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Correlation of numerical and experimental analysis for dynamic behaviour of a 3 blade propeller structure

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Abstract. In pursuance of deciding the dependability of data gathered by testing a finite element modal in the software version, experimental data is frequently used for validation. On account of finite element analysis, it can sometimes be considered as inaccurate particularly when applied to the complex structure, for example, a propeller blade. This is because of challenges that may happen in the modelling of joints, boundary conditions, and damping of the structure. In this research, a procedure of correlation and validation of the model-based test plan with modal testing results was conducted. Modal properties (normal frequencies, mode shapes, and damping ratio) of a propeller blade structure were resolved by using both test experimental modal analysis (EMA) and finite element analysis (FEA). Correlation of both sets of data was performed for validation. It created the impression that there was a noticeable estimation of error between those two sets of data. Small discrepancies of percentage error of obtained natural frequency for FEA and EMA makes both of the methods can be applied to determine the dynamic characteristic of the propeller structure.

1. Introduction

The dependability of basic mechanical numerical investigation, for example, numerical analysis (FEA) can generally be approved by using experimental analysis data. The difference of qualities accumulated through experiments demonstrates the level of precision for the existing finite element model used in numerical prediction analysis [1-2]. It is critical to guarantee that the existing finite element model that was created during the design process is a dependable and ready to give an exact prediction of structural behaviour and performance before the real structure experiences large scale manufacturing in the assembling zone. As expressed in numerous past experiments, finite element modelling is the most basic instruments used to deride up the complex system or structure [3-7].

One of the most generally used propulsion tool, the propellers plays an essential role on submerged vehicles. For the propellers on the marine vehicles, the working conditions are extremely complicated and numerous off-plan working conditions will be endured like crash back or rapid reversing. Along these lines, the increased efficiency and the thrust of propellers will be useful for their working conditions[8].Other than that, the propeller which have a curvy profile on the structure, can be classified as one complex structure as well. Modelling the exact propeller structure in finite element can be tricky and very hard to achieve. Thus, the goal of modelling in this case to come up with a representative model that is simple enough for mathematical manipulation yet capable for describing, inducing, and reasoning complicated phenomena. By using principle from finite element method, a complicated structure can be assembled using these element matrices by considering connectivity and all the boundary condition [9].

Therefore, in order to validate the existed finite element model whether it is sufficient enough to imitate the response that will be created by real structure, many scientists had proposed the use of modal data obtained both through FEA and experimental modal analysis (EMA) [10-15]. The modal properties of the structure in the subject which have the natural frequencies, damping proportions, and mode shapes will be gathered through both FEA and EMA [16-19]. These two sets of data will be correlated so as to compute the level of discrepancies between them [20-23].

Although discrepancies between prediction analysis and experimental on the real structure are inaccessible because of the presence of many local impacts that are not considered by FE modelling while predicting frequencies and modes, model updating is a technique generally recommended and mostly used when it comes to improving the relationship between the FE model and the experimental data [24]. Therefore, the present research is conducted with the interest of performing dynamic correlation of experimental modal data with the data collected through numerical analysis of a three blade propeller structure which can be considered as a complex structure.

2. Finite element modelling and analysis

Propeller structure, which is the important part of marine vehicle's transportation system, can be considered as a complex structure. Because of this reality, modelling the structure accordingly to the actual structure might be difficult. Along these lines, major simplification in modelling the structure was done while designing the finite element component model of the propeller. The majority of the spaces and curvatures on the surfaces of the propeller structure, just as the accessible joints on the structure, were altogether neglected during modelling process.

Computer-aided design (CAD) model was designed first before being imported into a computer-aided engineering (CAE) software, MSC Nastran/Patran, in order to change the model into a finite element model, the propeller is modelled according to and based on the actual propeller structure. The whole propeller model was modelled as a solid structure where the thickness for the whole structure created will be assigned in properties manager in MSC Nastran/Patran software.

The finite element model of the propeller was created by using 10540 elements of tetrahedral-10 shaped elements while applying Tet Mesh mesher. The propeller model was assigned with the same material properties of aluminium; which details are shown in Table 1. All those properties were assigned according to condition of each surface on actual structure. Since the propeller is a complex structure, few properties are neglected for the free-free boundary condition testing.

Table 1. Nominal value of material properties (aluminium) assigned to propeller model.

Properties	Nominal Value
Young's modulus	69 GPa
Poisson ratio	0.3
Density	2800 kg/m^3

Neither boundary condition nor external forces were applied to the model as the model was let to be in free-free boundary condition for calculation of modal properties using SOL 103 in MSC Nastran/Patran, which is the solution for the normal modes analysis. The arrangement of the condition of movement for natural frequencies and typical modes requires a special decreased type of the equation of motion. The reduced equation of motion in matrix form is as shown in Equation (1):

$$[M]\{u\}+[K]\{u\}=0 \tag{1}$$

where [M] is the mass matrix, [K] is the stiffness matrix and *u* is the vector of the variable describing the motion. Equation 1 was solved by assuming a harmonic solution of the form as Eq. (2)

$$\{u\}=\{\Phi\}\sin\omega t \tag{2}$$

where $\{\Phi\}$ is the eigenvector or mode shape and ω is the circular natural frequency. This harmonic solution is the key to the numerical solution of the problems and indicates that all the degrees of freedom of the vibrating structure move in asynchronous manner. The structural configuration does not change its basic shape during motion and the only thing that changes is its amplitude. If the differentiation of the assumed harmonic solution is performed and substituted into the equation of motion, the simplification of the equation will be represented as Eq. (3).

$$([K]-\omega^2[M])\{\Phi\}=0 \tag{3}$$

As Eq. (3) was reduces to an eigenvalue problem, it will be represented as Eq. (4)

$$[K]-\omega_i^2 M\{\Phi_i\}=0 \tag{4}$$

where Φ is the eigenvector (mode shape) corresponding to its eigenvalue and the eigenvalue Z_i is related to the natural frequency. The constructed finite element model as viewed in graphic interface of MSC.Nastran/Patran software is as shown in Figure 1. Meanwhile, the computed first 5 mode shapes obtained in FEA is shown in Figure 2.

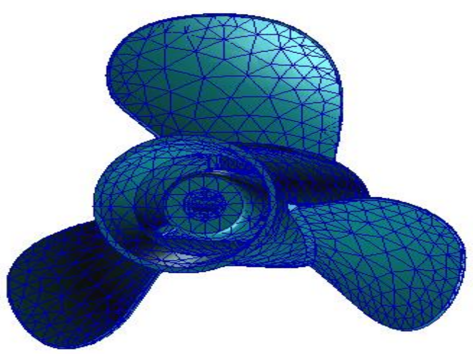

Figure 1. Finite element model of propeller structure

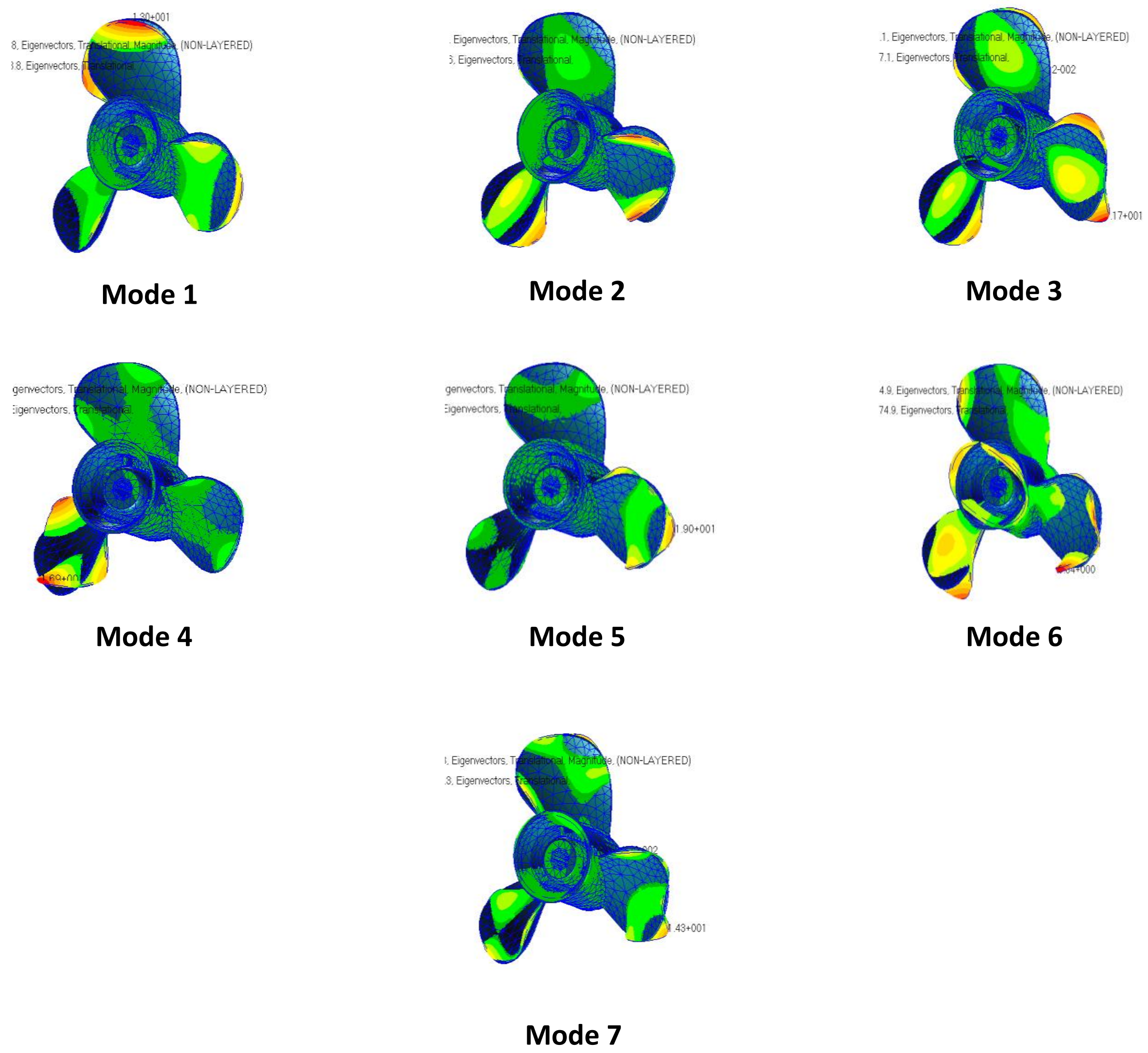

Figure 2. FEA mode shapes of propeller structure.

3. Experimental modal analysis

Experimental modal analysis (EMA) or once in a while called as modal testing, is the way toward separating dynamic qualities of a system, hardware or structure experimentally. Completing EMA on a structure or system has the advantage of having modal characteristic defined from actual measurements. A vital property of modes or the measured frequency response functions from modal testing can be used to describe the structure's dynamic or modal properties, which are the natural frequencies, damping ratios, and mode shapes.

There are a few kinds of response domain (regardless of whether frequency or time domain) that can be accumulated by EMA so as to extract those modal properties. On the other hand, the most normal information utilized for parameter extraction, and was utilized in this investigation, are the accumulated frequency response functions (FRFs), which use excitation input and the corresponding output of the test structure. The technique for excitation is the impact hammer test. Impact hammer testing is one of the most frequently used methods in modal testing. Aside from the capacity to figure FRF estimations in an FFR analyser, impact hammer testing is likewise a quick, advantageous, and minimal effort method for finding the methods of machines and structure.

Before conducting the impact hammer testing, an experimental model of the propeller was created by using post-processing software. The model consists of lines and points which virtually represent the geometric shape of the propeller structure (refer Figure 3). Data gathered through numerical analysis was used as a guide to performing the experiments in a way of indicating the best location for accelerometers on the propeller structure. In order to perform the impact hammer test, the propeller structure was hanged from a test rig by using the elastic cable in order to put the structure under the free-free boundary condition (see Figure 4). The measurements were made using modal analysis software and several other types of equipment such as PCB 086D20 impact hammer with medium soft tip attached, 4-channel NI DAQ device, and a tri-axial PCB accelerometer. Roving accelerometer method was adopted for the testing procedure, where one knocking point and 36 measurement points were assigned on the structure. Roving accelerometer test was done by creating an initial disturbance on the propeller structure at one fixed position while the single tri-axial accelerometer was roved around other measurement points. Nodal points were ensured to be avoided when choosing the impact and measurement point. The vibrational response was measured by using the 4- channel NI DAQ device. Curve fitting procedure available in the modal analysis software was used to extract the modal properties of the propeller structure from the computed FRFs.

The computed FRF based on all measurement points is shown in Figure 5. The estimated modal parameters were extracted by applying a curve fitting method to the FRF graph in order to obtain a set of experimentally derived data. The outcome of curve fitting, which is a set of modal parameters, which consist of natural frequencies, damping, and residues, for each of the identified modes within the range of frequency of interest, is shown in Figure 6. After the curve fitting process was completed, the modal parameters are stored in a Shape Table as residue mode shapes. The mode shapes were then displayed through the created experimental model. The computed modal parameters are shown in Figure 6. According to the computed FRF graph, the natural frequency for the first mode is 1530 Hz.

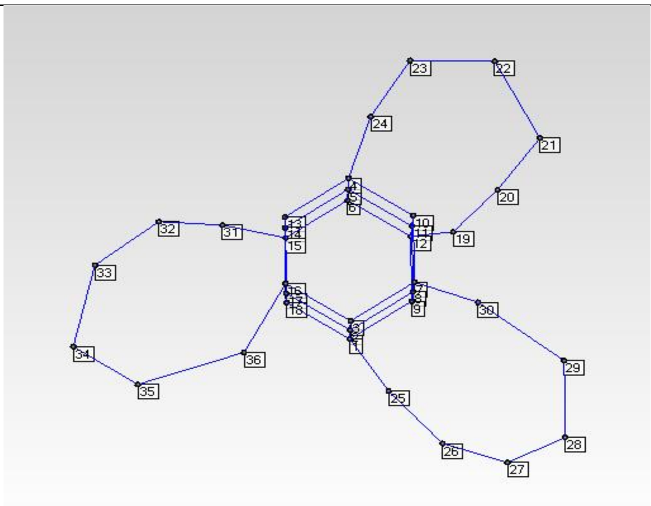

Figure 3. Experimental model of propeller structure.

Figure 4. Hanging propeller structure under free-free boundary condition.

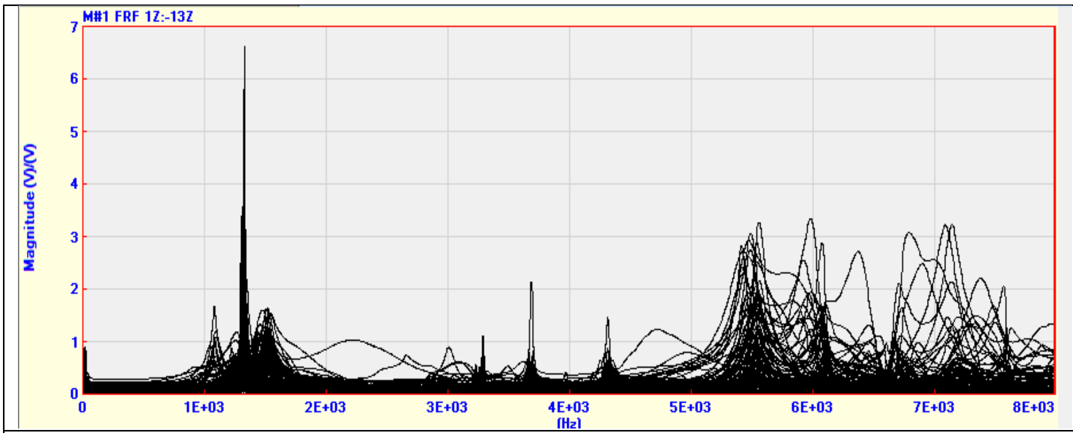

Figure 5. Computed FRF for all measurement points.

	Select Shape	Frequency (or Time)	Damping	Units	Damping (%)	Label	MPC
1	Yes	1.53E+03	38.9	(Hz)	2.54	G-PLY-PLY	0.0317
2	Yes	3.29E+03	4.68	(Hz)	0.142	G-PLY-PLY	0.104
3	Yes	3.36E+03	0.224	(Hz)	0.00666	G-PLY-PLY	0.61
4	Yes	4.34E+03	21.5	(Hz)	0.495	G-PLY-PLY	0.0253
5	Yes	5.54E+03	36.7	(Hz)	0.663	G-PLY-PLY	0.528
6	Yes	6.1E+03	34.2	(Hz)	0.56	G-PLY-PLY	0.302
7	Yes	7.59E+03	25.3	(Hz)	0.333	G-PLY-PLY	0.395

Figure 6. Computed modal data from FRF graph.

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4. Result and Discussion

Correlation of data that was obtained through finite element analysis and modal testing was conducted in order to analyze the discrepancies existed between those two sets of data. In addition, correlation of data is essential in order to have accurateness estimation on the existing propeller model. Table 2 represent the correlation of natural frequencies of propeller structure that was gathered via experimental and numerical (finite element) analysis. Value of discrepancies between those two sets of data was calculated by accepting the value obtained through experiment as the actual value.

Table 2. Correlation of natural frequencies between EMA and FEA.

Mode	Experimental natural frequency (Hz)	Numerical natural frequency (Hz)	Percentage of error (%)
1	1530	1933.8	26.39
2	3290	3284.6	0.16
3	3360	3387.6	0.82
4	4340	4351.8	0.27
5	5540	5440.8	1.79
6	6100	5974.9	2.05
7	7590	7576.3	0.18
		Average Error	4.52

Since there is a discrepancy between the result of numerical analysis and modal testing, the percentage error is calculated and been tabulate at table 2. The highest percentage error for portal frame structure obtained is about 26.39% while the other modes (mode 2,3,4,5,6 & 7) were just below 10%. Mode 2, mode 3, mode 4 and mode 7 is the most perfect mode among all since the error just below 1%. Mode 5 and mode 6 in moderate range as the error is below 10%. Mode 1 has the highest error which more than 10% and it shows the worst result. This is due to some errors encounter during performing the FEA and EMA analysis.

There are few errors resulting from the assumptions made to characterize the mechanical behavior of the physical structure. Such errors typically arise from simplifications of the structure, inaccurate assignment of mass properties, incorrect modeling of boundary conditions, incorrect modeling of joints, incorrect geometrical shape assumptions. Other than that, when the finite element formulation neglects particular properties, Errors in the connectivity of the mesh i.e. some elements are not connected or are connected to the wrong node.

In order to reduce the existing discrepancies, model updating procedure can be applied on the finite element model of the propeller, thus improving the model to have better correlation with the actual structure. Several updating parameters (Young's modulus and all the thicknesses used in finite element analysis) can be considered to be included in model updating procedure.

Besides that, during performing modal analysis using impact hammer test and run analysis in ME'Scope VES, the noise may occur because during the knocking process, it is possible to wait longer until the structure perfectly stops being moving or vibrate before the next knocking process can be done. There may be internal vibrate inside the structure which invisible to be seen. This may contribute to longer time to complete the testing since there are 36 node points on the structure. Moreover, by improving higher number of node points, it can result the more accurate mode shape.

5. Conclusion

This study was undertaken to correlate the experimental modal data to the data gathered from the finite element analysis of the propeller structure. A finite element model of the propeller structure was produced and the percentage of errors between those two sets of data was obtained. Defined that the outcome obtained from the numerical analysis is close to the modal testing and because of some existing error, will affect the imperfection of both results.

Issues of each close mode frequently occur in engineering designing practice because of structure symmetries with small damping and exact determination of the model parameters. The percentage differences between finite element analysis and experimental analysis are within 10% except for mode 1 by cause of the factor been discussed previously. Small discrepancies of percentage error of obtained natural frequency for FEA and EMA makes both of the methods can be applied to determine the dynamic characteristic of the propeller structure. It is recommended that further research be undertaken by performing modal updating in order to diminish the percentage of error. The updating procedure is observed as parameter identification which means to bring the finite element prediction to be as close as possible to the actual test subject.

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