots \\ a_N \end{Bmatrix} = \begin{Bmatrix} \sum_{i=1}^{M} y_i \\ \sum_{i=1}^{M} x_i y_i \\ \vdots \\ \sum_{i=1}^{M} x_i^N y_i \end{Bmatrix}. \quad (5)$$