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ORIGINAL ARTICLE

Computational Modal Analysis on Finite Element Model of Body-in-white Structure and Its Correlation with Experimental Data

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ABSTRACT – Nowadays, computational modelling and simulation are highly popular to increase the efficiency, productivity and shorten the product development period. The quality of a structure also can be determined by using computational analysis such as finite element analysis. Body-in-white structure, as one of the most important structures in the automotive field, has gained a lot of interest as the topic of research. This increase the demand of having a good finite element model of the structure. However, since body-in-white is a highly complicated structure, sometimes modelling simplification cannot be avoided. This study intended to investigate the level of accuracy of the simplified body-in-white model that was modelled by using several modelling strategies. The first body-in-white finite element model was modelled by neglecting the existing joint element in its actual structure. The other body-in-white model includes the joint element by including two different one-dimensional elements to replicate the joining in BIW actual structure. Validation on these body-in-white models are performed by correlating the finite element modal properties with the experimental modal properties. The discrepancies that had surfaced after the correlation was reduced by using a model updating method. The discussed results showed that as the model is under major simplification, several parameters were inaccurately assumed in the initial body-in-white model. Thus, the model updating method has successfully determined the less accurate parameter and the level of discrepancies between the model and experimental data were successfully reduced.

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INTRODUCTION

The automotive industry is one of the most fast-growing sectors worldwide as vehicles have become a necessity in daily life. As vehicle manufacturers competitively strive to produce a better car every day, there are numerous works and researches on various car or vehicle component had been conducted. One of the basic automotive structure that is constantly gaining popularity as the main topic of research is a body-in-white structure (BIW). When discussing on BIW structure, there are a lot of studies that had been investigated due to the reason that BIW itself is a large and complex structure consists of many components. Among the topics that yet to be studied are such as calculation of vibrational characteristics, whether it is experimentally [1, 2] or numerically [3]. Substructure from BIW such as the joints elements [4–7] and crash energy absorbing members [8] are also among the popular topics.

In order to perform or analyse the BIW and its components' performance better, usually, computer-aided design (CAD) and finite element analysis (FEA) is utilised as aiding tools. The application of computer simulation such as FEA is very wide and important in the automotive industry. Therefore, the design and modelling phase of an automotive structure, for instance, BIW structure, is very crucial and demands great attention. A good computational model is greatly needed by manufacturers to predict their vehicle structural performance before continuing for mass production. However, it had been commented by many researchers that for a complex structure such as BIW, accurate modelling is very difficult to achieve [3, 7, 9, 10].

The accuracy of the constructed computational model such as finite element (FE) model always needs to be validated experimentally [2, 11–13]. This is because the computational model is merely an assumption of the actual structure and problem of discrepancies will always exist. For large and complex structure such as BIW, the discrepancies are even bigger. Reference [14–18] shows that sometimes, simplification in modelling a very complex structure such as BIW will lead to the inaccurate assumption of properties and parameters whether it is structural or material properties. Sometimes, the inaccuracy of modelling local sub-structure such as joining element can contribute to discrepancies of a model. Moreover, BIW is made up of many sub-components and many types of joining that are impossible to be modelled accurately. Therefore, the problem of discrepancies in the computational model cannot be avoided. However, to solve or reduce the problem of discrepancies in the FE model, researchers had addressed a method call model updating. This method is widely suggested and frequently applied to improve the correlation between the FE model and experimental data [5, 16, 17, 19, 20]. In fact, the model updating method is not only proved to be useful in the automotive industry but

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also other fields such as civil engineering and others [21–24]. Model updating also normally utilised the structural modal properties that are obtained through computational calculation and experimental analysis. In fact, modal properties are also used for validation of models. Many works have reported the application of modal properties such as natural frequencies, mode shapes and damping ratio as the benchmark of producing a valid model. Also, the study of modal properties on BIW structure is considered as important due to the fact that the vibration and noise of car is one of the criteria in evaluating the quality in the process of manufacturing and assembling [3, 25, 26].

While modelling of BIW structure is being crucial in the automotive field, strategies on producing reliable BIW model need to be studied. As it is a complex and difficult to model structure, the level of simplification that can be used to obtain reliable BIW model need to be investigated. It can be seen based on the literature survey that demands having good and trusted BIW model is high due to the vast research topics that concern on BIW structure. The present study aimed to study the level of accuracy of several FE model of BIW with different modelling strategies by correlating their computational modal properties with the modal properties obtained experimentally. Level of discrepancies was analysed and improvement on the model was made.

NORMAL MODES FINITE ELEMENT ANALYSIS (FEA) OF A BIW STRUCTURE

As the BIW structure is originally considered as a complex structure, it was difficult to model the structure exactly according to its actual structure. Therefore, simplification of modelling is done where many indentations and curvatures on the BIW's surface were neglected. In real structure, BIW structure also consists of numerous types of joint and stiffener in several areas. However, due to the modelling simplification process, the joints on the structure are also neglected at first. The BIW structure is modelled based on wireframe and surface design in computer-aided design software before several clean-up was performed in a pre-processing finite element software. The BIW is modelled based on the several basic components which are listed as follows

i. Floor and underbody
ii. Dash panel assembly
iii. Frontal structure
iv. Body sides
v. Roof

As the model of BIW is created by using surface modelling, the FE model of BIW is created by using CQUAD plate/shell elements. The whole BIW's FE model has 6548 elements with 6814 nodes. The number of elements and nodes that were created was the most optimum number based on the mesh convergence test. Therefore, the issues of having excess computational operating time during the analysis can be avoided. The first modelling strategies is by ignoring the availability of joint element in the BIW model. Therefore, the properties assigned to the FE model of the BIW structure only consist of material and thickness on the selected area. Several different thicknesses were assigned on the FE model according to the existence of multilayer and stiffening substructure on the actual structure. It was intended that the created surface can replicate the stiffness of the actual structure at their designated area. The assignments of the different thickness on the different plates on the BIW structure and the value of thickness assigned was displayed in Figure 1 and Table 1 respectively. The properties of steel material with Young's modulus of 200 GPa, Poisson ration of 0.3 and mass density of 7860 kg/m^3 was assigned to the model.

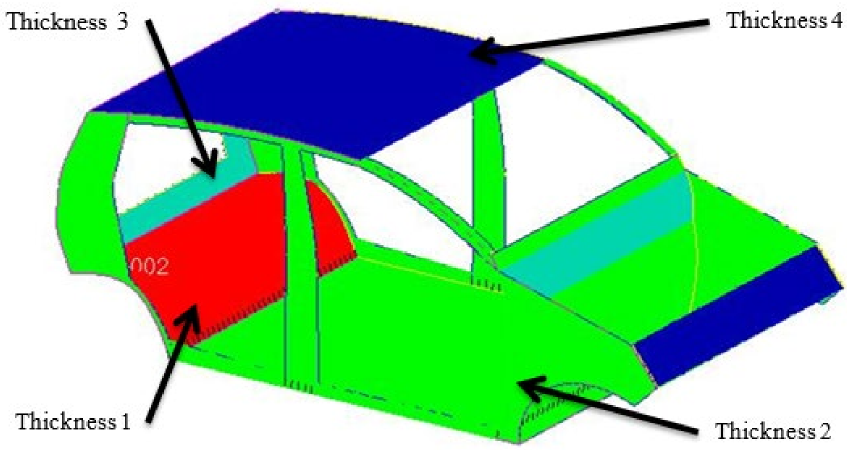

Figure 1. The assignment of different thickness on the BIW model

Second modelling strategy of BIW structure was done by including joint element at eight different locations. The locations were selected to match the position of the available joints on the real BIW structure as shown in Figure 2, which are marked with green colour. Two approaches were carried out for joint modelling on the BIW FE model, which were by using beam element (CBAR) and also grounded scalar spring element (CELAS) as a connector element. These different approaches were conducted to determine which simplified model can represent the actual BIW structure better.

For CBAR elements, the assigned properties include the cross-sectional area of the circular beam with diameter 0.005m and very high value of Young's modulus of 1×10^6 GPa. The high value of Young's modulus was assigned to replicate the stiffness of the joint elements. On the other hand, for CELAS elements, the value of scalar spring stiffness was assigned with a high value of 1×10^6 N/m to replicate the stiffness of the joint elements.

Table 1. Nominal value of thickness assigned on BIW model.

Thickness area	Nominal value (m)
Thickness 1	0.012
Thickness 2	0.008
Thickness 3	0.006
Thickness 4	0.003

Normal modes finite element analysis was conducted on all three constructed model to determine their modal properties (natural frequencies and mode shapes). MSC.Nastran/Patran software was used to conduct this analysis. The properties of steel material with Young's modulus of 200GPa, Poisson ration of 0.3 and mass density of 7860 kg/m^3 was assigned to the model while their modal properties were determined by the software by using SOL103. The values of the first five natural frequencies obtained for all three models are displayed in Table 2. These values will be correlated with the values that were obtained experimentally. In this work, only the first five lower order modes are considered for analysis as lower modes are mainly associated with lower energy input. Higher modes that are associated with higher energy input is not included in analysis. Further discussion on the data correlation will be provided in later part of this paper.

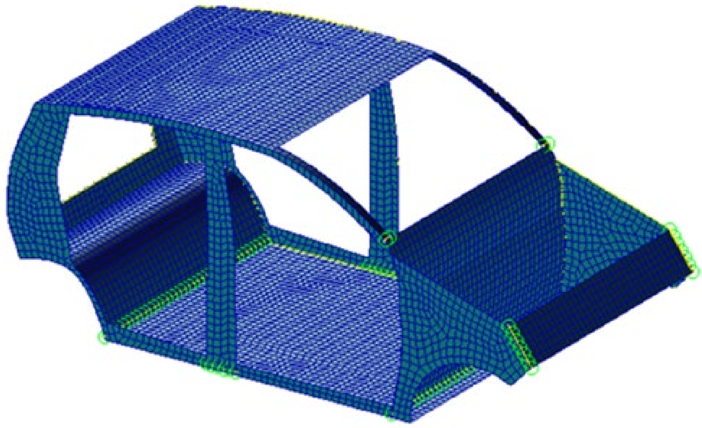

Figure 2. Locations of the joint element that are created on the BIW model.

Table 2. Numerical natural frequencies of BIW model using different modelling approaches.

Mode	Natural frequencies (Hz)		
	Without joint elements	With CBAR elements	With CELAS elements
1	29.37	29.29	29.30
2	41.30	43.22	43.27
3	52.55	55.70	55.91
4	67.15	62.14	62.41
5	74.59	69.35	69.48

IMPACT HAMMER MODAL TESTING ON BIW STRUCTURE

In frequency analysis, experimental data is always used and taken as the benchmark and considered as most trustworthy. This is because the experimental modal analysis was conducted on the actual structure, and the responses gathered is directly gathered from the structure itself. However, precautions need to be taken to ensure that the gathered responses are not disturbed by other external factors. For example, the point where the structure is to be excited, and the measurement point must be carefully selected. The nodal point has to be avoided. In this work, experimental modal analysis is conducted by using an impact hammer test. Several set up was used conducting the impact hammer test on BIW structure. The set up is stated as follows:

a) Roving accelerometer using one tri-axial accelerometer
b) Roving accelerometer using three tri-axial accelerometers
c) Roving hammer using one tri-axial accelerometers
d) Roving hammer using three tri-axial accelerometers

The roving accelerometer method was performed by moving the accelerometer to all measurement points on the structure while the impact hammer was used to provide excitation force at one measurement point. On the other hand, the roving hammer method was carried out by roving the impact hammer around to several excitation points while having the accelerometer to measure the response stationary at one point. When utilising three different accelerometers in roving accelerometer and roving hammer method, the accelerometers are all placed at the different measurement points.

An experimental model of BIW (see Figure 3) was constructed by using post-processing software so that the responses gathered can be animated as mode shapes. All 61 measurements points that were assigned on the structure was labelled in the experimental model according to its location in the actual structure. The BIW structure was suspended from a test rig to provide free-free boundary condition for the structure (see Figure 4) to match the boundary condition assigned in finite element analysis. Data acquisition was made by using 4-channel NI DAQ device (one channel is connected to impact hammer, and other three channel is connected to the accelerometer in X, Y, and Z direction respectively). A 4-slot compact DAQ chassis device was used to combine three 4-channel NI DAQ device of the same model when measuring was done using three accelerometers. The unutilised channel was closed in acquisition set up. The sampling rate is set to the lowest value possible in the acquisition system which is up to 1000Hz.

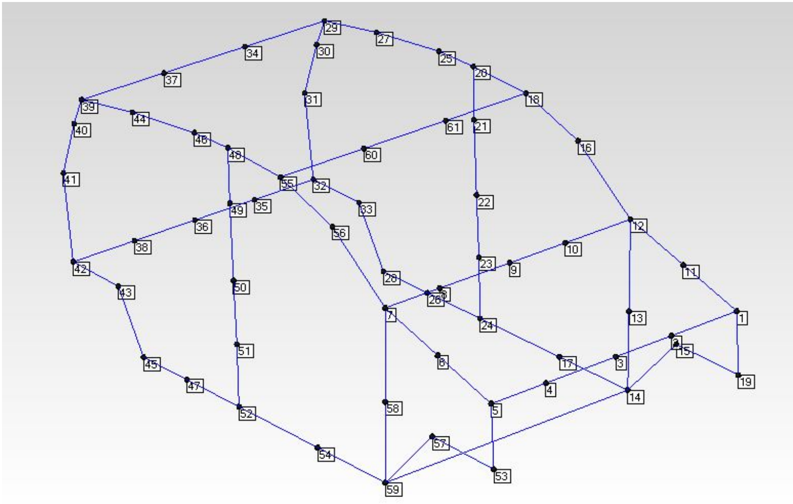

Figure 3. An experimental model of BIW structure.

Figure 4. Hanged BIW structure under test rig in a free-free boundary condition.

The usage of single and multiple sensors in this study was intended to observe whether the number of sensors used while taking measurement affects the quality of measurement. Theoretically, the number of sensors used can affect the value of the measured natural frequency of the measured structure as more number of sensors will increase the structural mass. However, in case of large structure such as BIW which the structural mass is already large, the effect of additional sensors in the term of mass can be neglected.

For each of the measurement set up, impact hammer test was carried out twice. Both the frequency response function (FRF) obtained in each measurement by using roving accelerometer method show almost the same shape and peak location. The response recorded while using one accelerometer and the one recorded using three accelerometers show no huge difference (see Figure 5 and Figure 7). However, while using roving hammer method with one accelerometer, the response in the second test is less clear (see Figure 6). Also, the response from all directions and locations cannot be gathered completely. Several measurement points failed to record any excitation which resulting only less stable response was recorded. Even so, the response obtained when using three accelerometers in the test is more steady than using only 1 accelerometer (see Figure 8). There are also slightly different locations of peaks when compared to the FRF obtained in the previous test. Mode indication function available in the post-processing software was used to determine the stable peak which shows the value of natural frequency.

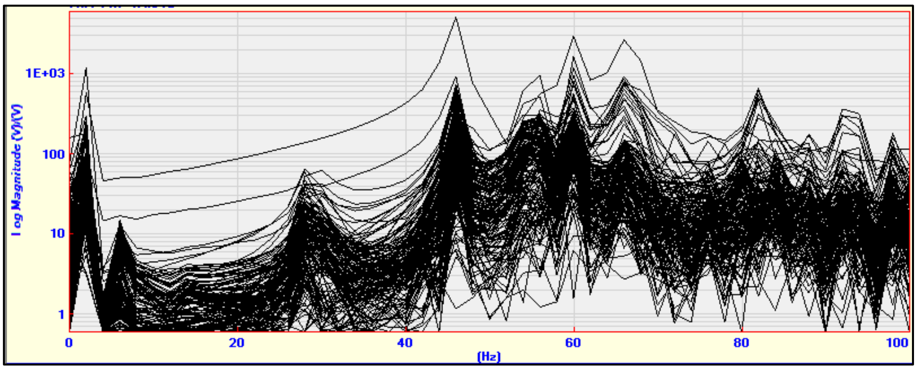

Figure 5. Response sample of roving accelerometer impact hammer with one accelerometer.

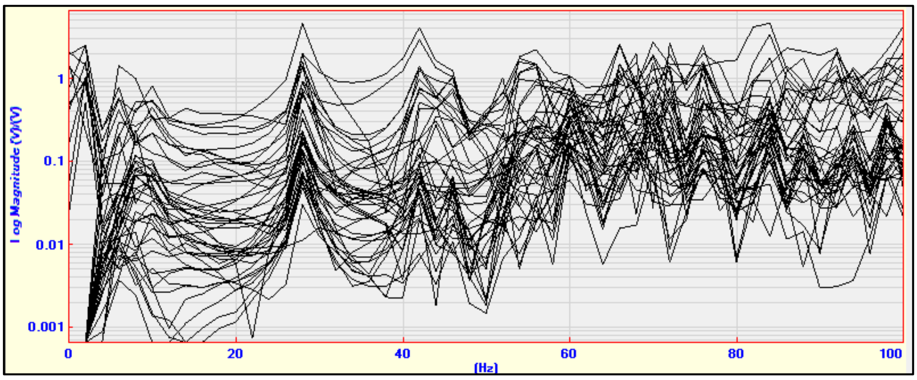

Figure 6. Response sample of roving hammer impact hammer test with one accelerometer.

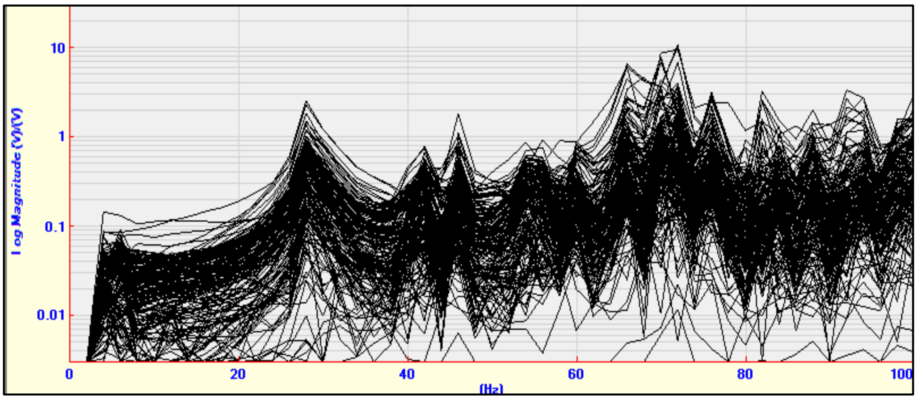

Figure 7. Response sample of roving accelerometer impact hammer test with three accelerometers.

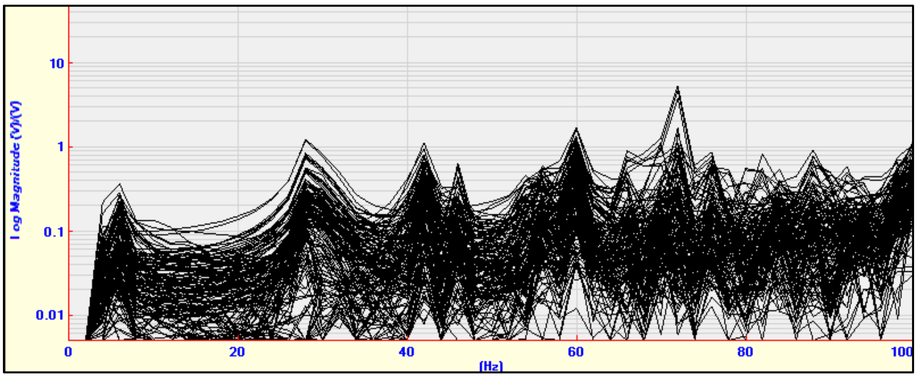

Figure 8. Response sample of roving hammer impact hammer test with three accelerometers.

The coherence for measurement using one accelerometer and three accelerometers are shown in Figure 9 and Figure 10, respectively. Poor coherence is shown as the frequency range goes higher when using one accelerometer. Even so, the measurement can still be considered as valid as the coherence for frequency within the range of interest (0 – 100Hz) is still in good quality. The coherence of the test using three accelerometers shows better outcomes.

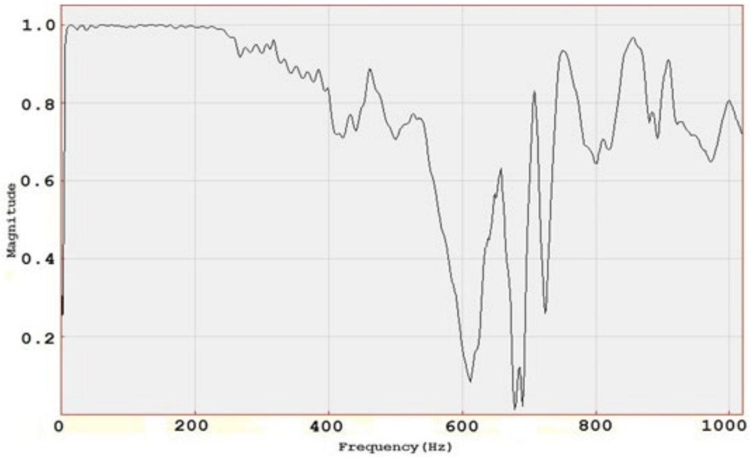

Figure 9. The coherence of measurement when using one accelerometer.

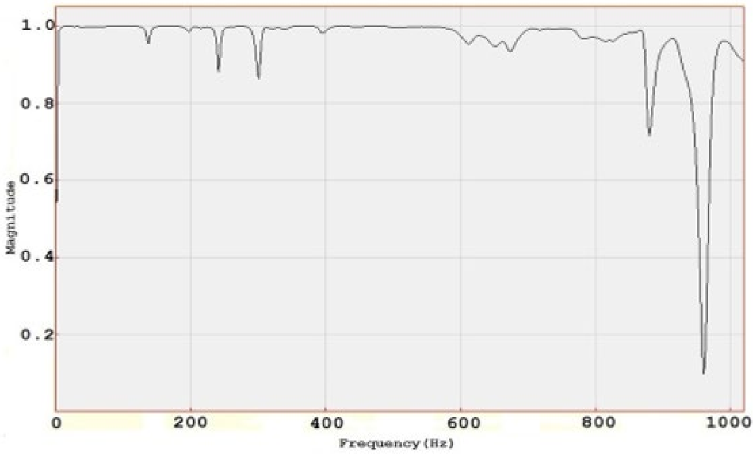

Figure 10. The coherence of measurement when using three accelerometers.

Table 3 and Table 4shows the value of the BIW's natural frequencies acquired through curve fitting process in all test conducted by using one accelerometer and three accelerometers. Even if the sampling rate is much higher which is up to 1000Hz, the curve fitting process for the response only applied to the responses that are within the range frequency of interest (up to 100Hz). The average for all reading was calculated, and the average value was used for correlation purpose, which is explained in the latter part of this paper.

Table 3. Experimental natural frequencies of BIW structure when using one accelerometer.

Mode	Natural frequencies (Hz)				
	Roving accelerometer		Roving hammer		Average
	Test 1	Test 2	Test 1	Test 2	
1	28.4	28.4	28.4	28.8	28.5
2	42.4	42.4	44.4	45.6	43.7
3	55.1	57.9	59.3	55.1	56.9
4	66.4	67.4	69.1	68.8	67.9
5	76.3	76.4	75.6	71.9	75.05

Table 4. Experimental natural frequencies of BIW structure when using three accelerometers.

Mode	Natural frequencies (Hz)				
	Roving accelerometer		Roving hammer		Average
	Test 1	Test 2	Test 1	Test 2	
1	28.6	28.6	28.8	28.7	28.7
2	45.8	41.5	42.8	42.0	43.0
3	55.1	55.1	59.2	60.0	57.4
4	66.4	66.4	66.6	66.6	66.5
5	70.4	70.8	71.8	71.7	71.2

INITIAL CORRELATION OF FINITE ELEMENT AND EXPERIMENTAL DATA

Correlation of all of the gathered modal properties in finite element analysis and impact hammer test was performed to observe how far the result obtained in numerical analysis agree with the one obtained through experimental work. Table 5 and Table 6 shows the correlation of natural frequencies value obtained from normal mode analysis on all the constructed models with the natural frequencies value obtained through impact hammer test using one and three accelerometers, respectively. The experimental data is used as the benchmark data to determine the accuracy of finite element analysis. Based on the experimental results by using one accelerometer, BIW model without joint elements shows the lowest error as compared to the other two models. On the contrary, when comparing the experimental results by using three accelerometers, BIW model without joint showed the highest error. Consideration of experimental measurement quality was made to select the benchmark data. As shown previously in this paper, the data obtained while using three accelerometers is much more favourable because the response was seen as more stable and robust. The FRF graph as shown in Figure 7 and Figure 8 showed a better peak in indicating the vibrational modes for the BIW structure. Furthermore, the coherent graph displayed in Figure 10, which showed the coherence of responses when using three accelerometers looks more stable.

On the other hand, based on the correlated data, it is apparent that BIW models that include the joint element to replicate the flexibility and stiffness of the structure showed better accuracy than the model without joint. Model updating was performed with the intentions of improving the constructed model by reducing the existing discrepancies. The outcome of the updated finite element model is discussed in the next part of this paper.

Table 5. Correlation of natural frequencies obtained from all BIW FE models with experimental work using one accelerometer.

Mode	Natural frequencies (Hz)						
	Experimental	FE (with different modelling approaches)					
		No joint	Error (%)	CBAR joint	Error (%)	CELAS joint	Error (%)
1	28.5	29.37	3.05	29.29	2.77	29.30	2.81
2	43.7	41.30	5.49	43.22	1.10	43.27	0.98
3	56.9	52.55	7.64	55.70	2.11	55.91	1.74
4	67.9	67.15	1.10	62.14	8.48	62.41	8.09
5	75.05	74.59	0.61	69.35	7.59	69.48	7.42
		Avg. error	3.58	Avg. error	4.41	Avg. error	4.21

Table 6. Correlation of natural frequencies obtained from all BIW FE models with experimental work using three accelerometers.

Mode	Natural frequencies (Hz)						
	Experimental	FE (with different modelling approaches)					
		No joint	Error (%)	CBAR joint	Error (%)	CELAS joint	Error (%)
1	28.7	29.37	2.33	29.29	2.06	29.30	2.09
2	43.0	41.30	3.95	43.22	0.51	43.27	0.63
3	57.4	52.55	8.45	55.70	2.96	55.91	2.60
4	66.5	67.15	0.98	62.14	6.56	62.41	6.15
5	71.2	74.59	4.76	69.35	2.60	69.48	2.42
		Avg. error	4.10	Avg. error	2.94	Avg. error	2.78

MODEL UPDATING OF BIW STRUCTURE

Selecting the Updating Parameters by using Sensitivity Analysis

To reduce the discrepancies between the finite element and experimental results, model updating was performed and thus, the BIW model can have a better correlation with the actual BIW structure. Firstly, the updating parameters for each of the constructed BIW model need to be determined. This was done by performing a sensitivity analysis for all the existing parameters on each of the BIW model. The list of parameters that were included in sensitivity analysis for each BIW model is shown in Table 7.

Value of sensitivity coefficient of each of the studied parameters are obtained after sensitivity analysis is conducted. The value of the sensitivity coefficient obtained for each mode of all constructed models are displayed in Figure 11, Figure 12 and Figure 13. The sensitivity analysis showed that the most sensitive parameters on all BIW models are BIW's Young's modulus, density and some of the thickness properties. The selection of sensitive parameters is based on the larger magnitude of the sensitivity coefficients, such as explained in reference [5, 27]. Based on the figure, it appears that Young's modulus and density have the same sensitivity. However, because of their direct relation in the calculation of the natural frequency, only Young's modulus was selected as the updating parameter. For thickness properties, it appears that thickness 2 is the most sensitive. Thickness 4 is only sensitive for the fourth mode only. Some researchers argued that correction of thickness should be done manually rather than being used as updating parameter [28–30]. In spite of that, the thickness properties in this study are assigned to replicate the stiffness and the rigidity of the surface component. Therefore, the thickness parameter is chosen as one of the updating parameters. This is done so that the suitable thickness value can be assigned to the surface of the FE model.

Table 7. List of potential updating parameters in each model.

BIW model	List of parameters to be included in a sensitivity analysis
Without joint element	Young's modulus Poisson ratio Density Thickness 1 Thickness 2 Thickness 3 Thickness 4
With CBAR elements	Young's modulus Poisson ratio Density Thickness 1 Thickness 2 Thickness 3 Thickness 4 CBAR diameter CBAR's Young's modulus
With CELAS elements	Young's modulus Poisson ratio Density Thickness 1 Thickness 2 Thickness 3 Thickness 4 Spring constant

In no-joint BIW model, thickness 2 properties are determined as the most sensitive thickness. Thickness 4 shows high sensitivity coefficient in the fourth mode while thickness 1 and 3 show the smallest value. For the BIW model with CBAR elements, thickness 2 is sensitive towards the fourth mode, thickness 3 is sensitive towards the third mode and thickness 4 is sensitive towards the second mode. The properties of CBAR was found out not to be sensitive and therefore cannot be considered to be selected as the updating parameter. The same situation also occurred to BIW model with CELAS elements where the properties of CELAS elements is not sensitive. These outcomes agree with reference [5, 14] that exhibit that the joint element properties are not sensitive enough to be included as updating parameter. Thickness 2 shows high sensitivity towards the fourth mode, Thickness 3 shows high sensitivity towards the third mode, and Thickness 4 shows high sensitivity towards the second mode. By considering the obtained value of the sensitivity coefficient for each parameter in each mode, the updating parameters were selected. The list of the updating parameters and their updated values is shown in Table 8.

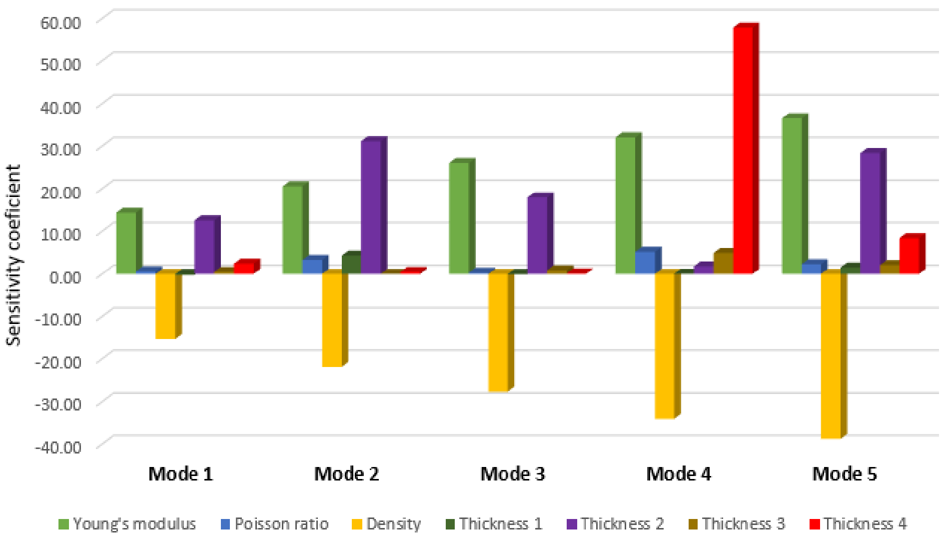

Figure 11. Sensitivity coefficient for potential updating parameters of BIW model without joint elements.

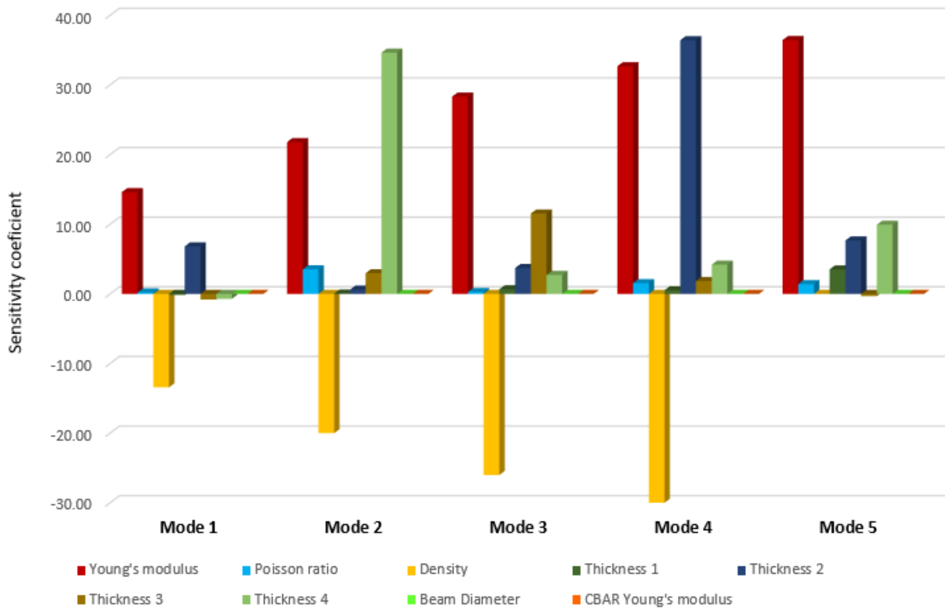

Figure 12. Sensitivity coefficients for potential updating parameters of BIW model with CBAR elements.

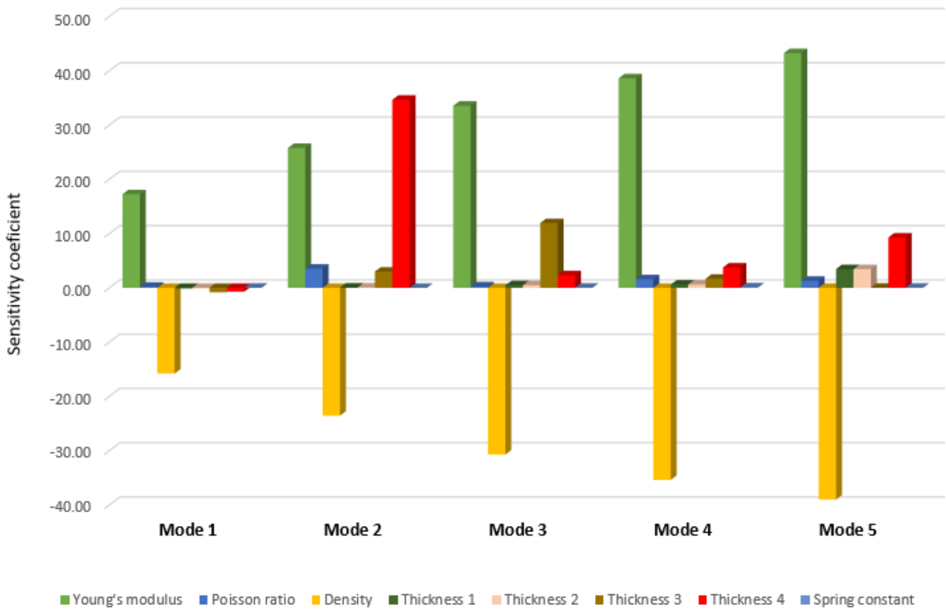

Figure 13. Sensitivity coefficients for potential updating parameters of BIW model with CELAS elements.

Table 8. Updating parameters for all BIW models.

BIW model	Selected updating parameters		Initial value	Updated value	Deviation (%)
	Parameter	Units			
Without joint element	Young's modulus	GPa	200	211.56	5.78
	Thickness 2	m	0.008	0.0084	5.00
	Thickness 4	m	0.003	0.0029	3.33
With CBAR elements	Young's modulus	GPa	200	185	7.5
	Thickness 2	m	0.008	0.01	25.00
	Thickness 3	m	0.006	0.0073	21.67
	Thickness 4	m	0.003	0.0031	3.33
With CELAS elements	Young's modulus	GPa	200	184.84	7.58
	Thickness 2	m	0.008	0.01	25.00
	Thickness 3	m	0.006	0.0073	21.67
	Thickness 4	m	0.003	0.0031	3.33

Correlation of Natural Frequencies Value of Initial and Updated BIW Models.

As the updating parameters were selected, and the optimised value was obtained, the value of their properties was reassigned. The modal properties of the updated models with updated properties or parameters were recalculated and the new correlation with the experimental data was made. Table 9 exhibits the value of updated natural frequencies of the BIW model without joint elements and its comparison with the initial natural frequencies. Average error calculated showed a reduction in discrepancies. This revealed that although in small value, the simplified model that neglected joint components can still be refined and improved.

In Table 10, the natural frequencies of the updated BIW model with CBAR joint elements displayed. The results of the correlation show that the updated value of natural frequency for the first and second mode increased from their original value by 1.08 % and 1.77 % respectively. In spite of that, the average error for each model for the updated data is minimised by 1.2 % from the initial value.

Table 11 shows the updated BIW model's natural frequencies with CELAS joint elements. In this case, after updating, only the first and second mode is showing the increase in the value of natural frequencies. For the first mode, the natural frequency value has risen from its original value by 1.01 %, while for the second mode, the value of natural frequency value increased from its initial value by 1.72%. After updating, the average error for each mode is decreased by approximately 1.05 % from the initial average error value for each mode. Reference [5, 18] also acknowledged that when modelling of a joint element of a structure is included, the level of accuracy may increase.

Table 9. Deviation of natural frequencies value of initial and updated BIW model without joint elements.

Mode	Natural frequencies (Hz)				
	EMA	Initial FE model	Error (%)	Updated FE model	Error (%)
1	28.70	29.37	2.33	29.43	2.54
2	43.00	41.30	3.95	42.27	1.70
3	57.40	52.55	8.45	53.27	7.20
4	66.50	67.15	0.98	66.51	0.02
5	71.20	74.59	4.76	75.28	5.73
		Average error	4.10	Average error	3.44

Table 10. Deviation of natural frequencies value of initial and updated BIW model with CBAR elements.

Mode	Natural frequencies (Hz)				
	EMA	Initial FE model	Error (%)	Updated FE model	Error (%)
1	28.70	29.29	2.06	29.60	3.14
2	43.00	43.22	0.51	43.98	2.28
3	57.40	55.70	2.96	57.35	0.09
4	66.50	62.14	6.56	65.92	0.87
5	71.20	69.35	2.60	72.85	2.32
		Average error	2.94	Average error	1.74

Table 11. Deviation of natural frequencies value of initial and updated BIW model with CELAS elements.

Mode	Natural frequencies (Hz)				
	EMA	Initial FE model	Error (%)	Updated FE model	Error (%)
1	28.70	29.30	2.09	29.59	3.10
2	43.00	43.27	0.63	44.01	2.35
3	57.40	55.91	2.60	57.38	0.03
4	66.50	62.41	6.15	65.96	0.81
5	71.20	69.48	2.42	72.87	2.35
		Average error	2.78	Average error	1.73

CONCLUSION

With the aim of constructing a more accurate computational model that can respond similar to the actual structure, this work had tried a few modelling strategies for BIW structure. As reported by the correlation results, it can be concluded that:

i. The model of BIW structure that used joint elements such as CBAR and CELAS elements to reflect on the available joint components, shows the reduction in discrepancies. For each mode of study on the BIW model without the joint element is sporting the average error of 4.10%. Conversely, for the BIW model with a joint element such as CBAR and CELAS elements, these two models exhibit the average error of 2.94% and 2.78%

for each mode respectively. Besides, the discrepancies that are shown by the model that wields the usage of CELAS elements to represent its joint components is even lower.

ii. The assessment and comparisons of the experimental work unveil that when the measurement was made with an additional number of sensors, which in this work are accelerometers, more stable and robust response are gathered. Furthermore, there is a significant level of discrepancies between the experimental data and computationally simulated modal properties particularly when a comparison is made to the more simplified finite element model (modelling without any joint element).

iii. When the modal properties of the BIW were measured experimentally, the findings provide evidence that shows the use of roving accelerometer method is much more practical as compared to roving hammer method. In other words, the roving accelerometer method can produce better quality FRF. Nevertheless, the values of other modal properties such as the natural frequencies are still stable. There is no critical difference in its nominal value between those two experimental methods. For this reason, it can be indicated that both roving hammer and roving accelerometer method are appropriate to be used in measuring the modal response of the structure.

iv. From the findings of model updating work, the updating procedure that was conducted on the BIW model with CBAR reduced the average error for each mode from its initial correlation more successfully. Also, model updating on the BIW model without any joint elements indicates that the average error decrease for each mode from its original correlation is minimal. Nonetheless, the BIW model with CELAS elements exhibits the smallest value of discrepancies among other BIW model.

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