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Reconciliation of Finite Element Model of a Simplified Model of Oil Rig Platform Structure

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ABSTRACT

Vibration effects on the complex structures such as oil rig platforms are extremely difficult toinvestigate due to operation conditions and harsh environments. The information of thestructural vibration behaviour of such structure are extremely significant at the design stage, inorder to overcome failures and disaster especially during the structure's operation. In this paper,the vibration responses of the simplified oil and gas platform structure is investigated using finite element analysis (FEA). The simplified model oil and gas platform structure are modelledusing two type of elements namely shell element and beam element and the feasibility betweenthe two modelled are evaluated. The first ten elastic modes in terms of natural frequencies andmode shapes of the finite element (FE) model is validated with experimental modal analysis (EMA) counterparts to quantify accuracy of developed FE model of the structure. The result shows that FEA-SHELL Model was providing the greater accuracy compared to FEA-Beam Model despite burdened with modelling uncertainties. Nevertheless, reconciliation scheme via FE model updating was introduced for improving the structure's modelling uncertainties. In conclusion, despite the initial FEA-SHELL Model associated with modelling uncertainties, themodel can still be considered as the best choice to predict the dynamic responses of the simplified oil and gas platform structure with the aid of FE model updating method.

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INTRODUCTION

The development of complex structures for structural dynamic applications such as offshore structures have become the most challenging tasks faced in engineering field. Owing to the fact that an offshore structure such as jacket and jack-up of oil rigs possess their own dynamic behaviour [1], then vibration effect exhibits on the offshore structures due to the interaction between dynamic and hydrodynamic responses have become a major consideration in design phase.

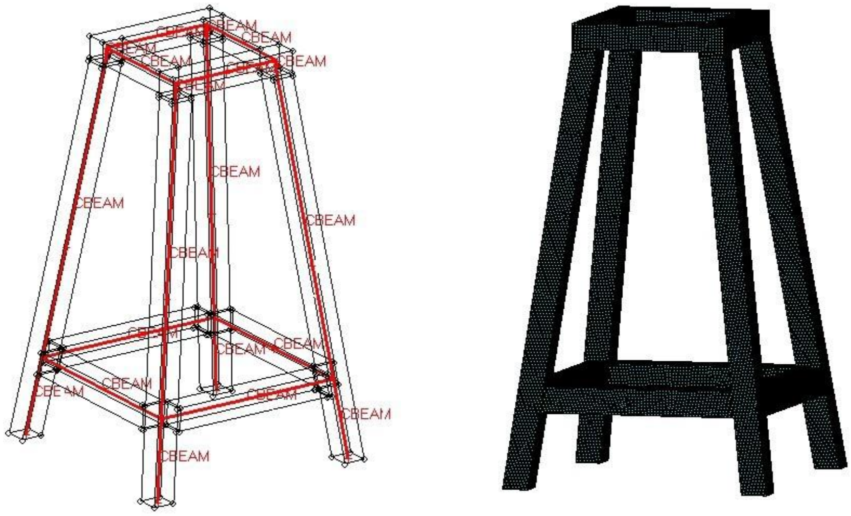
In design stage, the dynamic analysis is normally performed by considering the vibration source from the machineries such as reciprocating and rotating equipment. Therefore, during the design phase it is preferable to make minor changes to the structural design to avoid the structural resonance. The vibration characteristic of the structure can be identified by analytically, numerically via software analysis and vibration test. However, for simple structures like beams and plates, the responses can be calculated using closed form solutions. However, for the complex shape of structures such as engineering structure the iterative numerical method such as Finite Element method (FE) is more practical and efficient [2], [3]. understandably the FE model is a mathematically representation of the structure and the input parameters of FE model usually based on the idealisation and simplification of element material properties, geometrical properties, boundary conditions of the structure. Therefore, the developed FE model may not accurately represent the actual physical aspects of the structure [4] [5]. In contrast, the experimental modal analysis (EMA) is used to validate the initial dynamics behaviour of the base model of structure. The deterministic model correlation technique such as the FE model updating method can be used to improve the initial result of FE model to match the target responses based on experimental result [6]. The purpose of modal based updating is to modify the parameter values of input properties of the FE model and to obtain better with experimental result. Meanwhile the correlation between experimental and predicted FE mode shapes of the structure can be assessed by using a several techniques [7]-[9]. The Modal Assurance Criterion (MAC) is a technique to quantify the quality of mode shapes [10][11]. In this paper the modal based updating was utilised to enhance the initial FE model of the simplified model oil and gas platform structure by benchmarking with the experimental result. The updating parameters were identify using sensitivity analysis and the selected parameters were updated systematically to match with EMA result so that the accurate model can be used for the subsequence analysis.

FINITE ELEMENT MODELLING AND ANALYSIS

In this paper the simplified model of oil and gas platform structure was investigated. The structure was modelled using two types of structural element namely beam element and shell element. The FE models of the simplified model of oil and gas platform structure were created and defined according to the physical structure. Figure 1 shows the details of element meshing of beam and shell elements. The input properties of the FE models are shown in Table 1. The frequency of interest of the FE models is set between 0 Hz to 1000 Hz.

Table 1: Details of the input properties of the FE models

Properties	Input	Unit
Young’s modulus	210000	MPa
Poisson’s ratio	0.30	-
Mass density	7.85×10^{-9}	Tonne/mm^3



(a) Beam Element (b) Shell element

Figure 1: FE model (a) Beam Element and (b) Shell element

The normal mode solution was used to calculate the dynamic responses and the calculation was performed using the MSC Patran/Nastran. To calculate the vibration responses of the structure, the linear system of the vibration equations can be written as

$$\mathrm{M}\ddot{u}(t) + \mathrm{C}\dot{u}(t) + \mathbf{kk}u(t) = \mathrm{F}(t) \tag{1}$$

where $\mathrm{M}\ddot{u}$ denotes the matrix of the mass, $\mathrm{C}\dot{u}$ the damping matrix and $\mathbf{kk}u$ the stiffness matrix of the system. On top of that, in Equation (1) $\ddot{u}$ (u, t) denotes the acceleration, u ($\dot{u}$, t) the velocity, u (u, t) the displacement. Meanwhile, F (t) is the external time dependent loads apply to the system. Although the structural damping is theoretically present in plate structure, however the effect can be neglected since it has a little effect or no effect to the structure [11], [13]. If the system is assumed to have a lightly damping and can be neglected, therefore the Equation (1) changes to form,

$$\mathrm{M}u(t) + \mathbf{kk}u(t) = \mathrm{F}(t) \tag{2}$$

Boundary conditions are introduced to transformation the differential equation of Equation (2) into the frequency domain via the harmonic time approach,

$$u(0) = u0\ ;\ u(0) = \dot{u}0,\ \mathrm{F}(t) = 0 \tag{3}$$

The displacement and acceleration are given by the equations,

$$\mathbf{uu}\ (\mathrm{t}) = \mathrm{y}eeii\Omega tt \quad \text{and} \quad \mathbf{u}\ddot{\mathbf{u}}(t) = -\Omega 2\mathbf{yy}eeii\Omega tt \tag{4}$$

By substituting Equation (3) into Equation (4) into the equation of motion in the matrix form, therefore, The Equation (2) will form,

$$(-\Omega 2\mathrm{M}\mathbf{yy} + \mathrm{K}\mathbf{yy})eiint = 0 \tag{5}$$

where $eiint$ denotes the complex amplitude of the displacements Ψ and λ is the angular frequency of the excitation of the system. The classical eigenvalue problem in matrix notation is written as,

$$(\mathrm{K} - \lambda\mathrm{M})\Psi = 0 \tag{6}$$

DESIGN SENSITIVITY AND FINITE ELEMENT MODEL UPDATING

The deterministic reconciliation scheme was used to correct the invalid parameter inputs of the base FE model of the structure. The modal based updating is utilised systematically to enhance the correlation of base FE model of the structure by improving the initial input parameters to an acceptable level of by correcting the uncertain input of model parameters iteratively via systematic method. The selection of the sensitive parameters to the change of modal properties are very crucial to retain the physical meaning of engineering to avoid non convergence problems based on the objective function. The approximate optimisation problem is constructed based on Taylor series expansions as [14],

$$z(\boldsymbol{\theta}+\Delta\boldsymbol{\theta}) = z(\boldsymbol{\theta}) + \left.\frac{dz}{d\boldsymbol{\theta}}\right|_{\theta}\Delta\boldsymbol{\theta} + \left.\frac{d^2z}{d\boldsymbol{\theta}^2}\right|_{\theta}\frac{\Delta\boldsymbol{\theta}^2}{2!} + \left.\frac{d^3z}{d\boldsymbol{\theta}^3}\right|_{\theta}\frac{\Delta\boldsymbol{\theta}^3}{3!} + \ldots. \tag{7}$$

During updating process, the updating algorithm is formulated to obtain the optimum gradient containing the best configuration within a set of design spaces of the parameters and the design constraints by assigning the lower and upper bound values. The design constraint lower and upper bound values the values of design variables, given by

$$x_i^L \le x_i \le x_i^U \tag{8}$$

where x_i^L,is the lower bound and x_i^U, is the upper bound on the *i* th design variable values

The design variables are updated to fit best combination value of the objective function iteratively until the assigned design variables converge to the optimal values. The selection of the potential parameters can be identified using sensitivity analysis as given by [14],

$$\mathbf{S} = \Psi_i^{\mathbf{T}}\left[\frac{\partial\mathbf{K}}{\partial\theta_j} - \lambda_i\frac{\partial\mathbf{M}}{\partial\theta_j}\right]\Psi_{\mathbf{i}} \tag{9}$$

where, the sensitivity matrix is represented by **S** of the assigned parameters, meanwhile, the stiffness and mass matrices of the system are represented by **K** and **M**. The Ψ, λ and θ representing the eigenvector, eigenvalue, and parameter and the objective function can be written as [14],

$$J = \sum_{i=1}^{n} W_i \left(\frac{\lambda_i^{\mathrm{fe}}}{\lambda_i^{\mathrm{exp}}} - 1 \right)^2 \tag{10}$$

where, λ_i^{exp} is the *i*-th test natural frequencies and λ_i^{fe} is the *i*-th initial natural frequencies from the initial FE model and n is the number of natural frequencies included in the updating procedure.

EXPERIMENTAL MODAL ANALYSIS – IMPACT TESTING

Modal impact hammer was used to excite the structure to obtain the dynamic properties of the structure for subsequent analysis. The steel tip was used in the EMA test to ensure the optimum result during the impacting because the length and energy of the impulse is influenced by the mass and type of the hammer tip [8]. In the experimental set up, the structure was suspended using the soft springs to replicate in free-free boundary conditions to the structure. The experimental setup in Figure 2, was preferred to minimise the gravitational effects and provide stability to the structure during the impacting process.

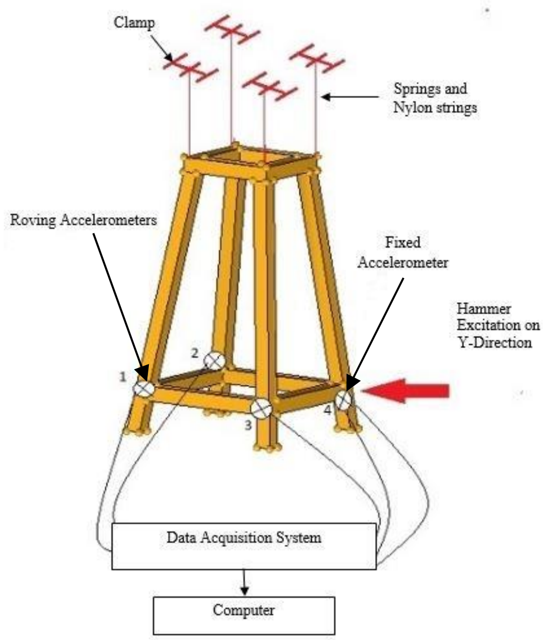


Figure 2: Experimental set-up for the test structure

The the dynamic properties of the structure were extracted using the Leuven Measuring System (LMS) data acquisition system. In experiment, there were 3 accelerometers (Dytran 3032A), and impact hammer (PCB 086C02) were used to extract the vibratory responses of the test structure.

The impact excitation and the measure points were chosen based on initial result of FE model to ensure that all the flexible body modes were well-covered based on the frequency of interest. The frequency band of interest for the experiment was ranging from 0 to 1000 Hz and the frequency resolution was set at 0.5 Hz. In this study, results of the dynamic responses in term of natural frequencies and mode shapes of the plate structure are tabulated in Table 2 and Table 4 respectively.

MODAL ASSURANCE CRITERION (MAC)

In EMA, the MAC analysis is to quantify the mode shapes by pairing the modes shapes derived from analytical models with experimental data [10]. The value of MAC determines the accuracy of the mode shape correlation between the base FE model and EMA results. For a high level of correlation, the values indicates that the base model is very close to the experimental counterpart and the MAC value is 0.90 and higher. However, if the correlation is very poor and having a low accuracy, the MAC value is lower than 0.5. The MAC equation is expressed as [11]:

$$\mathrm{MAC} = (\Psi_e \Psi_a) = \frac{|\Psi_e^T \Psi_a|}{(\Psi_a^T \Psi_a)(\Psi_e^T \Psi_e)} \tag{11}$$

RESULTS AND DISCUSSION

The investigation on the dynamic responses of the gas platform structure was performed numerically and experimentally using finite element analysis (FEA) and experimental modal analysis (EMA) respectively. Meanwhile, model updating algorithm was developed to improve the initial prediction obtained from the FEA. Table 2 shows the comparison of natural frequencies obtained from EMA and FEA using different types of elements and the result shows the FEA-SHELL model is closed to EMA result with the total discrepancies of 88.92 %. From Table 2, the FEA-BEAM model shows higher total discrepancies which is 392.18 % because of swap mode. In term of mode similarity, the MAC results were highlighted a good correlation with all the modes in both models recorded MAC values more that 70 %. Nevertheless, the presence of swap modes has led to high difficulty in reducing the total discrepancies in the FEA-BEAM model. From the result in Table 2, it can be assumed that the beam element is incapable to model the structure the due to higher stiffness of the element.

In Table 2, the EMA result shows the closely spaced modes in mode 8 with mode 9. Meanwhile in FEA, the sets of closely spaced modes occur in beam element model particularly on mode 3 with mode 4 and mode 8 with mode 9. However, there is no close modes occurs in the shell element FE model. From the result of Table 2, the shell element is providing the greater accuracy compared to beam element. Hence, the FEA-SHELL model was selected for the further improvement via FE model updating method.

The deterministic modal based updating has been applied to the FE model of the simplified model oil and gas platform structure of shell element. Table 2 shows that there are significant discrepancies in the of the initial FE results which accumulatively of 88.92 %. The result suggests that there were considerable shortcomings in the initial FE model because of incorrect assumptions of the input properties. Therefore, the initial FE model must be updated to reduce the discrepancies of the model. In contrast, the mode shapes of the initial FE model of the plate are found reasonably correlated well with the experiment data with more than 0.8. The attempt to improve the initial FE model was made by identify the most sensitive parameter in the FE model of the simplified model oil and gas platform structure based on the sensitivity analysis and it was found that the natural frequencies of the plate structure were found to be sensitive to Young's modulus of structure components, Young's modulus and thickness of the welded area. Therefore, the Young's modulus of structure components, Young's modulus and thickness of the welded area of the simplified model of oil and gas platform structure were used as the updating parameters. It can be seen, there is a significant improvement on the updated FE result, the total discrepancies of the predicted frequencies of the simplified model of oil and gas platform structure are sharply reduced from 88.92 % to 51.7%. The updated parameters slightly decreased from the nominal value of input parameters from 210 GPa to 190 GPa as shown in Table 3. Meanwhile Figure 3 shows the convergence graph of the selected updating parameters using normalised value.

Table 2: The comparisons of natural frequencies for beam and shell models.

Mode	EMA (Hz)	FEA-Beam model		FEA-Shell model			
		Frequency (Hz)	Discrepancy %	Frequency (Hz)	Discrepancy %	Updated (Hz)	Discrepancy %
1	119.12	433.40	263.8	143.47	16.97	121.64	2.1
2	283.65	309.54	9.1	312.36	9.19	296.85	4.4
3	325.78	427.7	31.3	384.47	15.27	363.52	10.4
4	348.82	427.7	22.6	385.08	9.42	363.64	4.1
5	540.22	589.13	9.1	565.78	4.52	528.68	2.2
6	551.1	595.84	8.1	591.98	6.91	560.24	1.6
7	593.6	772.17	30.1	596.85	0.54	565.28	5.0
8	627.5	651.88	3.9	671.43	6.54	636.78	1.5
9	627.72	651.88	3.8	672.01	6.59	637.31	1.5
10	777.56	697.17	10.3	688.27	12.97	653.58	19.0
Total Discrepancy			**392.18**		**88.92**		**51.7**

Table 3: Updating parameter for the shell model.

Parameter	Nominal value	Updated value	Difference (%)
Young's modulus, E (Structure)	210 000 MPa	190 000 MPa	10
Thickness (Structure)	1.5 mm	1.43 mm	25
Young's modulus, E (Weld)	210 000 MPa	190 000 MPa	10
Thickness (Weld)	1.5 mm	1.43 mm	5

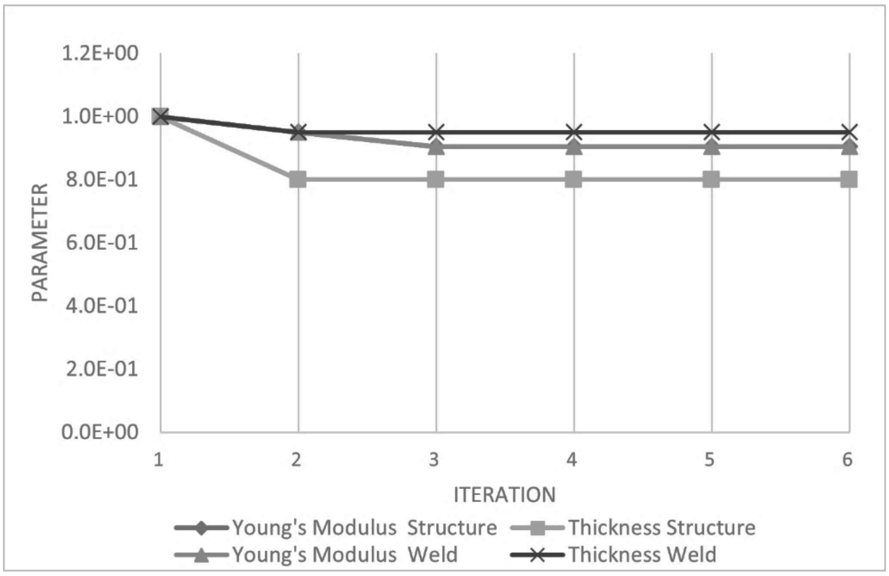
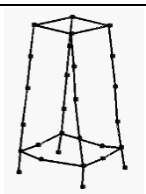
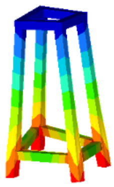
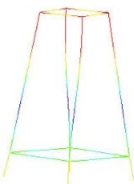
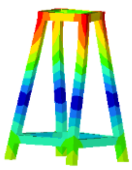
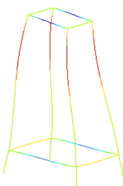
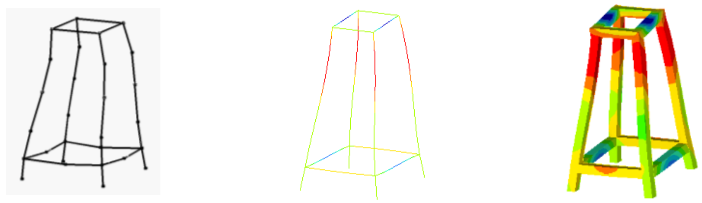
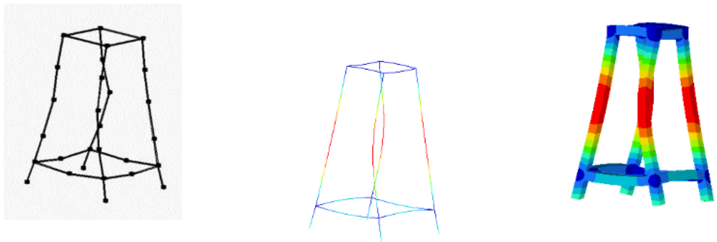
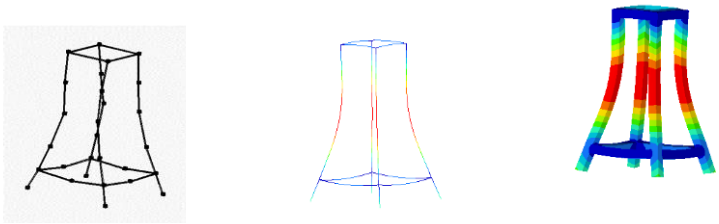
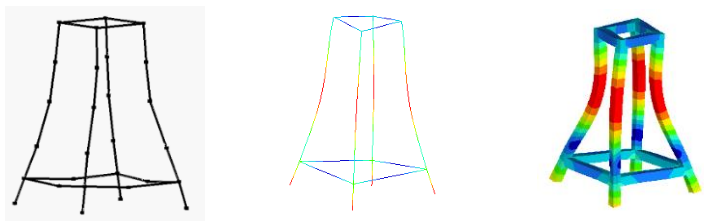
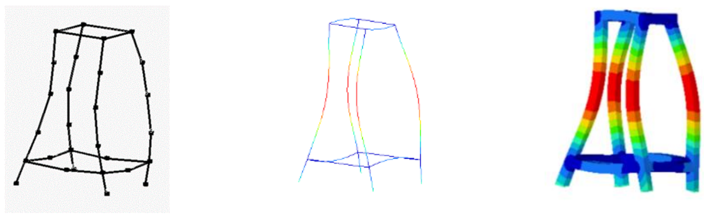
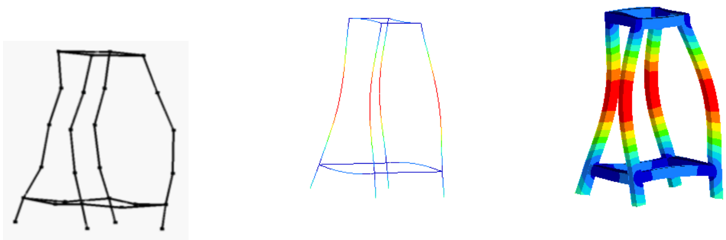
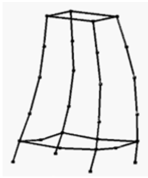
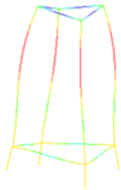
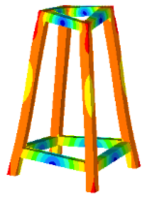


Figure 3: Parameter Convergence Tracking Based on Normalised Value.

Table 4: Pairing the mode shapes of predicted data with experimental data.

Mode	EMA	FEA-Beam model	FEA-Shell model
1			
2			
3			

4	
5	
6	
7	
8	
9	

10			

CONCLUSIONS

This paper demonstrates the investigation of vibration responses of the simplified oil and gas platform structure using finite element analysis (FEA). The aim of this paper was to evaluate the feasibility of the proposed FE models: (1) FEA-Beam Model and (2) FEA-SHELL Model. The dynamics characteristic of the FE model of the structure in terms of natural frequencies and mode shapes are observed and validated with the experiment result. It was found that the FEA-SHELL Model was providing the greater accuracy compared to FEA-Beam Model. Furthermore, it was found that, there are presence of swap modes in the prediction result via FEA-Beam Model. The results obtained shows that the properties in beam element were not suitable to be used as virtual investigation scheme in vibration induced structure such as oil rig platforms due to limitation in accurately mimic the physical behaviour of the structure. In this work, a systematic scheme via FE model updating was introduced for improving the modelling uncertainties of the simplified model of oil and gas platform structure. This is because the FEA- SHELL Model recorded quite large discrepancies, thus identification and minimisation of the sources of uncertainties is required. The sources of modelling uncertainties were investigated using sensitivity analysis. It was found that, input parameters of the structure components and weld such Young's modulus (structure and weld) and thickness (weld) played an important role in producing an accurate prediction of the dynamic behaviour of the structure. In conclusion, despite the initial FEA-SHELL Model recorded quite large discrepancies it still can be considered as the best choice to predict the dynamic responses of the simplified oil and gas platform structure with the aid of FE model updating method.

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