Modal properties investigation of car body-in-white with attached windscreen and rear screen

Z M Hafizi[1*], A M Aizzuddin[1], N I A Halim[2] and M F Jamaludin[2]

[1]Advanced Structural Integrity and Vibration Research Group, Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[2]PROTON Sdn. Bhd., HICOM Industrial Estate (Batu Tiga, PO Box 7100), 40000 Shah Alam, Selangor, Malaysia

*Corresponding author: hafizi@ump.edu.my

Abstract. Vibration analysis of car body in white (BIW) is crucial during design stage. Car BIW holds all the essential components; therefore, analysing its dynamic behaviour is necessary to understand how vibrations are transferred to the end rows from any vibration sources. This paper presents the modal properties of car BIW with attached windscreen and rear screen calculated by means of finite element analysis (FEA) and experimental modal analysis (EMA). The aim for the analysis is to observe the effect of windscreen and rear screen to the dynamic properties of car BIW. Detailed CAD models of BIW for both schemes were used for normal modes calculation in FEA, therefore providing the finest prediction of its modal properties. Actual car BIW was hanged on a metal frame to imitate free-free boundary condition as in FEA; prior to EMA. The EMA was done for both schemes, whereby the results for FEA were confirmed with EMA, at least for the first five modes with errors below 15%. It can be concluded from the analysis that the attached windscreen and rear screen is significantly affects the first five modes of the BIW. However, other higher frequencies remain unchanged.

1. Introduction

Vibration analysis of a car body in white (BIW) is important to understand the Noise, Vibration and Harshness (NVH) of a car during earlier design stage [1-3]. A car BIW must be able to meet the NVH design criteria as well as the stiffness, strength and fatigue life [4]. In most car manufacturing development cycle, this procedure take place during engineering design where computational aided engineering (CAE) is involved [5].

A car BIW can be referred to a car body's sheet metal components which have been welded together, before attachment of the moving parts (doors, hoods, and deck lids as well as fenders) the motor, chassis sub-assemblies, or trim (glass, seats, upholstery, electronics, etc.); and before painting [6]. The main parameters to be concerned in a vibration analysis of a car BIW are the natural frequencies and the vibration mode shapes [7-9]. Whenever these natural frequencies match with vibration sources, resonance will occur and causing serious effects to some components. The lower frequency range of vibration mainly contributes to the stress and critical loading on the individual component of the BIW, especially if it is subjected to vibration source from the rough road surface. On the other hand, the higher frequency range of vibration contributes to the interior and exterior noise to the vehicle. The main source can be from the second order vibration of engine, the wheel-road contact during cruising on highways or subcomponents such as air-conditioning system and cooling fans.

In most research works, the vibration analysis of a car BIW was done without the consideration of windscreen and rear screen attached to the BIW. If the car BIW definition is concerned, the vibration analysis with windscreen and rear screen attached to the BIW may contributes to the dynamic properties of the whole BIW as they are actually bind to the structure.

In the meantime, the analytical study of modal parameters using finite element analysis (FEA) is well establish and widely used in the engineering design stage of any structures. It significantly helps to save the development cost of car manufacturers. However, due to several assumptions made during the finite element modeling, there are some discrepancies to the actual measurement which may affect the credibility of the test result in the next car development stages. Therefore, the experimental modal analysis (EMA) is necessary steps to evaluate the integrity of the FEA [1, 10, 11]. Although EMA is traditional, yet is considered as the most accurate representation to the actual dynamic behavior of a structure, with the use of frequency response function (FRF) data [12, 13]. The combination of EMA with CAE makes the results more impressive and can provide theoretical simulations.

In this research work, normal modes investigation of a car BIW with attached windscreen and rear screen has been done, via FEA and EMA. The results were compared with the BIW only case.

2. Finite Element Analysis

The car model chosen for the analysis is a 4-door sedan car. A full meshing has been done by using *Hypermesh* software. The free-free boundary condition, with no constraint was chosen to match the experimental modal analysis setup. Figure 1 shows the FE model of the car BIW.
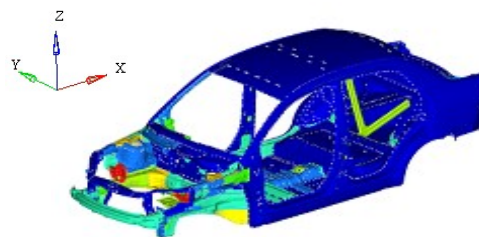

Figure 1. FEA model of the BIW.

The results have been calculated for the first 20 frequency modes, exclusive the rigid modes and frequency below 100 Hz was targeted. Figures 2 to 6 show the first five modes of car BIW only. It was predicted that the BIW experienced the first natural frequency at 30.11 Hz, in torsion mode about x-axis, with the maximum deformation appears to be localized at rear part of the roof, close to the rear screen.
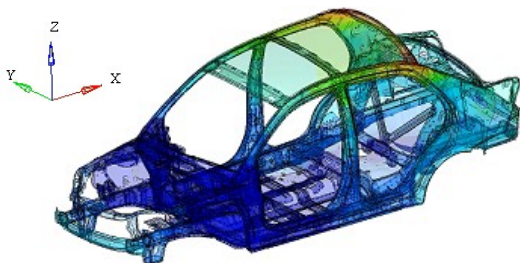

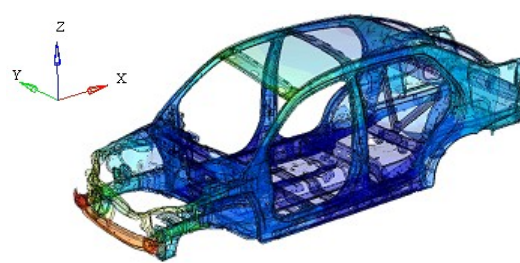**Figure 2**. First mode of car BIW.

Figure 3. Second mode of car BIW.

Meanwhile the second mode was 34.31 Hz, also twisting about x-axis; however, the largest deflection was at the front engine room area. In this mode, the front roof also displays a significant deformation. The third mode was the mix mode, with a large bending in y-axis at the front end of engine area at frequency of 41.08 Hz. Large twisting also can be seen at the front roof area. In the

meantime, the fourth and fifth mode shapes indicate the pure bending mode with frequency 45.06 Hz and 46.04 Hz, respectively.
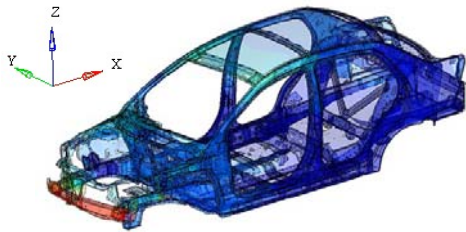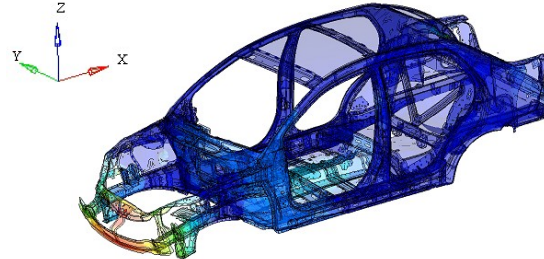

Figure 4. Third mode of car BIW.
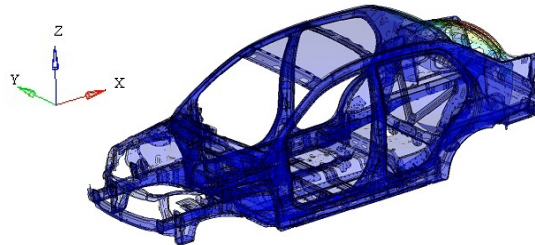

Figure 5. Fourth mode of car BIW.

Figure 6. Fifth mode of car BIW.

Figures 7 to 11 present the result of normal modes analysis for car BIW with attached windscreen and rear screen. The first natural frequency appears to be in bending mode at y-axis, with the most deflected area is at the front end of the BIW. Its frequency increase 24% compared to the first mode of car BIW only; 37.43 Hz. However, the first mode of the BIW only is in twisting mode. In the meantime, the second and third mode shape also bending mode, but in z-axis, with frequency are 44.70 Hz and 46.91 Hz, respectively. The significant deformation occurs similarly for both modes, which are at the front roof and front end area, however with vary magnitude. The second mode displays maximum deflection at front end while the third mode indicates maximum deformation localized at front roof attached to the windscreen.
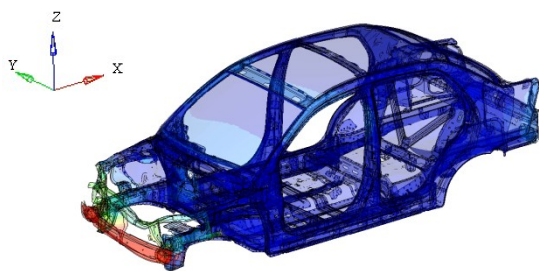

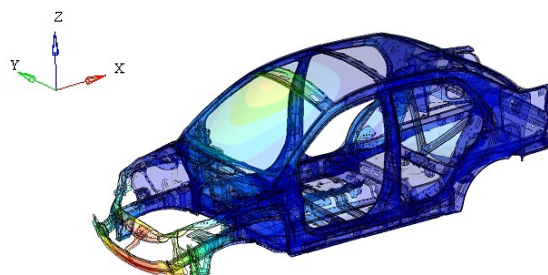**Figure 7.** First mode of car BIW with windscreen and rear screen.

Figure 8. Second mode of car BIW with windscreen and rear screen.

The first torsion mode experienced by this BIW scheme appears at the fourth mode; twisting about x-axis with frequency 51.59 Hz. It is 70% higher than the first torsion in the BIW only result. However, the first torsion in BIW with windscreen and rear screen experienced more global vibration compared to BIW only. Meanwhile, the fifth mode indicates the bending in z-axis with frequency at 54.09 Hz and maximum translation at the mid of rear screen along x-axis.
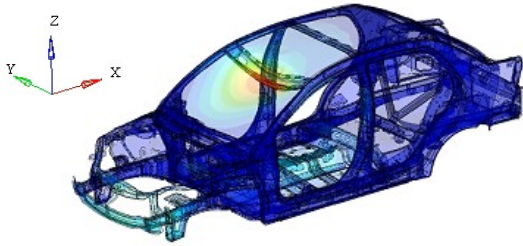
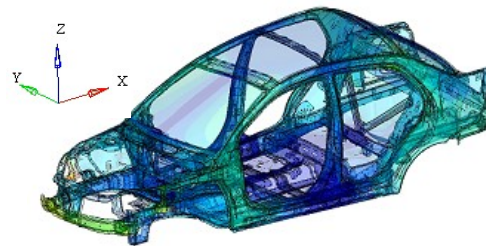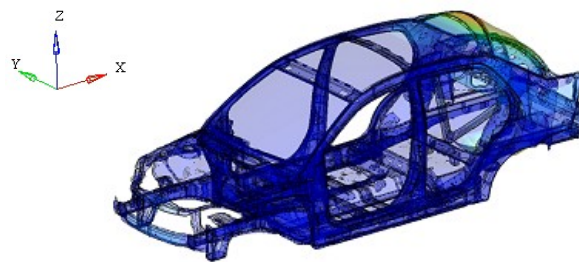| **Figure 9.** Third mode of car BIW with windscreen and rear screen.	**Figure 10.** Fourth mode of car BIW with windscreen and rear screen.

Figure 11. Fifth mode of car BIW with windscreen and rear screen.

The dissimilarity of the first 10 natural frequency values for the car BIW with windscreen and rear screen, over the car BIW only can be summarized as in Table 1. The frequency variances are significant only for the first five modes, while the rest fall below 5% discrepancies. Further comparisons for the mode shapes from mode 6 to mode 20 for both models also reveal no disagreement at all.

Table 1. Comparison between BIW only and BIW with windscreen & rear screen.

Mode	Mode BIW (Hz)	BIW with windscreen & rear screen (Hz)	Different (%)
1	30.11	37.43	24.29
2	34.31	44.7	30.31
3	41.08	46.91	14.21
4	45.64	51.59	13.03
5	46.04	54.09	17.49
6	54.47	56.15	3.08
7	56.18	57.61	2.54
8	58.57	58.97	0.68
9	60.78	60.94	0.27
10	62.39	63.52	1.82

3. EMA Set-up

The experimental modal analysis was performed for car BIW with attached windscreen and rear screen; and BIW only scheme. The structure was hanged up with bungee cord, which represent the free-free condition as setup in FEA. Total 213 points have been marked all over the BIW for modal testing. These points were selected based on clear deformation observed through the normal modes

analysis in FEA and appropriate location for transducer. They were plotted in *MEscopeVES* software with actual *x, y, z* coordinates obtained from the FE model.

Figure 12 presents the model setup in *MEscopeVES*. For better presentation, all points were combined with lines, and surfaces were added at the appropriate locations. Roving accelerometer scheme has been chosen for the experiment; whereby a tri-axial accelerometer was used to measure the *x, y, z* responses of the BIW at all 213 points. Note that, the numbering marked in EMA weren't follow the number of points. The numbering for EMA start with 10 (10, 11, 12, 13, ….223). Meanwhile, a shaker was used for the input excitation. Excitation at positive z direction was applied at point no 223, located at the rear bottom left of the BIW, as shown in Figure 13. A chirp signal ranging from 20 Hz to 100 Hz was selected as shaker input, which is expected to excite more than 10 modes.
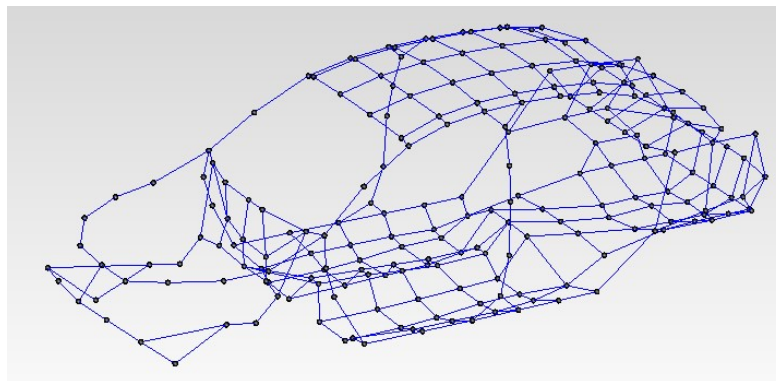

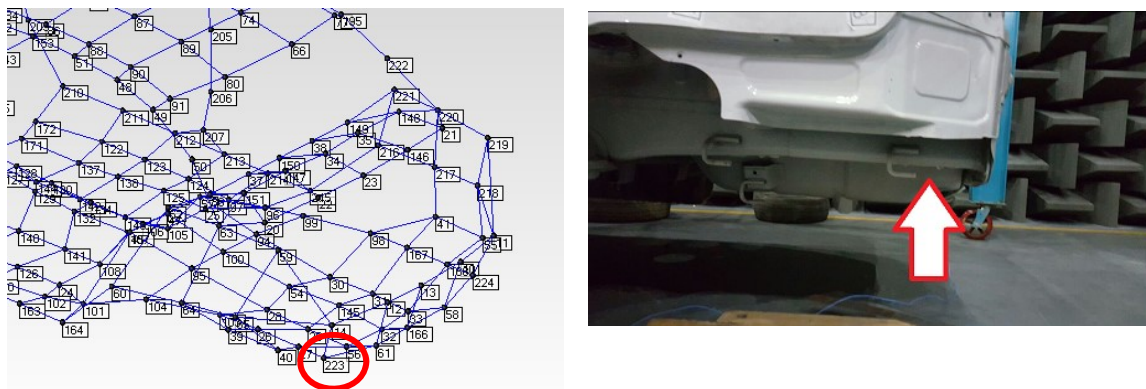**Figure 12.** BIW modeling in MEscopeVES.

Figure 13. Excitation point, with the red circle and red arrow indicates the point number 223.

Data acquisition system used for the experiment was the 4-channel National Instruments NI9234. The time domain data; the ratio of output responses due to an input, were converted into frequency domain representation; the frequency response function (FRF). These data will be included in *MEscopeVES* for mode shapes calculation of the BIW structures.

4. EMA Results and Discussion

Figure 14 and 15 show the FRF data generated for 213 points during the shaker test, for the first five modes. Total 639 of FRF traces inclusive *x*, *y* and *z* axes responses, were plotted. All 5 modes were visible for both BIW schemes. To estimate the frequency for each mode, complex mode indicator function (CMIF) method was used.
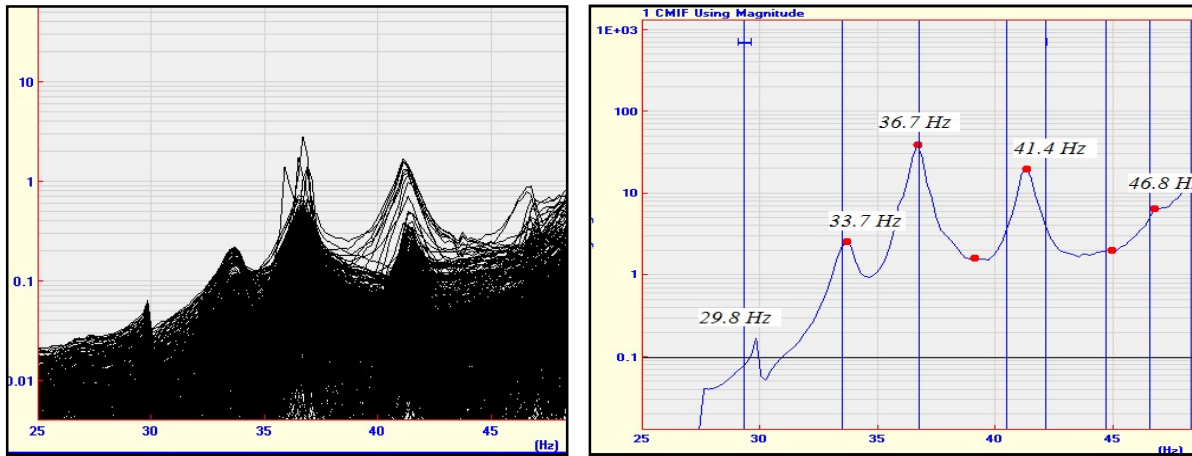
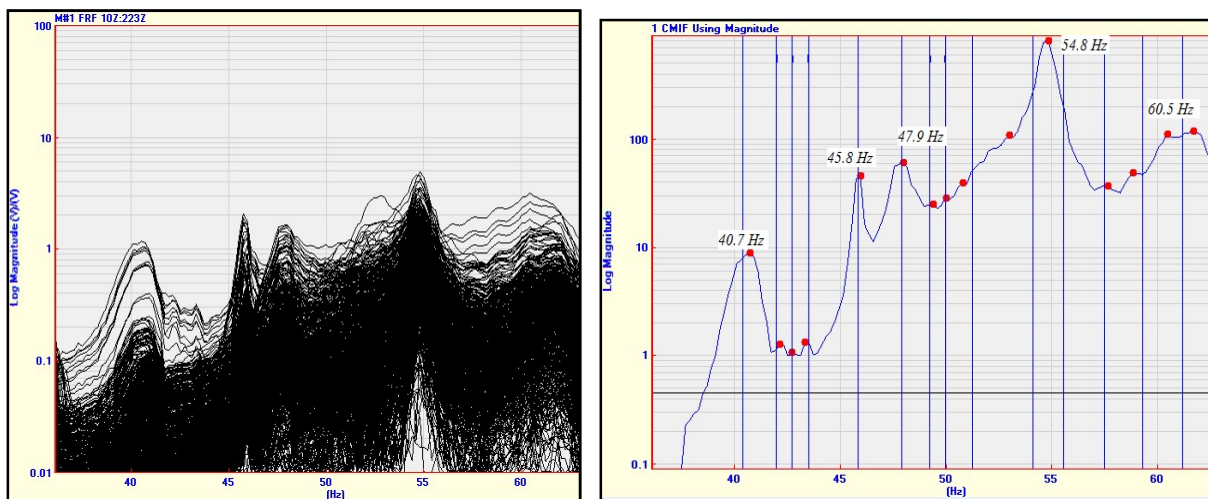**Figure 14.** FRF's data (left) and mode indicator using CMIF (right); for BIW only.
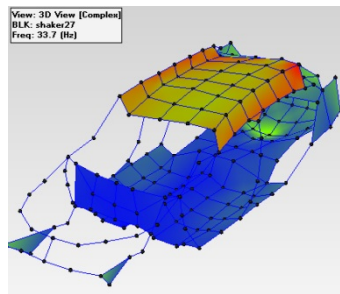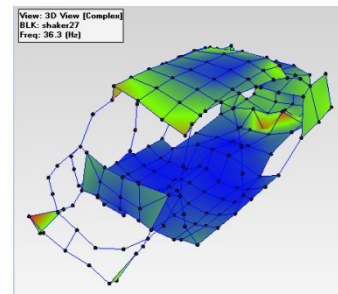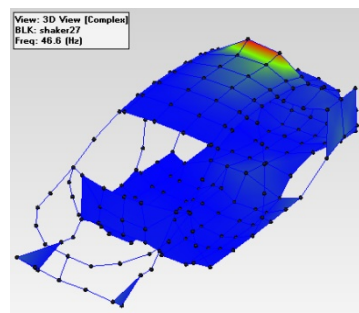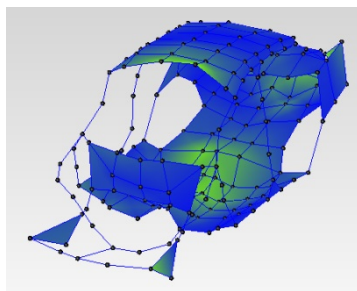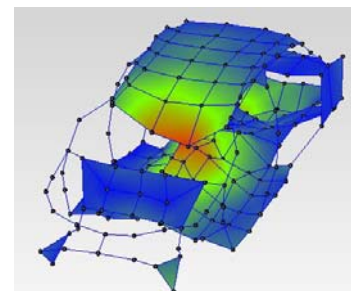

Figure 15. FRF's data (left) and mode indicator using CMIF (right); for BIW with screen.

In the meantime, Figures 16 to 20 reveal the mode shapes of BIW only structure, for mode 1 to 5, calculated based on FRF data. The results indicate similar mode shapes as were determined by FEA. The first 3 modes display a global twisting and torsion with several critical deformation areas. Meanwhile, mode 4 and mode 5 show huge deformation at the front end and rear roof area, respectively. Despite of the well correlation of FEA and EMA mode shapes, there are discrepancies in the natural frequency values; especially for mode 3 and 4, with 10.65% and 9.01% error respectively.
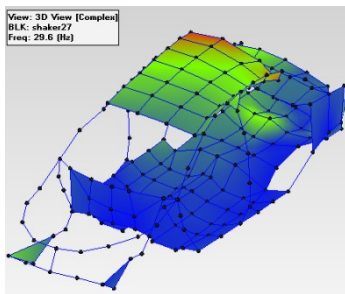
Figure 16. Mode 1 (29.8 Hz).   **Figure 17.** Mode 2 (33.7 Hz).   **Figure 18.** Mode 3 (36.7 Hz).
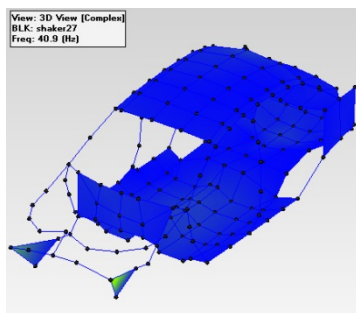
Figure 19. Mode 4 (41.4 Hz).   **Figure 20.** Mode 5 (46.8 Hz).

Figures 21 to 25, on the other hand, display the mode shapes for BIW with attached screen. The outcomes have confirmed the normal modes analysis by FEA, earlier. As predicted, the first, second and third mode experienced the bending mode. Meanwhile, the fourth mode shows a twisting mode about x-axis; and the fifth mode displays a big deformation at the rear roof. As for the BIW only scheme, there are small variation of the natural frequency values between FEA and EMA results, despite of well agreement of the mode shapes.
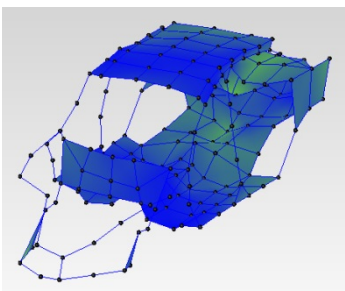
Figure 21. Mode 1 (40.7 Hz).   **Figure 22.** Mode 2 (45.8 Hz).   **Figure 23.** Mode 3 (47.9 Hz).
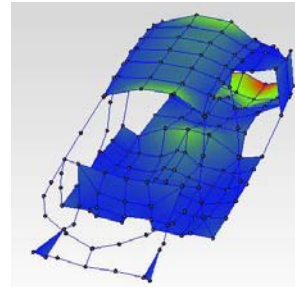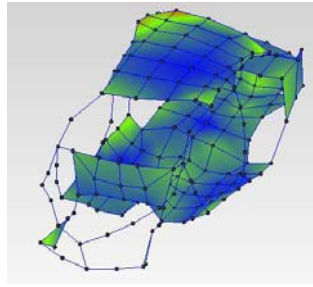
Figure 24. Mode 4 (54.8 Hz).   **Figure 25.** Mode 5 (60.5 Hz).

Table 2 presents the natural frequencies correlation of car BIW with attached windscreen and rear screen extracted from FEA and EMA, for the first five modes. Meanwhile, Figure 26 displays frequency pairing between both FEA and EMA. The comparison for both analyses is necessary to determine any inconsistencies. Mode 1 and mode 5 show excellent correlation, while mode 2, 3 and 4 have 10% errors. These discrepancies can be reduced by applying model updating techniques; however, beyond the scope of this study.

Table 2. Natural frequencies comparison from EMA and FEA.

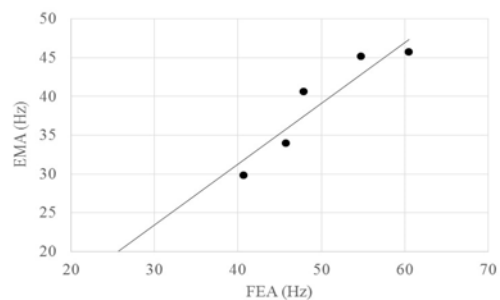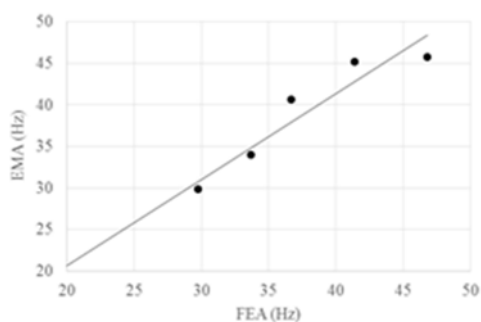|	Mode	FEA Frequency (Hz)	EMA Frequency (Hz)	Error (%)
BIW only	1	29.8	29.79	0.0
	2	33.7	33.93	0.7
	3	36.7	40.61	10.7
	4	41.4	45.13	9.0
	5	46.8	45.70	2.4
BIW with screen	1	40.7	37.4	8.1
	2	45.8	40.5	11.6
	3	47.9	42.7	10.9
	4	54.8	47.2	13.9
	5	60.5	54.2	10.4

Figure 26. Frequency pair between FEA and EMA for the first five modes, for BIW only (left) and BIW with screen (right).

5. Conclusions

This research work has presented the modal analysis of a car body in white by means of finite element analysis and experimental modal analysis. Comparison between the modal parameter; natural frequencies and mode shapes of the BIW only and BIW with attached windscreen and rear screen reveals that there were significant variances, especially for the first five modes. As the increase of the first natural frequency is expected, the mode shapes also indicate significant dissimilarity; whereby the first torsion and the first bending appear at different mode. Thus, the examination of BIW with attached windscreen and rear shows indispensable information to be considered during development stage.

References

[1]   Rajesh H, Patwardhan M A, Karanth N V, Bhatkhande M, Ramkumar R, Pachhapurkar N, Saraf M and Reddy Y 2017 LCV Chassis Frame Optimization Using Combined Simulation and Experimental Approach. (SAE Technical Paper)

[2]   Hanouf Z, Faris W F and Ahmad K 2017 An investigation into NVC characteristics of vehicle behaviour using modal analysis. In: *IOP Conference Series: Materials Science and Engineering*: (IOP Publishing) p 012027

[3]   Sun L, Chen N and Zhao Z 2016 Experimental Modal and Dynamic Performances Analysis of Car's Body-in-white *Journal of Residuals Science & Technology* **13**

[4]   Yahaya Rashid A S, Ramli R, Mohamed Haris S and Alias A 2014 Improving the dynamic characteristics of body-in-white structure using structural optimization *The Scientific World Journal* **2014**

[5]   Hirz M, Dietrich W, Gfrerrer A and Lang J 2013 *Integrated Computer-Aided Design in Automotive Development*: (Springer Berlin Heidelberg)

[6]   Genta G and Morello L 2009 *The automotive chassis* vol 1: (Springer Netherlands)

[7]   Van der Auweraer H 2001 Structural dynamics modeling using modal analysis: applications, trends and challenges. In: *Instrumentation and Measurement Technology Conference, 2001. IMTC 2001. Proceedings of the 18th IEEE*: (IEEE) pp 1502-9

[8]   Sani M, Rahman M, Noor M, Kadirgama K and Izham M 2011 Identification of dynamics modal parameter for car chassis. In: *IOP Conference Series: Materials Science and Engineering*: (IOP Publishing) p 012038

[9]   Zhang H and Tong M 2014 The results of experiment analysis on body-in-white research *Applied Mechanics & Materials* 6358-61

[10]   Rotondella V, Merulla A, Baldini A and Mantovani S 2017 Dynamic Modal Correlation of an Automotive Rear Subframe, with Particular Reference to the Modelling of Welded Joints *Advances in Acoustics and Vibration* **2017**

[11]   Lu J, Zhan Z, Song H, Liu X, Yang X and Yang J 2017 Design Optimization of Vehicle Body NVH Performance Based on Dynamic Response Analysis. (SAE Technical Paper)

[12]   Kranjc T, Slavič J and Boltežar M 2013 The mass normalization of the displacement and strain mode shapes in a strain experimental modal analysis using the mass-change strategy *J. Sound Vib.* **332** 6968-81

[13]   Wang B-T and Cheng D-K 2011 Modal analysis by free vibration response only for discrete and continuous systems *J. Sound Vib.* **330** 3913-29