

Experimental Analysis of Racing Car Chassis for Modal Identification

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ABSTRACT

Racing car chassis is a complex structure fabricated to suit highly demanding racing specifications. Its vibration modes range from a very low to high frequencies and need to be determined in order to ensure optimum performance. The purpose of this study is to determine modal parameters (e.g., natural frequencies and mode shapes) of a racing car chassis using Operational Modal Analysis (OMA). OMA is an experimental technique that applies random excitation while measuring only output response. Initially, the natural frequencies and mode shapes of chassis structure are determined from non-parametric OMA technique which is Frequency Domain Decomposition (FDD). Frequency Response Function (FRF) plots are then obtained from Experimental Modal Analysis (EMA) technique. Results from both FDD and EMA are validated and compared to ensure that FDD result can be further used in OMA methods of analysis. Only two out of four identification algorithms in parametric OMA techniques will be applied, namely Enhanced Frequency Domain Decomposition (EFDD) and Canonical Variant Analysis of Covariance-driven Stochastic Subspace Identification (SSI-CVA) methods. Finally, the natural frequencies and mode shapes obtained from each OMA techniques will be compared, discussed and concluded. The results from this study can be utilized to avoid resonance on chassis structures that will affect the performance of the racing car's structure significantly.

Keywords: *Operational modal analysis; Experimental modal analysis; Modal parameters; Racing car chassis structure.*

Introduction

The traditional experimental modal analysis (EMA) makes use of input (excitation) and output (response) measurements to estimate modal parameters (e.g., natural frequencies, mode shapes, damping ratios) of the test structure [1]. EMA has substantially progressed in the last few decades as it has been possible to determine the dynamic characteristics of small structures that could be conducted in a laboratory. During the test, it is essential to ensure that only the measurable force is acting on the test structure since any unmeasured input force will affect the Frequency Response Function (FRF) obtained.

However, it is not possible to apply Experimental Modal Analysis (EMA) for cases which involved some external uncontrollable in-situ forces such as those from wind turbines, pumps, engines and generators. Furthermore, large structures such as bridges, towers and dams are other examples of cases in which EMA is impractical. This is simply because these forces, in general, cannot be directly controlled or measured. Hence, it is impossible to apply the EMA technique in these circumstances since its accuracy depends on the estimation of the clean Frequency Response Function (FRF).

Thus, operational modal analysis (OMA) is introduced instead to characterize how structures behave dynamically under the presence of unknown excitation forces. The advanced signal processing tools used in operational modal analysis techniques allow the inherent properties of a mechanical structure to be determined by only measuring the response of the structure without using an artificial excitation [2]. This response is normally measured with accelerometers or any other devices such as strain gauges and laser vibrometers that can directly measure dynamic response.

One of the main components in automobile structure is the car chassis. The main function of the chassis is to hold various parts and to support the body of a vehicle. It requires enough strength to withstand both static and dynamic stresses as well as the vibration of the structure. Since the level of vibration depends on the inherent properties of the structure, it is essential to identify the modal parameters of the chassis structure. This study presents both Operational Modal Analysis (OMA) technique and Experimental Modal Analysis (EMA) technique to identify required modal parameters in the form of natural frequencies and mode shapes of a racing car chassis structure. The validity of the test is conducted under the free-free boundary condition. The measurements were taken using the Bruel & Kjaer PULSE™ Multi- Analyzer system, Bruel & Kjaer-PULSE LabShop and Artemis Modal Software for data post-processing.

Methodology and Experimental Set-up

Operational modal analysis

The test structure used in this study is a racing car chassis which was fabricated by students from UiTM Shah Alam used in the previous year racing car competition. In this experiment, chassis structure preparation was made first by measuring all dimensions of the chassis, simulating free-free boundary condition, attaching mounting clips at each desired node, tagging number on each node and wire channels as well as attaching accelerometers on selected nodes before performing OMA techniques. After that, measurement setup was made using Bruel & Kjaer PULSE™ Multi- Analyzer system while Bruel & Kjaer-PULSE LabShop software was used to create the geometry of the chassis structure as can be seen in Figure 1.

Other steps include allocating measurement degree of freedom (DOF's), arranging the measurement sequence task and finally capturing the data. Figure 2 shows the illustration of the experimental setup. For OMA, the chassis structure was excited randomly by continuous scrubbing using steel ruler with relatively enough energy. The excitation should be broadband in order to have a relevant contribution through all frequencies of interest. The impact hammer was used in the EMA technique.



Figure 1: The Bruel & Kjaer PULSE™ Multi-Analyzer System connects to a computer with PULSE LabShop software.

To determine the modal parameters of chassis structure, the desired nodes were identified and there were 36 nodes (which yield a total of 72 DOF's) selected and marked as can be seen in Figure 3. At each node, two accelerometers will be mounted on the chassis structure. A total number of accelerometers used in this study were 16 altogether. Hence, four accelerometers were set as references at two nodes while 12 other accelerometers were set at six nodes for every data set. The location of six

nodes will be switched at each data set with six measurement sequences or the total amount of data set for roving accelerometer along measured nodes.

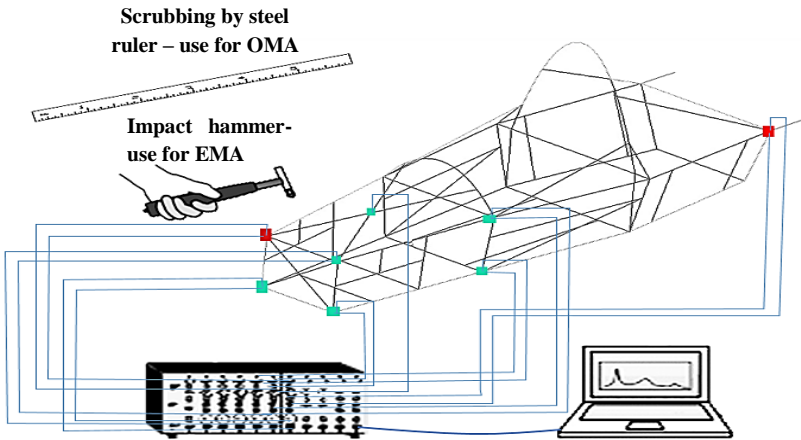


Figure 2: Schematic diagram of Experimental setup.

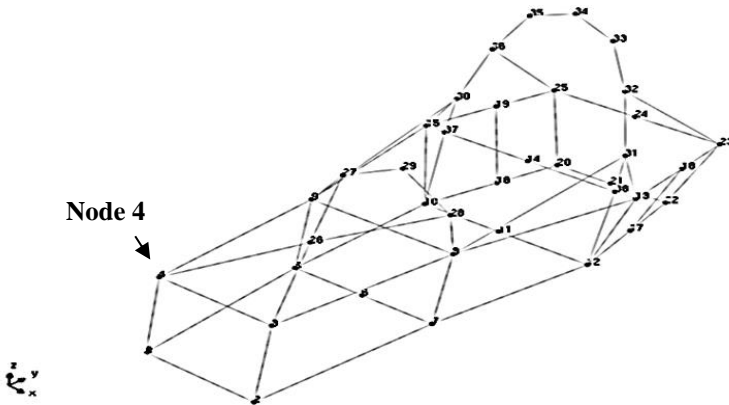


Figure 3: The structure of car chassis with 36 nodes (72 DOF's).

All the raw time data, geometry and series of measurement were then directly exported from the data acquisition system to the Artemis Modal software for signal processing, calculation and modal extraction. Frequency Domain Decomposition (FDD), Enhanced Frequency Domain Decomposition (EFDD) and Canonical Variant Analysis (SSI-CVA) algorithm were applied after all data were exported. It takes the benefit of SSI-CVA algorithm to be used in this study as compared to the two others algorithms such as SSI-PC

and SSI-UPC in Covariance-driven Stochastic Subspace Identification (SSI) method.

Experimental Modal Analysis

In contrast to the OMA technique, the requirement to conduct EMA is almost similar to OMA (see Figure 4) technique except an impact hammer was used as an input excitation. Measurement setup for EMA technique was almost similar to that of OMA technique in this study. The same measurement instrument which is Bruel & Kjaer PULSE™ Multi- Analyzer system was used while Bruel & Kjaer-PULSE LabShop Version 16.1.0 was used to create geometry, allocate measurement degree of freedom, measurement sequence and capture FRF data.

Same geometry and measurement sequence were used in this measurement setup as in the OMA techniques. For measurement of DOF's, it is similar to OMA technique except the first channel was set as a force (impact hammer) at node 4 with response point direction as Z-. Node 4 was selected as an appropriate location to impact the chassis structure because it produced a good response for modes of interest based on the pre-test. In addition, node 4 shows that energy is more than enough to supply along chassis structure with a known frequency content. For data analysis setup, it was observed that the 3 critical modes of interest in this study having the natural frequencies of interest below 200Hz. Thus, this frequency range was used further in OMA and EMA analysis. However, for EMA the frequency range up to 1600Hz was used in order to capture any additional modes of significant impact on the racing car chassis structure.



Figure 4: Experimental Modal Analysis and Operational Modal Analysis experimental set-up.

Results and Discussion

There are two types of vibration that can occur in the automotive chassis structure namely global and local vibrations. The global vibration means that the whole chassis structure is vibrating while the local vibration means the vibration is localized where only part of the car chassis is vibrating [3]. However, only global vibration on the chassis structure is considered in this study. In addition, the modes shape that is taken into consideration is flexural modes such as first bending (i.e., bending in x-direction and z-direction respectively) and first torsional mode.

The experimental analysis using OMA and EMA techniques was also carried out for initial validation purpose. After the modal parameters from OMA-FDD methods are obtained, the result is compared with EMA from FRF plot. The comparison between EMA and OMA was made only for the pre-validation purpose to support the result from OMA-FDD as a reference method before it will be compared with two identification algorithms in OMA technique.

The SVD plot (see Figure 5) presents the peak-picking which were conducted on the average of the normalized singular values for FDD method to extract the frequencies of the peaks. There are distinct peaks that can be clearly observed in the SVD plot for the frequency range up to 200 Hz. There are many additional peaks that have also been detected at first. However, only the first three peaks were selected since they represent three crucial modes for this structure which are the focus in this study, namely, first bending (in both x and z-direction) and first torsional mode. The frequencies were identified using Single degree of freedom (SDOF) in a user-definable frequency band around the peak while mode shapes were determined from singular vector weighted by singular values in the frequency band [4]. As can be seen in Figure 5, all the resonances peaks are well separated in this SVD plot.

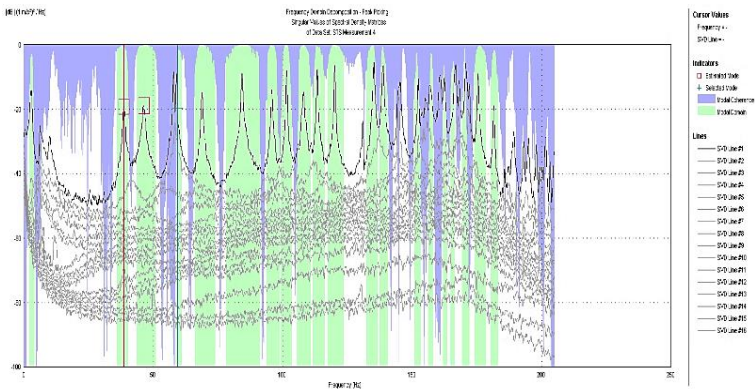


Figure 5: FDD peak-picking.

Meanwhile, frequency response function (FRF) plots from EMA technique are illustrated in Table 1. Peak picking was also performed to analyse how the chassis structure behaves dynamically at a particular frequency. Basically, every peak in this FRF plots is represented by amplitudes of the resonant peak at each resonant frequency. Since frequency range is set below 1600 Hz in analysis setup, there are several peaks that can be clearly seen in FRF plot and the first three peaks are selected manually based on the frequency as previously obtained using OMA-FDD method.

Table 1: EMA- FRF Plot peak picking.

Mode	EMA-FRF plots	
1		<p>Cursor values</p> <p>X: 39.00 Hz</p> <p>Y(Mg):0.33 (m/s²)/N</p>
2		<p>Cursor values</p> <p>X: 46.00 Hz</p> <p>Y(Mg):0.45 (m/s²)/N</p>
3		<p>Cursor values</p> <p>X: 59.00 Hz</p> <p>Y(Mg):0.91 (m/s²)/N</p>

Based on the SVD and FRF plots, a comparison was first made between EMA and OMA-FDD method as an initial comparison in order to support the result from FDD to be made as a reference for OMA analysis. Table 2 below shows a comparison of natural frequencies results between these two techniques. The correlation of natural frequencies between these two techniques gives a very small percentage of discrepancies which is between 0.67% and 1.04%. We conclude that the FDD method can be used further as a reference method to compare with the other two algorithms in OMA techniques.

Table 2: Comparison of natural frequencies between EMA-from FRF plot and OMA-FDD method.

Mode	EMA-FRF (Hz)	OMA-FDD (Hz)	Discrepancies Percentage (%)
1	39	38.6	1.04
2	46	46.4	0.86
3	59	59.4	0.67

Visual mode checking was done based on the mode shapes obtained at selected natural frequencies from both EMA and OMA as presented in Table 3. Both the frequencies and visual modes comparison show good agreement between these two techniques. The chassis structure experiences bending in the x-direction and z-direction for both mode 1 and mode 3 respectively. In mode 2, it is clearly seen that twisting or torsional mode presented.

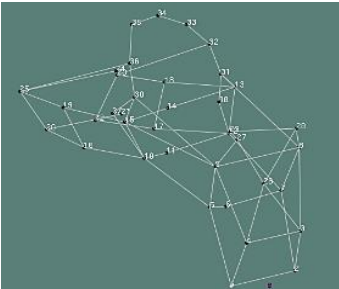
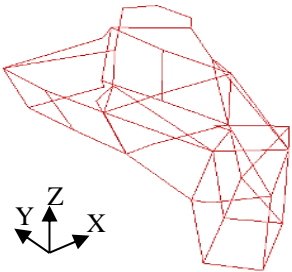
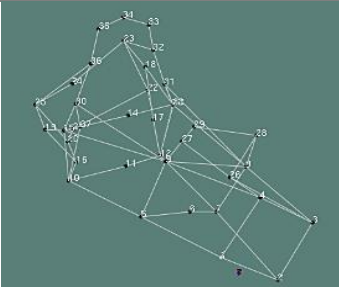
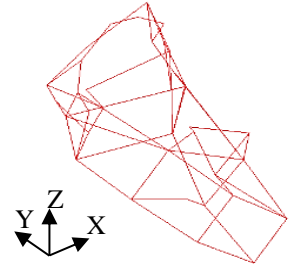
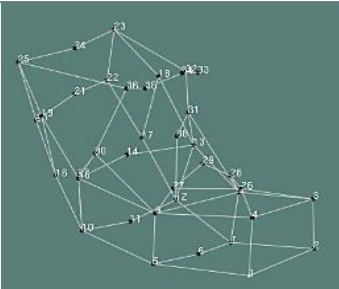
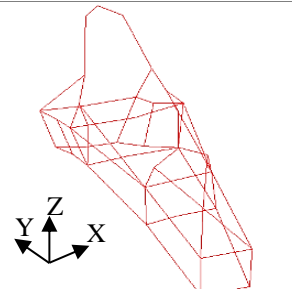
In Operational Modal Analysis (OMA), there is three identification algorithms method applied in this study. Frequency Domain Decomposition (FDD) method was chosen as a reference to compare with other identification algorithms since FDD is well known as one of the reliable and more users friendly for operational modal analysis of structures [5].

The SVD plot (as in Figure 6) indicates the peak-picking process which was conducted on the average of the normalized singular values for the EFDD method. There are a number of peaks that can be clearly observed in the SVD plot for the frequency range up to 200 Hz and three initial peaks were seen to represent three critical modes that are detected and are represented by the resonant frequency. It can be observed that all the resonances are well separated in the SVD plot.

As for time domain SSI-CVA techniques, stability diagram was obtained in this study and displayed in Figure 7. The analysis was performed in the same frequency range of 200 Hz. Furthermore, all projection channels were used in this analysis for SSI-CVA method. Three peaks seen in this plot represent three modes at the selected frequencies and it was observed at these peaks both first bending (x-direction and z-direction) and torsional modes are clearly dominant. The stability plot shows SSI-CVA algorithm identified all

three modes as stable modes (indicated by the red-dotted line and mode indicator).

Table 3: Comparison of visual mode shapes without un-deformed geometry between EMA-FRF plot and OMA-FDD method.

Mode	EMA-FRF	OMA-FDD
1	 <p>39 Hz</p>	 <p>38.6 Hz</p>
2	 <p>46 Hz</p>	 <p>46.4 Hz</p>
3	 <p>59 Hz</p>	 <p>59.4 Hz</p>

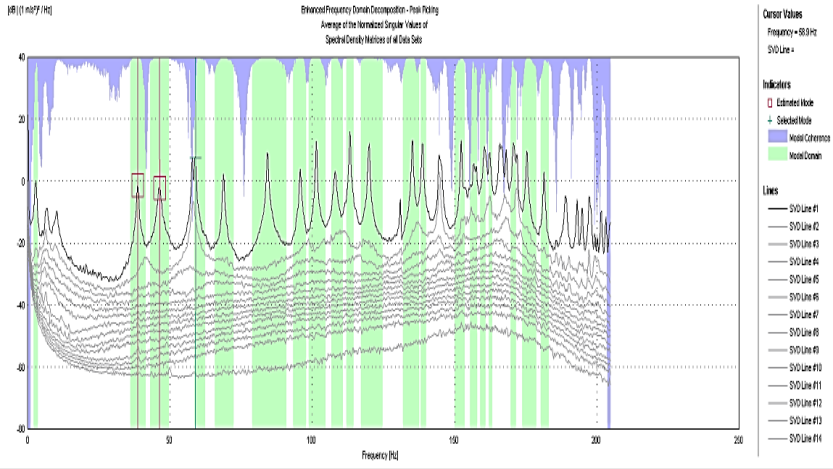


Figure 6 EFDD peak-picking.

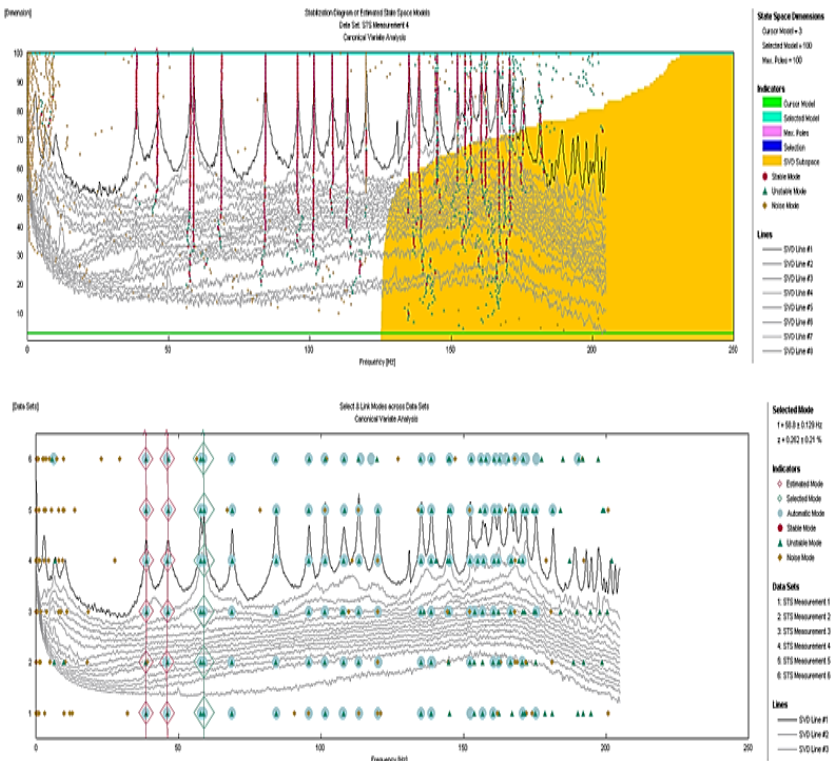


Figure 7: SSI-CVA identification peak-picking.

Comparison of natural frequencies for each of the OMA techniques is presented in Table 4 and Table 5 for both parametric and non-parametric method. In this case, the FDD method is considered to be a reference method for the percentage of discrepancies calculation and it is obvious that the results are relatively close for each method. The discrepancies percentage on each method is less than 10% which is in a tolerable range and is still in good agreement.

Table 4: Comparison of natural frequencies between OMA techniques.

Mode	Non-Parametric Method	Parametric Method	
	FDD(Hz)	EFDD(Hz)	SSI-CVA(Hz)
1	38.6	38.63	38.52
2	46.4	46.24	46.07
3	59.4	58.89	58.84

Table 5: Discrepancies percentage of natural frequencies between OMA techniques.

Mode	FDD and EFDD (%)	FDD and SSI-CVA(%)
1	0.078	0.21
2	0.34	0.71
3	0.86	0.94

Mode shapes were compared between each OMA technique for this study in Figure 8, Figure 9 and Figure 10. The blue line of chassis structure indicates un-deformed geometry while green and red line indicates deformed geometry. All the visual mode comparisons show good correlation between each method.

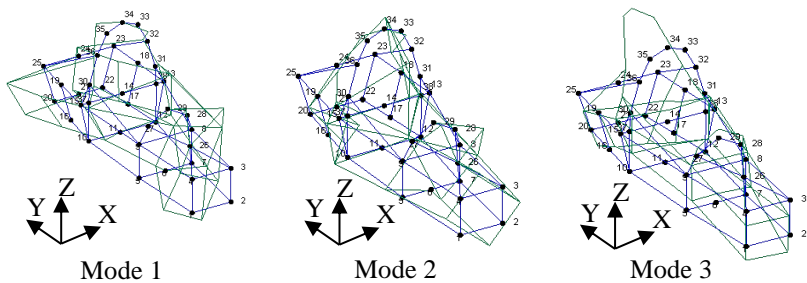


Figure 8: Mode shapes geometry from FDD method.

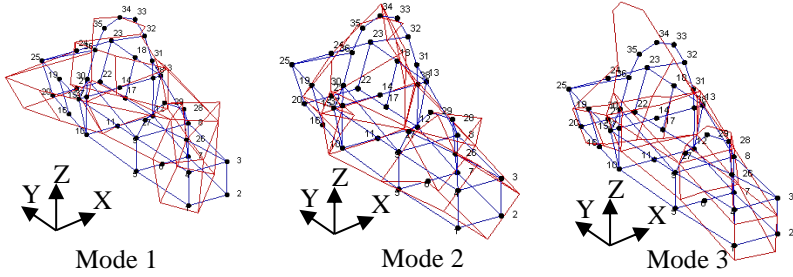


Figure 9: Mode shapes geometry from the EFDD method.

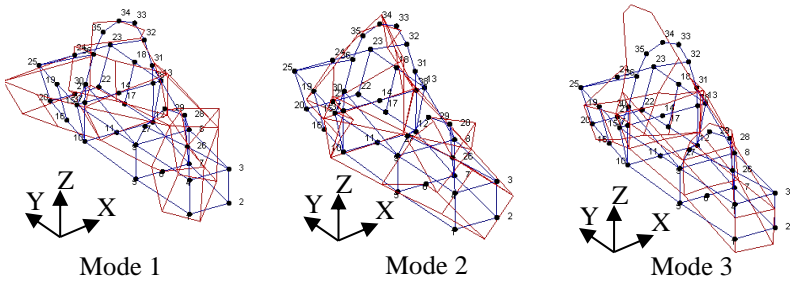


Figure 10 Mode shapes geometry from SSI-CVA method.

Modal Assurance Criterion (MAC) analysis is used as a statistical indicator for mode validation to indicate the correlation between mode shapes. MAC analysis also provides an additional confidence factor in the evaluation of a modal vector from a different modal parameter estimation algorithm [6]. Its value is bounded between 0 and 1. A value near 0 indicates that the mode shapes are not consistent while 1 signifies that mode shapes are fully consistent.

The MAC-plot and MAC-table between mode shapes for parametric and non- parametric method in this study are illustrated in Figure 11(a) and Figure 11(b). The result showed that all compared mode shapes give high MAC values close to 1. Thus, the results of this study indicate that all modes shapes obtained are well correlated with one another.

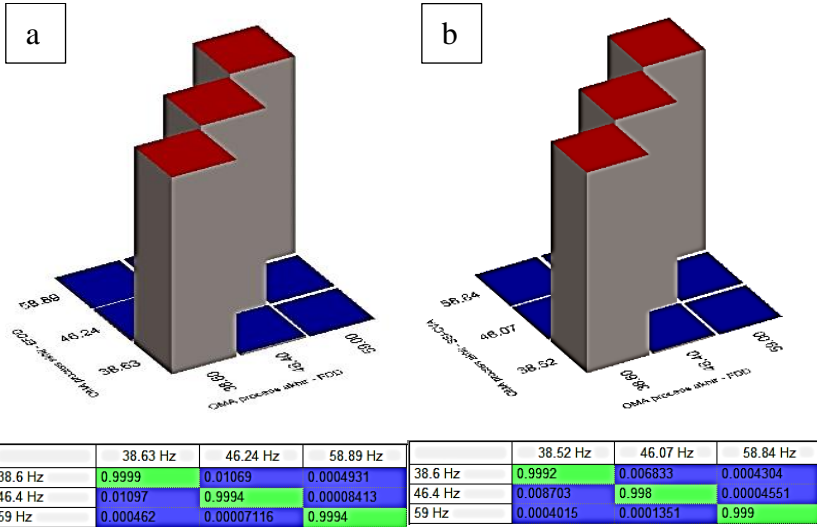


Figure 11: Mode validation between each OMA techniques using MAC; (a): MAC-mode comparison for FDD and EFDD, (b): MAC-mode comparison for FDD and SSI-CVA.

Conclusion

OMA and EMA techniques were successfully conducted on the racing car chassis structure. All the objectives of this study have been achieved as the modal parameters of chassis structure under free-free boundary condition were extracted. Good correlation of natural frequencies and visual mode analysis were obtained for EMA from FRF plot and OMA-FDD method as an initial validation before they were subsequently compared with other identification algorithms in OMA technique. Good modal parameters were determined from both parametric and non-parametric methods in OMA technique. Natural frequencies from EFDD and SSI-CVA methods were nearly close to the FDD method. Moreover, MAC-value showed that mode shapes from EFDD and CVA methods are well correlated with that of the FDD method. In general, the results of this study indicate a strong correlation of modal parameters for the racing car chassis structure using both parametric and non-parametric methods.

It is recommended that the research is extended to investigate the damping ratios of the chassis structure in view of its significance for a racing car competition. For further comparison, Finite element analysis (FEA) can be conducted to study dynamic characteristic of this chassis structure. Furthermore, finite element updating can also be performed by using the discrepancy result between FEA and test (OMA) to correct errors in FE models for further structural vibration analysis with much more confidence.

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