Chapter 9
Evaluation of Modal and Frequency-based Representation for Integrating a Battery Pack into a Vehicle Body

Fabio Bianciardi, Bart Forrier, Mahmoud Elkafafy, and Marc Brughmans

Abstract The integration of the battery pack into a vehicle body has a large impact on the full-vehicle noise, vibration and harshness (NVH) behaviour of e-vehicles. It presents a major challenge for the vehicle development, due to the strong structural-dynamic coupling between the battery pack and the body. To avoid costly design improvements late in the development stage, predictions on the full-vehicle NVH performance are required early in the development cycle.

Frequency based sub-structuring (FBS) is a technique allowing the prediction of the structural behavior of an assembly based on the individual substructure models. FBS makes direct use of the FRFs that describe the substructures' interface dynamics and is an established method for applications with a limited number of point connections (such as, e.g. motor to vehicle body coupling).

In this study, the FBS will be applied to the case of a battery-to-body integration. The numerous point connections distributed over the mating surfaces posed a challenge for the stability of the FBS, and a high-quality and consistent FRFs model is required. A modal representation of the experimental FRFs is often considered as a way to mitigate potential inaccuracies in the experimental data. However, obtaining an accurate and representative modal model poses significant challenges when dealing with large interface DoF due to the large number of FRFs involved in the modal parameter estimation process. A strategy to obtain an accurate test-based modal model of a battery pack will be discussed.

The objective of this work is to validate the FBS for a battery to body integration study. A fully experimental model and a test-based modal model of a battery pack will be coupled to an experimental model of a vehicle body. The results will be validated against a reference experimentally measured in a fully assembled e-vehicle.

Keywords Substructuring · Modal analysis · Experimental · Electric vehicle

Introduction

The shift of the automotive industry to Electric Vehicles (EV) brought new challenges to the development of vehicle body. The introduction of the battery pack has deeply changed the structural and dynamic behavior of the vehicle. The presence of the battery pack highly influences the vehicle body dynamics. Figure 1 shows an example of an FRF measured between a motor mount and a target seat vibration response. The body design is therefore reviewed, and structural improvements are proposed to accommodate the heavy battery structure. In this development process an accurate simulation model is needed for both body and battery structures. The simulation of body structures has been around for a long time, so a lot of experience is available to build an accurate model. Less experience is available for building an accurate battery structural model. When creating a full FE based body-battery system model there is a risk of jeopardizing the quality of the simulation results by a lower quality FE representation of the battery, and directions for body design improvements may be biased by inaccurately simulated battery behaviour. Therefore, in cases where the battery design is fixed, and hardware is available, a much option for the body designer is to represent the battery by an accurate test-based modal model.

A first step in building a test-based modal model is to perform FRFs measurements on the battery at all points that interface with the body structure. These measured FRFs can directly be used in Frequency Based Substructuring (FBS) techniques to build a full vehicle model. However, due to the large number of interfaces degrees of freedom (DoF) between

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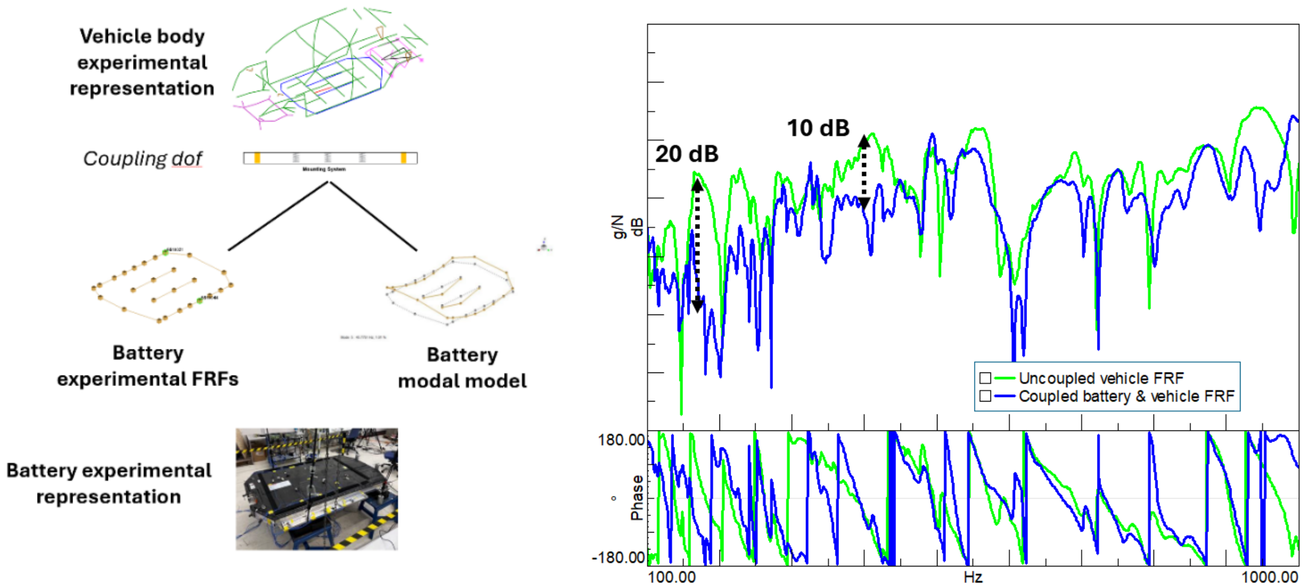

Fig. 1 (on the left) Overview of the substructuring framework presented in this paper; (on the right) example of the effect of the battery integration in the vehicle body, measured FRF between a motor excitation DoF and seat vibration response DoF for the uncoupled vehicle (green curve) and the coupled battery & vehicle (blue curve)

body and battery, the number of involved FRFs in the coupling is high ($>$ 6000 FRFs) and this poses high challenges to the quality of the experimentally acquired data ensuring a consistent dataset of FRFs [1].

In this paper, the integration of the battery pack to an experimental vehicle body will be explored and validated on an existing passenger vehicle. Classical Frequency Based Substructuring (FBS) technique will be used to assemble the vehicle components. Two battery models will be investigated: i) a fully experimental FRFs based model; ii) a modal model derived from the experimentally acquired FRFs. In both cases the FBS substructuring will be challenged by the large amount of degrees of freedom involved in the coupling interface (78 coupling DoF). In addition, a method for realizing a high quality modal model that provides an accurate smoothed approximation of the measured FRFs is applied in this work [2]. Several building blocks have to be resolved to obtain such a modal model in an accurate and efficient way giving the fact that a large number of potentially magnitude-unbalanced FRFs needed to be processed. The next sections will present these challenges and discuss the developed solutions.

The advantages of using a modal model are twofold, on one hand, it allows to get a consistent and accurate component model mitigating potential experimental errors, and, on the other hand, it could be coupled to any numerical vehicle model enabling the possibility to optimize the structural behaviour of the assembly (or of the components) thanks to readily interpretable results (e.g. mode shapes).

Finally, the new developed technique to model the battery is firstly validated using frequency response functions (FRFs) measured on a battery structure provided by Hyundai Motor Company (HMC), and then the structural behaviour of the assembled components is validated against a reference target experimentally measured on the fully assembled vehicle.

The Substructuring Framework

FBS (Frequency Based Substructuring) is a dynamic substructuring method formulated by Jetmundsen et al. [3][4]. It allows obtaining the dynamic behavior of an assembled system starting from the uncoupled substructures dynamics. FBS is a very valuable method in the experimental field since it can be directly applied to experimentally measured FRFs. When assembling FRFs that are experimentally measured, the process puts high demands towards data quality during the component characterization, requiring appropriate boundary conditions at the connections. Nevertheless, it supports also FRFs obtained from a numerical model or FRFs synthesized from a modal model, as in the application case described in this paper.

Let's consider the subsystem's FRF matrices and model them as an uncoupled system in free-free boundary conditions. The schematic model presented in Fig. 2 represents an assembly composed of two uncoupled systems, representing for example a battery pack and a vehicle body. The equation of motion for the uncoupled systems A and B can be written as in

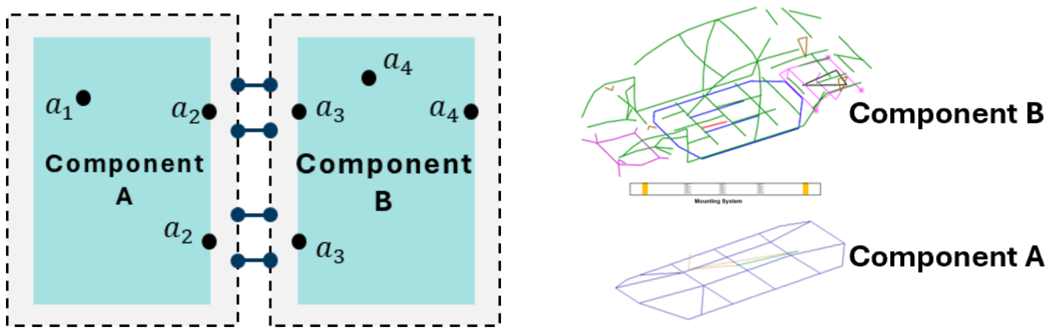

Fig. 2 Schematic overview of the assembly model

eq. (1). Here, the subscripts refer to the DoF (1 any point inside the source DoF, 2 and 3 any point at the interface connection DoF, and 4 any receiver DoF), and the superscripts refer to the component.

In this system, the effect of the coupling is represented by a set of contact forces **g** acting in the connections DoF of both bodies, as shown in fig 2. Following the dual formulation, the contact forces inherently adhere to the force equilibrium principle (eq. (3)) and must enforce the compatibility condition of the connecting DoF (eq. (2)). $\boldsymbol{B}$ in eq. (2) and eq. (3) are the boolean matrices that maps the DoF. And $\boldsymbol{\lambda}$ are Lagrange multipliers representing contact forces.

$$a = \begin{bmatrix} H_{11}^A & H_{12}^A & 0 & 0 \\ H_{21}^A & H_{22}^A & 0 & 0 \\ 0 & 0 & H_{33}^B & H_{34}^B \\ 0 & 0 & H_{43}^B & H_{44}^B \end{bmatrix} \left(\begin{bmatrix} F_1 \\ F_2^A \\ F_3^B \\ F_4 \end{bmatrix} + \begin{bmatrix} 0 \\ g^A \\ g^B \\ 0 \end{bmatrix} \right) = H(f+g) \quad (1)$$

$$\begin{bmatrix} 0 & -I & I & 0 \end{bmatrix} a = Ba = 0 \quad (2)$$

$$g = B^T \lambda \quad (3)$$

By combining the above equations, the following formulation for the coupled FRFs can be derived, as presented in eq. (4). This equation is known as the dual assembly formulation or LM-FBS [3][5], which will be used later in this paper.

$$H^{AB} = H - HB^T \left(BHB^T \right)^{-1} BH \quad (4)$$

One of the experimental challenges of FBS is the requirement of the FRFs of all the connection degrees of freedom. The difficulty can arise for different reasons, such as the case of a continuous interface, for which a discretization strategy would be needed to make the approach practically feasible, or a lack of accessibility of the connection interface DoF, for which indirect additional measurements should be performed and then reduced to the point of interest using the virtual point transformation.

In this work, the connection interface was discretized in 26 coupling points corresponding to the bolting positions, each represented with 3 translational degrees of freedom, for a total of 78 DoF. This discretization was considered sufficient for the frequency range of interest (100Hz-1000Hz), and at the same time maintaining the measurements effort within the limits of practical feasibility.

The Battery Model

The battery experimental model

In this paragraph, the description of the experimental tests to obtain the battery model are presented. The battery was free-free suspended in bungees (cf. Figure 3) and excited up to $2kHz$ at 78 coupling DoF (26 battery-to-body connection points in x, y and z- directions) using the Simcenter Qsources hardware integral shaker (QISH-Integral shaker) mounted on a Qtrx excitation adaptor. Frequency response functions were measured consecutively, exciting at different angles as shown in Figure 3. The obtained FRF set is processed to reconstruct the FRFs with the excitations aligned with the global axis system. The acceleration responses were simultaneously acquired at the 78 coupling DoF using modal accelerometers PCB 356A15. This results in a 78x78 ($No \times Ni$) FRFs matrix at each frequency line in the excited frequency range. Some typical measured FRFs are shown in Figure 3. The acquired experimental FRFs can be directly used in the substructuring equation, or as input for the modal modelling identification process presented in the next paragraph.

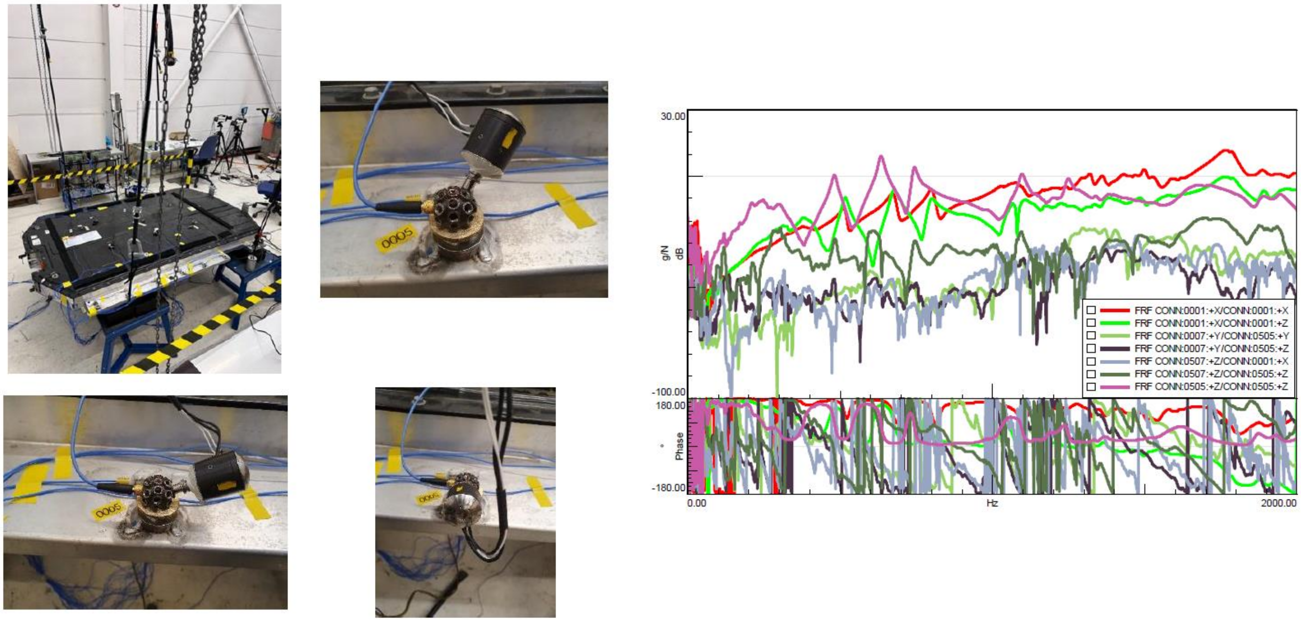

Fig. 3 The battery test setup and some typical measured FRFs at the connection points

The battery modal model

For the battery model, we introduce a workflow for estimating in an efficient manner a high-quality modal model which can be used in a substructuring framework, such as coupling with a vehicle body. Given the large size of the raw FRFs matrix to be processed (78 rows $\times$ 78 columns at each frequency line), and a wide variation in FRF amplitudes, the workflow aims to address two key aspects: 1) ensuring reasonably accurate modal synthesis for all FRFs, regardless of their magnitude level, and 2) executing the modal estimation process in a time-efficient manner. The different blocks of the proposed workflow are extensively described in [2]. As shown in Figure 4, the workflow consists of two main steps: 1) estimating a reduced-size,

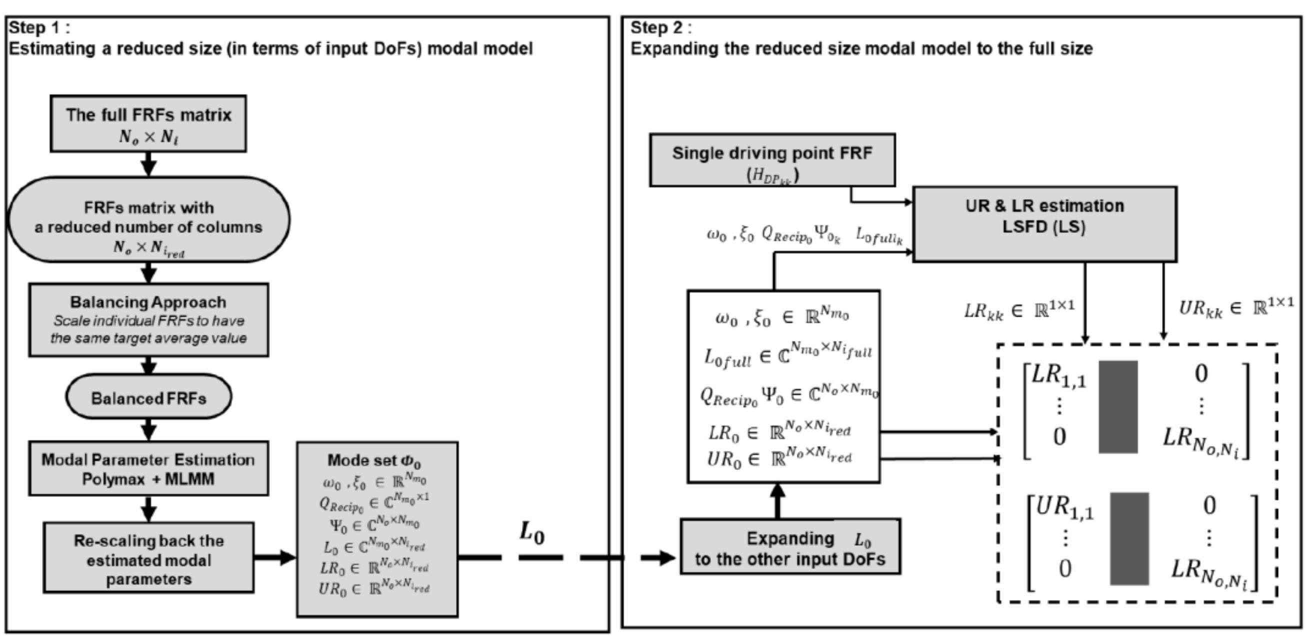

Fig. 4 Workflow of the proposed enhanced modal parameter estimation approach

in terms of reference DoF, modal model, and 2) expanding the reduced-size modal model to the full original-size FRFs matrix.

To estimate a reduced-size modal model, a selection of a few columns (e.g., $NiRed = 4$, with $NiRed$ the reduced selected number of columns) from the full-size FRFs matrix must be made. After selecting the reduced number of columns, the first step in the workflow (i.e. estimating reduced-size participation factor vectors) consists of three main sub-steps. In the first sub-step, a magnitude-based balancing approach is applied to the reduced FRFs matrix to equalize the different FRFs in terms of magnitude. In the second sub-step, the modal parameters of the component under test are estimated in the frequency band of interest by applying the Polymax and MLMM (Maximum Likelihood estimation of a Modal Model) estimators [6][7] to the balanced reduced-size FRFs matrix. Finally, in the third sub-step, the estimated mode shape vectors, participation factor vectors, and elements of the lower and upper residual terms matrices are rescaled to make them consistent with the original magnitude levels of the processed FRFs. Once the reduced-size modal model is estimated, a full-size modal model is retrieved by extending the estimated participation factor vectors, the lower residual matrix, and the upper residual matrix, as in the second step of the proposed workflow (i.e. expanding the reduced-size modal model to the full original-size FRFs matrix).

The developed workflow has been tested and validated using test data that were measured during the experimental tests of the battery structure.

In this analysis, the targeted frequency application range was 100-1000Hz. A reduced FRF matrix consisting of only four columns is selected from the full FRF matrix to perform the modal estimation of the global flexible modes within the frequency band of interest more efficiently. Before applying the Polymax and MLMM modal parameter estimators to the reduced FRF matrix, the matrix is first balanced using the implemented balancing technique [2].

The Polymax estimator with a model size of 200 is then applied to the balanced reduced-size FRF matrix to estimate an initial modal model. Starting with this Polymax-based initial modal model, the MLMM estimator was run for 30 iterations, imposing constraints, i.e., reciprocity, real mode shapes, and negative mass sensitivity, on the optimized modal model. For comparison, the modal estimation process was also conducted using the unbalanced (raw) FRFs with the same user settings. Once the modal parameters are estimated they are scaled back to match the original magnitude levels of the raw FRFs.

In Figure 5, it can be observed that for FRFs with higher initial magnitudes (see Figure 5 - top), the solution based on the balanced FRFs (blue curve) is similar to that from the raw FRFs (green curve), indicating that applying the balancing technique does not negatively affect the quality of the modal synthesis for FRFs with higher initial magnitudes. For FRFs with lower initial magnitudes (see Figure 5 - bottom), the final retrieved modal synthesis shows clear improvements when the FRF matrix is balanced (blue curve) before performing the modal parameter estimation.

In the final step, the reduced-size ($\in \mathbb{C}^{78\times4}$) modal model is expanded to the full size of the measured FRF matrix ($\in \mathbb{C}^{78\times78}$) by filling in the missing elements of the participation factor vectors and the diagonals of the residual term matrices. The missing participation factors for each mode are calculated using the estimated reciprocal scaling factor, thanks to the reciprocity constraint imposed in the MLMM optimization.

Figure 6 illustrates the modal synthesis over the frequency band of interest for some selected expanded driving point FRFs. In general, it was found that the expansion process delivers a reasonable modal synthesis for most of the driving point FRFs that were originally not considered in the modal estimation step. The key takeaway from these plots is that expanding only the contributions of the global flexible modes is insufficient to achieve accurate synthesis for a driving point FRF that was not originally included in the modal estimation step. The inclusion of residual effects, which compensate for the truncation of higher-frequency modes (i.e., local flexibilities), is essential for achieving an accurate modal synthesis of such FRFs. Furthermore, the resulting modal model is suited to be coupled to the vehicle body model in a modal coupling framework. Nevertheless, in this paper a fully experimental FRFs model of the vehicle will be considered for further validation purposes of the substructuring process.

The Vehicle Model

In this paragraph, the description of the experimental tests to obtain the vehicle body model are presented. The vehicle (without the battery) was let standing on slightly deflated tires. Shaker excitations up to $2kHz$ were performed at the 78 interface coupling DoF and at a motor mount location using the Simcenter Qsources hardware integral shaker (QISH-Integral shaker) mounted on Qtrx excitation adaptor. Frequency response functions were measured consecutively, exciting at different angles. The obtained FRF set was processed into FRFs with the excitations aligned with the global axis system. The acceleration responses were simultaneously acquired at the 78 coupling DoF and at a couple of seat target locations using modal accelerometers PCB 356A15. This results in a 84 x 82 ($No{\times}Ni$) FRFs matrix at each frequency line in the excited frequency range.

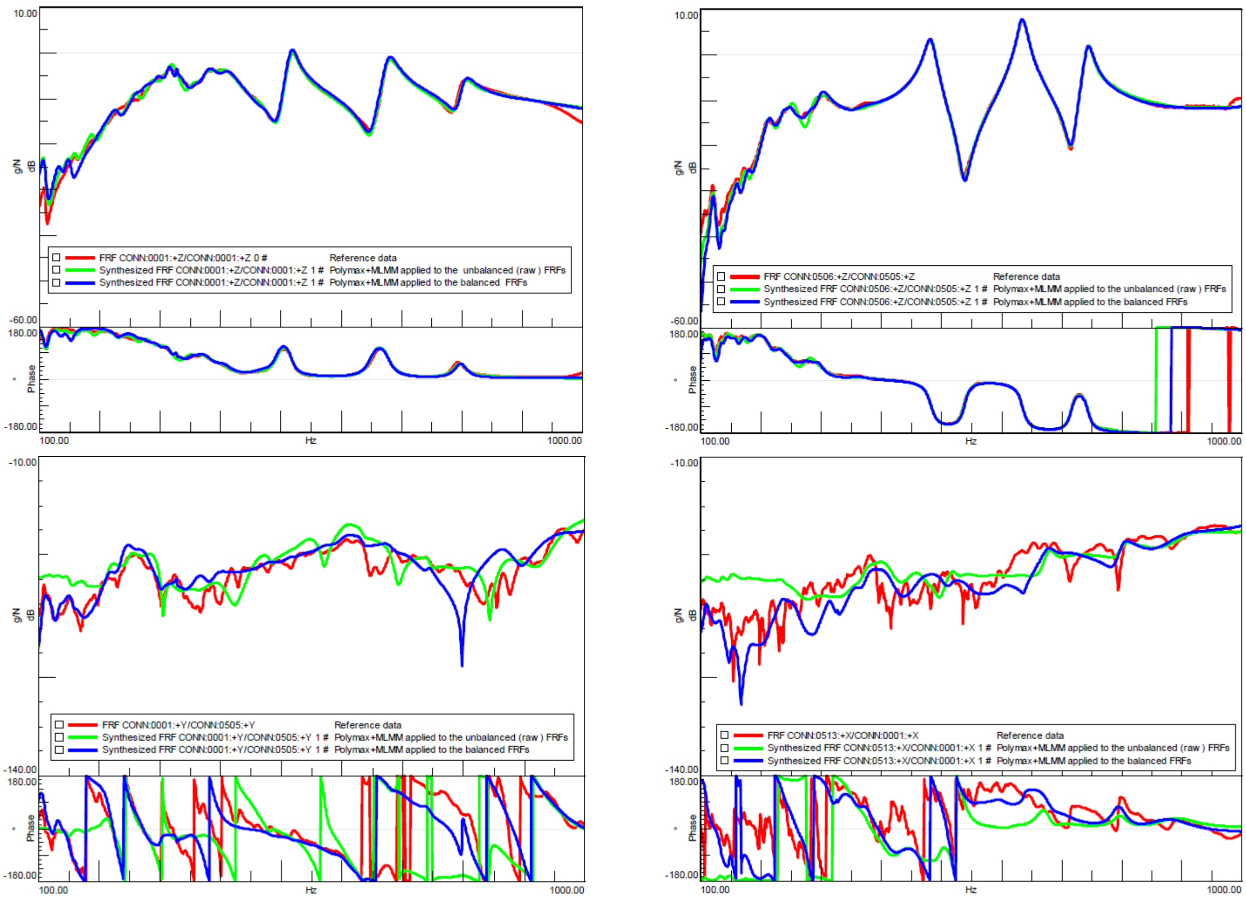

Fig. 5 Modal synthesis of the test-based MLMM estimated battery modal model for different FRFs. (Top: FRF with higher magnitude, Bottom: FRF with lower magnitude)

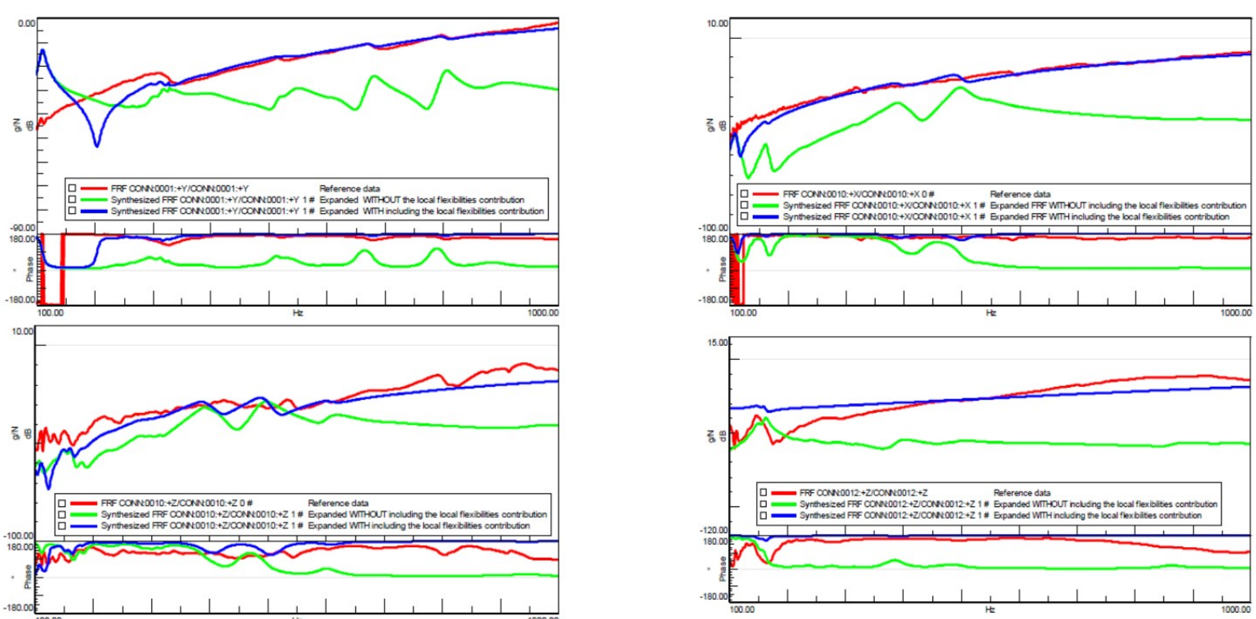

Fig. 6 Modal synthesis for driving points FRFs that were not included in the modal estimation step (i.e., FRFs calculated from the modal model expansion process)

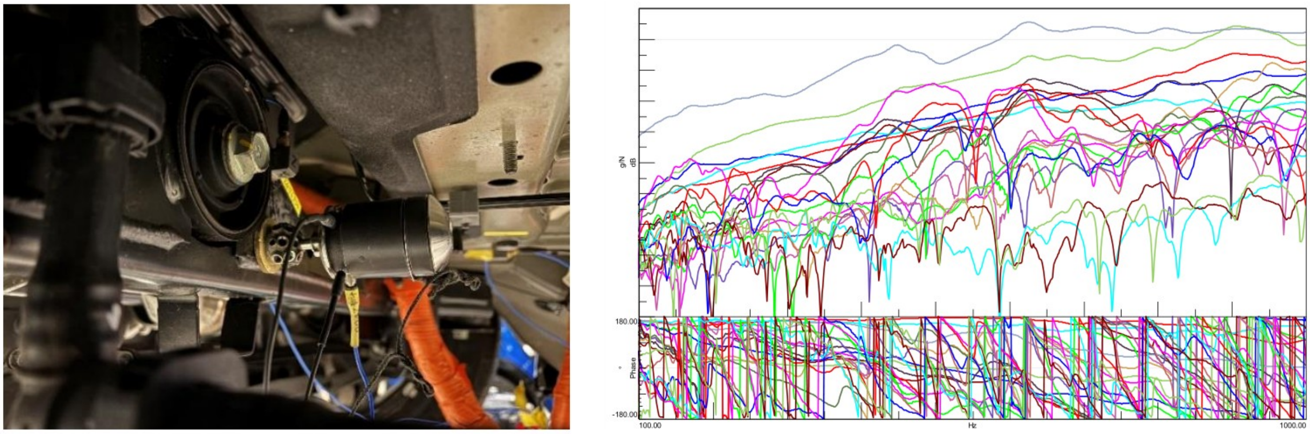

Fig. 7 The vehicle body test setup and some measured FRFs

The Substructuring Results

In this section, the virtual integration of the battery and the vehicle body is validated against the experimentally measured FRFs acquired on a fully assembled vehicle integrated with the battery pack which are considered as the reference for this study. The framework used for the components integration is the FBS substructuring. Two battery models (fully experimental and modal model) were virtually integrated to the experimental model of the vehicle body to predict the coupled system dynamic behaviour. The substructuring results were compared with the experimentally measured reference FRFs between a motor excitation DoF and a seat vibration response DoF. Figure 8 presents the results obtained by: i) the fully experimental substructuring, coupling fully experimental models of the battery and of the vehicle body (left figure); and ii) the hybrid substructuring, coupling the modal model of the battery and the experimental model of the vehicle body (right figure).

From the presented results, we can notice, that the predicted coupled FRF for the fully experimental substructuring follow very well the reference FRF, validating the capability of the substructuring method in such a challenging application with large amount of interface connection DoF. Moreover, it proves that the proposed 2-step modal parameter estimation workflow is successful in delivering a full-size modal model, in an efficient manner and with good accuracy, which generates coupled FRF results comparable to the fully experimental substructuring. This result gives good confidence to the quality of the obtained battery modal model, making it suitable to be coupled to a vehicle modal model in a future research work.

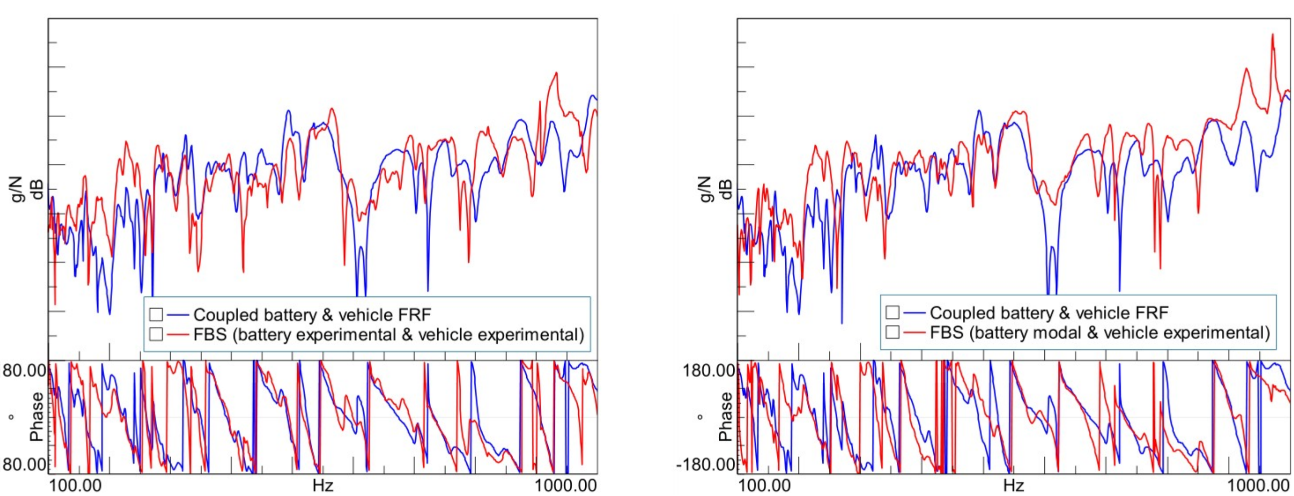

Fig. 8 Comparison of the FRF experimentally measured on the assembled battery & body (blue curve) and the predicted FRF obtained from FBS using the experimental model of the battery (on the left), using the modal model of the battery (on the right)

Conclusions

In this paper, a substructuring problem consisting of integrating a battery pack to a vehicle body has been presented and validated on an industrial application case. The coupling challenges linked to the large amount of connecting interface DoF required accurate measurements of the FRFs. Moreover, the potential inconsistencies in the experimental FRFs data have been mitigated by fitting a modal model to the experimental data of the battery pack. An enhanced modal parameter estimation workflow, aiming at obtaining accurate component modal models in a very efficient way, has been introduced and validated. The workflow, leveraging the MLMM modal parameter estimator, demonstrated effectiveness in addressing common issues such as magnitude imbalances in FRF data and computational inefficiencies when dealing with large FRFs matrix. The findings highlight the importance of considering both global flexible modes and local flexibilities in order to have an accurate modal synthesis for all the considered DoF. Finally, the substructuring results have shown that the use of a modal model in a hybrid substructuring application case (battery modal model & experimental vehicle body model) have led to similar results as when using fully experimental substructuring models. Future research will attempt to apply the new modal parameter estimation workflow to the vehicle body for a fully modal coupling. In this context, weaking interface strategies, potentially beneficial for multi-point connections problems, will be investigated.

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