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Development of Ship Vibration Analysis Software PFADS-R3 and Its Applications

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Abstract

PFFEM software, PFADS has been developed for the vibration predictions and analysis of coupled system structures in medium-to-high frequency ranges. PFFEM is numerical method which solves energy governing equation using finite element technique for complicated structures where the exact solutions are not available.
Through the upgrades, present PFADS R3 could cover the general beam and plate structures including various kinds of beam-plate rigid joints and other joint systems such as spring-damper junction and rigid bar connection. This software is composed of 3 parts; translator, model converter and solver. The translator makes its own FE-model from bulk data of commercial FE software, and the model converter is used to convert FE-model to PFFE-model automatically. The solver calculates vibrational energy density and intensity for PFFE-model by solving global matrix equations of PFFEM.

For the applications of real transportation systems, a container ship model has been examined with respect to major parameters, and reliable results have been obtained.
Keywords: PFFEM, vibration software, medium to high frequency

1 Introduction

PFFEM is numerical method for Power Flow Analysis which recently has been recognized as NVH tool in medium to high frequency ranges. In the beginning, PFFEM could only analyze the averaged vibration response of structural elements such as simple beam and simple plate structures.(Nefske and Sung 1989, Bouthier and Berhard 1992) Since a methodology was presented to solve coupled problems between structural elements by Cho(1993), many researches have been developing for various built-up structures; such as built-up structures with plates and stiffened plates with reinforcing beams.(Seo 2000, Seo et al 2003) Recently, problems of more complex joints have been settled in order to extend application of PFFEM to real built-up structures.

SNOVIL(Ship Noise and Vibration Lab. in Seoul National University) has been developing a vibration analysis software based on PFFEM called by PFADS(Power Flow Analysis Design System). The most recent version, PFADS R3 has a powerful main solver for the various elements and joints of structures, especially rigid bar elements and spring-damper elements commonly used in real built-up vehicle structures.

In addition to main solver, PFADS R3 provides utility functions; loading other FE model(Translator) and converting FE model to PFFE model(Model Convertor). PFFEM is partially similar to FEA due to same numerical technique, but analysis models are distinctly different. PFFE model is more complex than FE model because PFFE needs joint elements to cover junction problems. In PFADS, a PFFE model can be easily obtained from the original FE model for commercial FE software using Translator and the Model Convertor.

In this paper, implementation on PFADS R3 is presented with data structures and functions. At first, overview for PFFE model of PFADS and procedures getting its model is described, and then structures and functions of PFADS solver are explained. For the purpose of confirming the usefulness of this software, an application is performed for the large scale structure system.

2 PFFE model

FE model is not suitable in power flow finite element analysis because nodal energy density at a joint is discontinuous. PFFEM needs a unique PFFE model different from FE model. In FE model, structural elements such beam and plate share nodes with adjacent elements because of compatibility of displacement at the joint nodes of structural elements. In the case of PFFEM of which primary variable is averaged vibration energy density, the compatibility at the joint nodes cannot be satisfied due to energy attenuation (Cho 1993). Therefore, PFFE model requires joint elements which are physically unseen to connect structural elements.

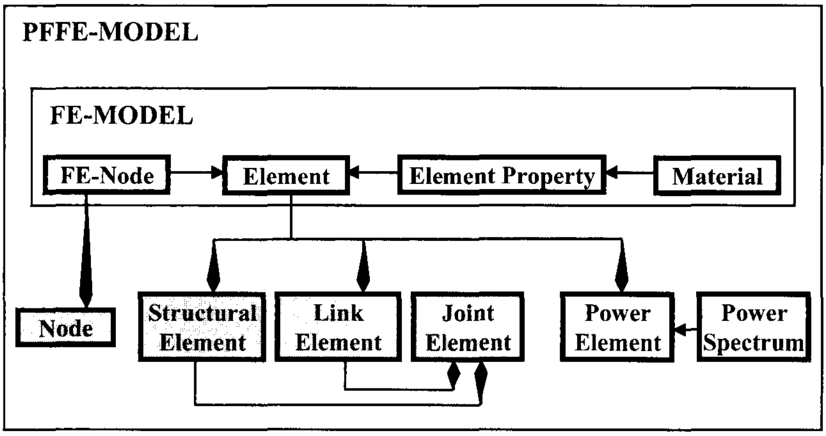


Figure 1: Data Structures of PFFE Model

Data structures of PFFE model for PFADS are shown in Figure 1. Arrows mean referring relations among data. As a part of PFFE model, FE model of PFADS plays an important role in forming structural geometry for numerical analysis. FE model is composed of 4 key FE data; FE nodes, material property, element property and element. FE model can be loaded from a bulk file with specific formats similar to other FE software. PFFE model has three different elements; structural, link, and joint elements. Structural elements of PFADS are defined as elastic continuum elements occurring energy dissipation within the elements, and can be expressed as energy governing equations. PFADS R3 supports four node plate, three node plate, beam and rod structural elements. Figure 2 describes shape, DOF, and other parameters for the structural elements. In this version, rod structural element is added to propagate a longitudinal wave.

Two kinds of link elements of PFADS, new concept of this version, are defined. One is non-structural elements connecting structural elements, such as spring-damper element and rigid bar element. The other is structural elements including predefined structures such as beam or rod stiffener of stiffened plates. Link element is only used in a part of joint elements for analysis. Structural elements and link elements are obtained from element data of FE model.

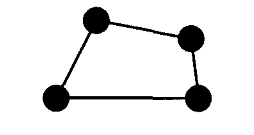
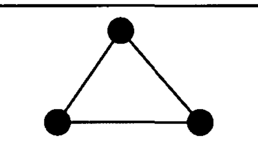
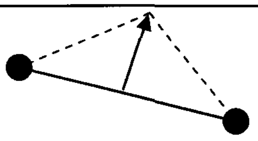
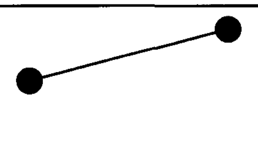
ELEMENT	SHAPE	DOF	MATERIAL	CROSS SECTION
PLATE4		Flexural wave Longitudinal wave Shear wave	Density Elastic Modulus Poisson ratio Damping coeff.	Thickness
PLATE3		Flexural wave Longitudinal wave Shear wave	Density Elastic Modulus Poisson ratio Damping coeff.	Thickness
BEAM		X-dir. flexural wave Z-dir. flexural wave Longitudinal wave Torsional wave	Density Elastic Modulus Poisson ratio Damping coeff.	Area Iyy Izz J
ROD		Longitudinal wave	Density Elastic Modulus Poisson ratio Damping coeff.	Area

Figure 2: Structural Elements

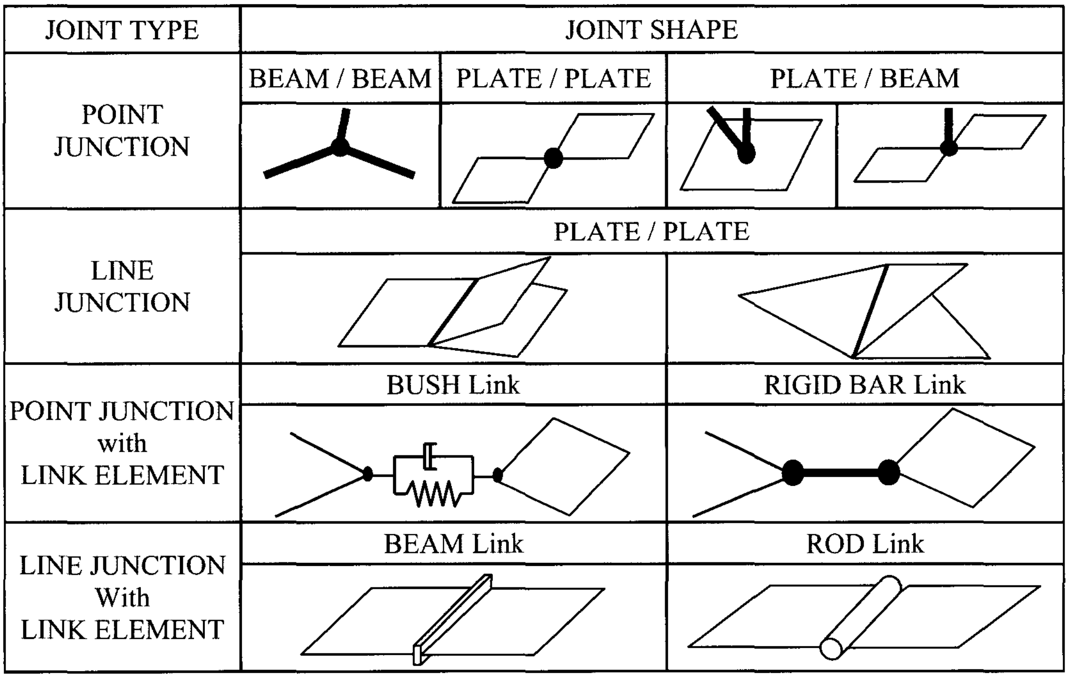


Figure 3: Joint Elements

Joint elements of PFADS mean the joint changing power transmission among structural elements. Figure 3 shows joint element structures PFADS R3 supports. There are 4 kinds of structures for joint elements; (1) point-joined of structural elements, (2) line-joined of plate structural elements, (3) point-joined of structural elements at both ends of spring-damper or rigid bar link element, and (4) line-jointed of plate structural elements along beam or rod link element.

More nodes are needed in PFFE model than FE nodes due to the joint elements in PFFE model. Several PFFE nodes can exist in same location, because at the joint FE nodes are separated and duplicated for PFFE nodes considering joint elements inserted between structural elements. A PFFE node, of course, holds only ID number of original FE node and the location information of the PFFE node could be obtained by referring the FE node. In PFFE model, Power spectrum and power elements are related with excitation condition. Power spectrum is frequency-dependent vibration power to be applied to FE elements, and the FE element holding the power spectrum is power element.

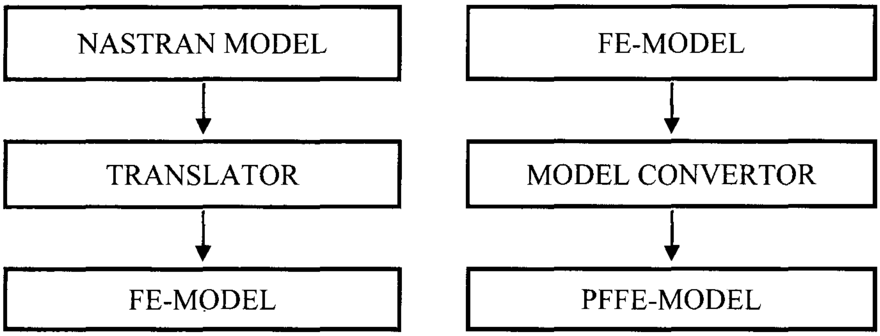


Figure 4: Translator and Model Convertor

PFADS provides the functions easily acquiring the PFFE model, and those are translator and model convertor shown in Figure 4. Translator generates a FE bulk file for PFADS from bulk files of other commercial FE program. Model convertor automatically changes the FE model obtained from translator to PFFE model.

From now the procedures of generating PFFE model are explained. The first stage starts with the translator, which reads FE model data of NASTRAN bulk file and extracts 4 key FE data and then writes FE model data for PFFEM. The translator for NASTRAN has the following features;

- Translates entries of model geometry, element connectivity, element property and material property except constraint and load entries.
- Translates NASTRAN bulk in binary and ascii formats.
- Translates FE model for PFFEM to NASTRAN bulk file for cross-checking.
- Works as an independent module.

The next stage is to convert FE model for PFFEM to PFFE model by using the module of the model convertor. The model convertor finds the joints from the FE model by searching element by element, inserts new PFFE nodes, and generates joint elements. Here, new effective algorithm is applied and enhances searching time in contrast to the previous PFADS.

The last stage is to determine various anlaysis condtions. The PFFEM based on vibrational energy is such system that vibrational power is used as input and vibrational energy is used as output, while conventional FEM inputs force and outputs displacement by solving the motion of equations. Therefore, as the boundary conditions for PFFEM, vibrational power or energy should be determined at nodes or elements instead of force or displacement valid in general FEA. In this software, boundary conditions are limited to the distributed power input to structural elements using frequency-dependent power spectrums and power elements. The other analysis conditions are as follows;

- Shows fluid loading effects by changing structural internal loss factor and group velocity using fluid property similar to SEA programs.
- Selects DOFs(wave types) to include in main analysis. A plate element has 3 DOFs with flexural, longitudinal and shear waves, and a beam element has 4 DOFs with 2 kinds of flexural wave, longitudinal and torsional waves. More DOF model allows accurate results and spends much calculating time.
- Selects a linear equation solver. This software offers wave frontal solver as a direct method and various indirect methods of conjugate gradient series.
- Selects miscellaneous option in wave transmission analysis.

3 Solver

Generally, energy governing equation for the wave propagation of structural elements is expressed as the following second-order differential form (Seo 2000, Seo et al 2003),

$$-\frac{c_g^2}{\eta\omega}\nabla^2\langle e\rangle + \eta\omega\langle e\rangle = \Pi \qquad (1)$$

where ω is the angular frequency, η is the structural loss factor in the structural component, $\langle e\rangle$ is time- and space-averaged energy density, c_g is the group velocity and Π is input power to the structure. The time- and space-averaged farfield smoothed power flows of that wave is given by

$$\langle I\rangle = -\frac{c_g^2}{\eta\omega}\nabla\langle e\rangle \qquad (2)$$

To implement the energy governing equation numerically with finite element method, the following matrix equations are obtained through weak form of the energy governing equation and Galerkin weighted residual method,

$$\left[K^{(e)}\right]\left\{e^{(e)}\right\} = \left\{F^{(e)}\right\} + \left\{Q^{(e)}\right\} \qquad (3)$$

$K_{m\,ij}^{(e)}$ is a term in the coefficient matrix which contains both stiffness- and mass-matrix terms, $F_{m\,i}^{(e)}$ is the input power and $Q_{m\,i}^{(e)}$ is power flow of which the positive direction is defined as a vector into its element. Subscript m means wave type; for example, one of flexural, longitudinal and shear waves in plate elements.

The global matrix equations for the various wave types can be represented, by assembling the element matrix Equation (3), as

$$\begin{bmatrix} K_1 & & \\ & \ddots & \\ & & K_n \end{bmatrix} \begin{Bmatrix} e_1 \\ \vdots \\ e_n \end{Bmatrix} = \begin{Bmatrix} F_1 \\ \vdots \\ F_n \end{Bmatrix} + \begin{Bmatrix} Q_1 \\ \vdots \\ Q_n \end{Bmatrix} \quad (4)$$

where the subscripts mean all wave types of structural elements. Because of the discontinuity of energy density at a joint, it is necessary to insert joint elements at the joint to connect the coupled structural elements. The joint elements are expressed with partially transmitted and reflected wave power coefficients and group velocities. The general matrix equation form $\{Q\}=[J]\{e\}$ of the joint elements implies the relationship between energy density and power flow at the joint. By substituting this joint element form into global matrix equation, the final multi-DOF matrix equations of PFFEM for complex structure systems is expressed as (Nefske and Sung 1989)

$$[\mathrm{K}-\mathrm{J}] \begin{Bmatrix} e_1 \\ \vdots \\ e_n \end{Bmatrix} = \begin{Bmatrix} F_1 \\ \vdots \\ F_n \end{Bmatrix} \quad (5)$$

The PFADS solver calculates vibrational energy density for the PFFE model obtained in the pre-processing by solving above linear equation. For the structural elements, elemental matrices are very quickly formed by several matrix operations similar to FEA in the PFFEM formulation of the energy governing equation. Nodal coordinate transformation, proper shape functions and quadrature position are used.

For the joint element matrices, partially transmitted and reflected power coefficients are calculated by using wave transmission approach for the entire joints, which offer frequency-averaged responses of the real finite structures through analyzing alternative infinite structures. After forming elemental matrices, global matrices are assembled considering the selected DOFs and boundary conditions are applied to final linear equations. By given linear equation solver method, the energy density is obtained at the nodes.

Then intensity inside each element can be calculated using the energy density obtained, and numerical derivatives, and motion components (e.g. RMS acceleration, peak velocity, etc) can be also roughly estimated by the concept that total vibration energy is approximately equal to 2 times of kinetic energy for the low damping structures.

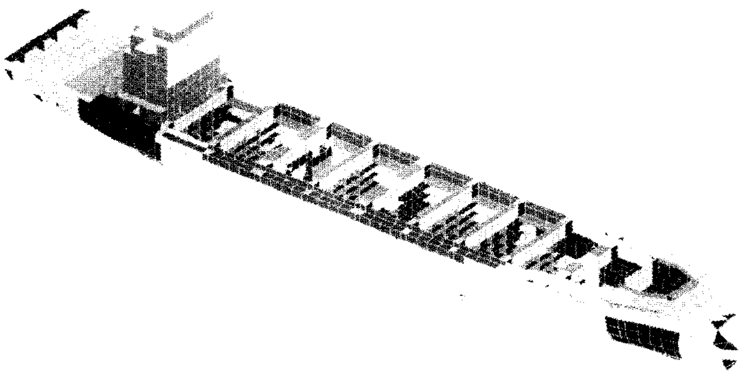


Figure 5: FE model of 2300TEU container.

4 2300TEU Container Ship Vibration Analysis

As an application of the software, a container-ship model is selected as shown in Figure 5. 9446 plate elements are used in forming the hull and 3155 beam elements are added as stiffeners. 124 different types of element property are applied in order to consider the plate thickness of the real system. By converting the FE model to a PFFE model through the model convertor of PFADS, 31931 PFFE nodes are generated and 7186 plate-coupled joint elements and 2904 beam-stiffened joint elements are added.

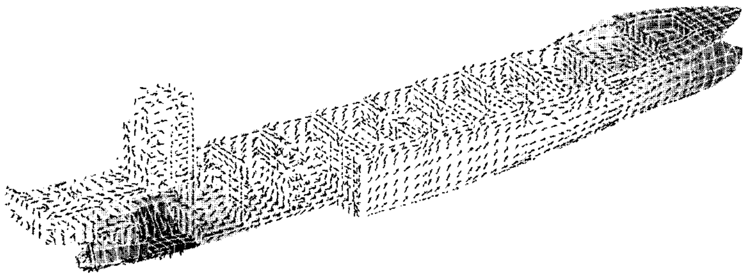


Figure 6: Energy density and Intensity.

Input power is applied to the engine bed. Figure 6 shows energy density levels and intensity vector fields for the 1000Hz excitation frequency. It is found that vibration energy flows toward the bow and the superstructures far from the exciting position. Figure 7 shows the RMS acceleration levels for the container model. The global distributions of acceleration levels do not coincide totally with those of energy density levels because of the different element properties (See Figure 6 and 7). Figure 8 show the energy density of the stern part and distinct difference of energy levels at the engine bed(exciting position) and the superstructure.

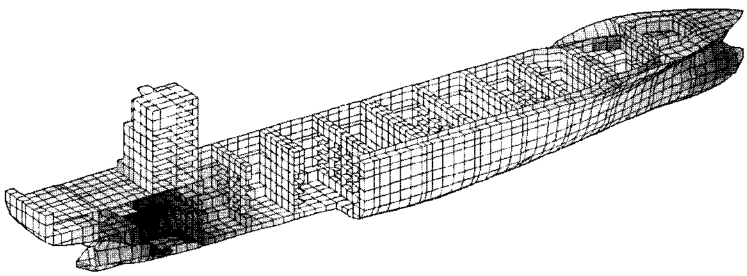


Figure 7: Acceleration level(dB).

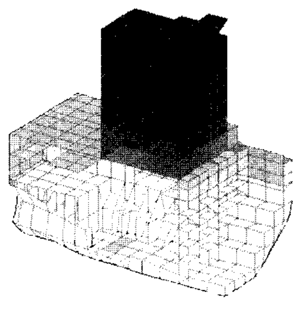


Figure 8: Energy density of stern part.

5 Conclusions

The PFFEM software, "PFADS R3" is developed with many useful functions. As link elements and others are added in this version, it is possible to apply to general structure system. The translator and model convertor are also developed as utility programs independent on main program. For an automobile and ship model, energy density, intensity and acceleration are effectively predicted with using the developed software. The results confirm that this software can be an excellent tool for the vibration control and prediction used in automobile, shipbuilding and other fields of industry.

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