Identifying the Appropriate Frequency Response Function Driving Point of a Car Door Using Finite Element Analysis and Modal Testing

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Abstract. Identifying the appropriate frequency response function (FRF) driving point of complex structures is crucial to experimental modal analysis (EMA), but it is often found to be challenging and problematic. Traditionally, EMA analysts tend to place a reference sensor at several potential driving points and excite the points during testing. However, the approach is time-consuming. The aim of this work is to demonstrate an effective procedure for identifying the appropriate FRF driving point of a complex structure using finite element pre-test analysis and modal testing. The demonstration is performed on a car door structure comprising several geometrically complex structural components. The effective impedance method (EIM) is used to identify thirty potential driving points from the finite element model of the car door. The FRF data of the driving points is derived by using the FRF synthesis method and the derived data is compared with the EMA FRF data for validation purposes. Using EIM, three appropriate driving points covering all the modes required within the frequency of interest that is 0 to 100Hz has been successfully identified. The achievement suggests that the use of the effective impedance method for identifying the appropriate driving points is highly dependent on the accuracy and reliability of the finite element model.

1. Introduction

Identifying the appropriate frequency response function (FRF) driving points of a structure is a crucial to experimental modal analysts as the driving points are extremely important for excitations to be performed in modal testing [1,2]. However, when it comes to performing modal testing on a dynamically complex structure, identifying FRF driving points using modal testing has been seen to be more challenging and time-consuming [3–5]. Therefore, finite element pre-test analysis [6] is a good alternative approach for the identification.

The pre-test analysis can be performed using various methods as presented in [7]. One of the popular pre-test methods is the effective impedance method (EIM). Algorithms used in the method define a summation of all terms corresponding to particular DOF and yield vectors whose elements represent one DOF’s contribution to all modes of interest [8]. The detailed information about the method can be found in [9]. The method has been successfully used in identifying the optimal sensor placement for system identification and structural health monitoring as demonstrated in [10]. Another striking example as shown in [11] the optimal sensor placement for hyperbolic paraboloid fabric structure was successfully determined using EIM.
The pre-test analysis for a geometrically complex structure, however, requires a comprehensive procedure as the pre-test analysis is a case dependent [12]. This paper puts forward an idea of effectively identifying the appropriate FRF driving points of a complex structure using EIM pre-test analysis and experimental modal analysis. A geometrically complex car door consisting of several structural components is used for the identification. The accuracy of the pre-test analysis is evaluated by comparing the FE FRF with the measured counterparts obtained from modal testing.

1.1. Description of the test structure
Figure 1 shows the car door that consists of several structural components. The structural components are assembled using spot welded joints. The structure is made of galvanized steel, and the thicknesses vary from 0.8mm to 1.5mm. The height and width of the structure are approximately 1000mm and 1200mm respectively. The mass of the structure is 13.6kg.

![Figure 1. The car door structure](image)

Initially, the dynamic behaviour of the structure is calculated using the finite element method. The FE model is then used to identify several appropriate measurement points. The test structure is investigated under free-free boundary conditions in accordance with previous studies [13,14]. The frequency of interest for the investigation is between 15Hz and 100Hz, which contains twelve modes. The rigid body modes are neglected during the investigation.

2. Finite Element Modelling
Figure 3 presents the finite element model of the car door. The model was developed approximately similar to the test car door in [15]. The model of the structure was discretised into 35000 2D shell elements, and the size of the elements varies from 7mm and 8mm. The standard material properties for galvanized steel [15,16] was defined to the elements as follows; density; 7.850 kg/l, Poisson’s ratio: 0.3, and Young’s Modulus: 210,000 MPa. The natural frequencies and mode shapes of the finite element model were calculated using Nastran normal modes solution.
The effective impedance method (EIM) was used to identify and suggest the appropriate measurement points based on the modal data calculated from the FE model [9]. The identification was only carried out in a single direction that is Z-direction. The measurement points were determined with the aid of Siemens Virtual.Lab software. Figure 3 shows the suggested measurement points obtained from the FE model.

Since the FE model was developed based on assumptions, the FRF derived from the FE model is compared with the measured counterparts for validation purposes. The finite element FRF was derived using FRF synthesis method. For this method, the synthesized FRF matrix $H_{\text{syn}}(\omega_k)$ and mode shapes are expressed by:

$$H_{\text{syn}}(\omega_k) = \sum_{i=1}^{N} \frac{\{\Phi\}_i (\{\Phi\}_i^T)}{(\omega_n^2_i - \omega_k^2) + j2\xi_i \omega_k \omega_n_i}$$

(1)
where $N$ is the number of calculated modes, $\{\emptyset\}_i$ is the $i$th mass normalised mode shapes, $\omega_{ni}$ is $i$th natural frequency and $\xi_i$ is the $i$th modal damping ratio.

3. Test Configuration for the Test Structure
In this work, thirty drive points FRF were measured using experimental modal analysis (EMA). The experimental configuration of the test car door is illustrated in Figure 4. The experimental work was carried out by suspending the test car door using two soft springs to simulate free-free boundary conditions. This experimental configuration was designed as to the FE model [17–20]. The test car door was excited by using an impact hammer, and the resulting response was measured using a uniaxial accelerometer. The sensitivity of the transducers used was 21.65mV/N and 10mV/g respectively. Leuven Measurement System (LMS) SCADAS was used to acquire the dynamic data. In this study, the frequency bandwidth was set between 0 to 100 Hz with the frequency resolution of 0.5 Hz.

4. Results and Discussion
The level of accuracy of the pre-test analysis is evaluated by comparing the FE FRF data with the measured counterparts. In this work, thirty sets of FRF data were acquired from the synthesised and modal testing. Based on the normal modes analysis carried out, twelve modes have been identified within the frequency of interest between 0 to 100 Hz and the data is presented in Table 1 in which the number of modes indicates the number of the resonance frequencies found in the FRF peaks.
Table 1. The modes of the test model within the frequency of interest

| No. of Mode | Resonance Frequency, Hz |
|-------------|-------------------------|
| 1           | 39.756                  |
| 2           | 47.950                  |
| 3           | 55.068                  |
| 4           | 64.481                  |
| 5           | 67.131                  |
| 6           | 71.160                  |
| 7           | 76.768                  |
| 8           | 78.058                  |
| 9           | 85.506                  |
| 10          | 89.304                  |
| 11          | 91.549                  |
| 12          | 95.886                  |

4.1. FRF data calculated from the FE model
The appropriate FRF driving point points are identified based on the visibility of the resonance peaks within the frequency of interest. Table 2 shows the patterns obtained from the comparison of data between modes and FRF driving points. Green colour indicates a good and clear peak, yellow shows a poor peak and red illustrates no peak at all. Meanwhile, blue colour confirms a good driving point covering all modes with a good quality of FRF. From Table 2, it can be seen that only 37 per cent (11 points) of the total of the driving points has yielded a good quality of FRF data with good and clear peaks. The rest have shown evidence of missing modes and no peaks at all. However, the 14th driving point has marked the lowest visibility of resonance peak.

Table 2. Pattern summary of the number of modes against a number of the FE FRF driving points

| Mode | FE Driving Points |
|------|-------------------|
| 1    |                   |
| 2    |                   |
| 3    |                   |
| 4    |                   |
| 5    |                   |
| 6    |                   |
| 7    |                   |
| 8    |                   |
| 9    |                   |
| 10   |                   |
| 11   |                   |
| 12   |                   |


To reinforce the understanding of the pattern summary, two different driving points, which are points 4 and 14, were used in plotting FRFs as shown in Figure 5. It clearly shows that the FRF plotted from point 4, covering all resonance peaks required in this study is far superior to that of point 14 with missing several resonance peaks. The missing resonance peaks are at 55.07 Hz and 85.51 Hz. Therefore, point 14 may be inappropriate to be used for a driving point.

Figure 5. The FRF of point 4 and point 14

4.2. FRF data obtained from experimental modal analysis
As mentioned before, the FE model used was developed based on initial assumptions. The predicted results obtained from FE models sometimes differ from the measured counterparts. In this work, modal testing was performed on the car door to evaluate the accuracy of the numerically derived FRF driving points. Table 3 presents the summary of the number of modes related to the thirty points of measured driving points.
Table 3. Pattern summary of the number of modes against the number of the measured FRF driving points

| Mode | Measured Driving Points |
|------|-------------------------|
|      | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 |
| 1    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 2    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 3    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 4    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 5    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 6    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 7    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 8    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 9    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 10   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 11   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 12   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

From Table 3, it shows that most of the measured driving points have yielded a poor quality of results in FRF. However, only three driving points (points 16, 23 and 24) have evidence of good visibility of the resonance peaks, in contrast to the FE driving points, which it has gained 11 driving points. The comparisons of FRF data between the FE and measured driving points, particularly of points 16, 23 and 24 are depicted in Figures 6, 7 and 8.
Figure 6. The comparison between the FE and measured FRF of point 16

Figure 7. The comparison between the FE and measured FRF of point 23

Figure 8. The comparison between the FE and measured FRF of point 24

From Figures 6, 7 and 8, the measured FRFs of the car door have low amplitude resonance peaks, indicating that the car door is a highly damped structure [21]. In addition, the FE FRF patterns presented in the figures are not in good agreement with the measured counterparts. This demonstrates that the FE model is incapable of accurately predicting the actual dynamic behaviour of the car door [22–24], whereas the FE model can be effectively used to identify the appropriate FRF driving points that are shown in Figure 9.
5. Conclusions and Recommendations

The procedure of identifying the appropriate FRF driving points of a car door using finite element and modal testing has been presented. The appropriate FRF driving points of the car door have been successfully identified using the effective impedance method, which is highly dependent on the accuracy and reliability of the FE model. The procedure demonstrated may be useful to the structural dynamics and experimental modal analysis community for confidently determining the dynamic behaviour of large, complex structures that are prevalent in the automotive and aerospace industries.

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