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MODAL MAPPING AND MAIN TRANSFER FUNCTION ANALYSIS OF A SAE BAJA VEHICLE

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Abstract. *Excessive vibration can be more than an uncomfortable and deciding purchasing factor for the vehicle user. Could also be read like a warning or indicator of the vehicle behaviors. To avoid issues relating to excessive vibrations from the main sources, road and the engine, it is crucial to know the subsystems inherent frequencies, the most energetic excitation ranges, and the path though the vehicle. To understand and control the vibration response levels and guarantee the quality of the finished product. Different simulation models are utilized during the vehicle development and validation process, starting from the single components, and passing through sub-systems, systems, and entire vehicles. To prevent resonances and the harmful excessive vibration effects (loose bolts, component premature wear and drive discomfort feeling) it is important to map the component's natural frequencies. The frequency map is one of the management tools used in the automotive industry. The primary goal is to reduce the resonance effects avoiding, as much as possible, the excitation range of sources and managing the different modes positioning to minimize potential modal coincidences. In this study, an off-road full vehicle model map was built using a simulation model. Parts of the vehicle were simplified, and the geometry of the main components was drawn in Autodesk Inventor®. The parts meshing and finite element model assemblage was all made on Altair Hypermesh® using diverse types of elements chose to better represent the geometry. For the Roll cage a high percentage of 2D Quads on tubes and a Trias elements in the welding joints. The frequency range studied was defined based on the main excitation order of a four-stroke single cylinder engine used in the Baja SAE competition. The engine on runup excitation was performed on inertial bench and the modal analysis between 0-150 Hz and the FRF was performed with Altair Optistruct®. The frequencies of some of the main subsystems were confirmed using frequency response functions (FRF). Furthermore, the frequency map was compared to the engine excitation curve to identify potential risks, the modes of the main components, and the transfer functions from engine to the steering wheel and the accelerator pedal.*

Keywords: *Baja SAE Vehicle, FEM, Modal Analysis, Modal Map Management*

1. INTRODUCTION

The BAJA SAE Competition is an event at regional, national, and international levels promoted by the Society of Automotive Engineers (SAE) that brings together engineering professionals and students with the aim of encouraging teams to develop off-road vehicle prototypes.

In a vehicle, according to Gillespie (1992) and Xu Wang (2010), there are several sources of excitation, with the main ones coming from the interaction between road/tires and from internal sources such as the engine and transmission. It is known that high levels of excitation from these sources can cause discomfort for the driver, as assessed by ISO 2631-1 (Table 1), and also lead to structural problems in the vehicle (weld and tube cracking, component fatigue, etc.). Therefore, with this in mind, a proper understanding of the vibrational characteristics is of fundamental importance in the development of a vehicle. This area of study is commonly known by the acronym NVH (Noise, Vibration, and Harshness).

Table 1. Typical human responses due to vibration, according to ISO 2631-1 (1997).

Acceleration	Reaction
<0.315 m s^{-2}	Comfortable
0.315-0.63 m s^{-2}	A little uncomfortable
0.5-1.0 m s^{-2}	Fairly uncomfortable
0.8 – 1.6 m s^{-2}	Uncomfortable
1.25 – 2.5 m s^{-2}	Very uncomfortable
> 2.0 m s^{-2}	Extremely uncomfortable

Modal Mapping is a strategy used by automotive companies as a simple and effective way to visually gather frequency values of the vibration modes of the assembled vehicle's structure, subsystems, and main components, by comparing them against the sources of excitation. This strategy helps to prevent the concentration of modes in the most energetic excitation bands and identify potential modal couplings (alignment at specific frequencies of different modes from structural components), this enables the repositioning of modes, preventing or minimizing resonances and potential design failures.

In this article, a prototype of a BAJA SAE vehicle is modeled and simulated using the finite element method (FEM), entirely constructed with the aid of the Altair® Hypermesh®. Experimental measurements were also carried out to specify the frequency range investigated in transfer functions and modal analysis. The test comprised gradually increasing the engine's acceleration from idle to maximum rotation (Run-Up) over 15 seconds on an unloaded inertial table to determine the engine's major excitation orders. The curve extracted from the results was used to detect probable resonance locations of the vehicle's primary components in the 0-150Hz range.

From a modal analysis, the main frequencies of subsystems and specific parts, as well as global modes such as vehicle torsion and bending modes, were mapped. In order to identify the sensitivity of the tactile points in contact with the driver, frequency response functions (FRFs) were also performed from excitation sources, such as engine and suspension, to the steering wheel, seat back and accelerator pedal.

This work is thus divided into three main parts. First, the construction of the finite element model, with its simplifications and considerations detailed in section 2.1. Additionally, a measurement of the engine on a test bench was conducted to define the main orders and the most energetic frequency range to which the vehicle will be subjected, as described in section 2.2. Finally, modal analyses and transfer functions were performed, and the results will be presented in section 3 and discussed in the conclusions.

2. SIMULATION PROCEDURE AND EXPERIMENTAL TEST

2.1 The vehicle FE modeling

Based on the 3D drawings of the PBN22 prototype provided by the Parahybaja team from UFCG, we constructed the finite element model using Altair® Hypermesh®. The model comprises approximately 120 components represented in finite elements, including elements of the suspension, steering, and powertrain, as shown in Figure 1. The construction and analysis of the model took approximately 260 hours, and the total mass, including the pilot, is 275kg.

Figure 1. Full vehicle FE model.

In general, the constructed model comprises approximately 3.8 million elements, including 3D (solid) elements for cast and thick components, 2D (shell) elements for the tubular structure and slender plates, and 1D elements for bolted connections (beams) represented as springs, beams, and rigid bodies, as shown in the percentage distribution of mesh types presented in Figure 2.

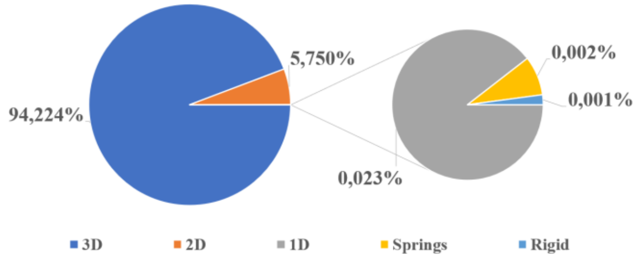


Figure 2. Distribution of mesh element types.

2.1.1 Modeling vehicle subsystems

Among the main subsystems of the vehicle, were prioritized the models of the prototype's structure, powertrain, suspension and steering, as shown in Figure 3. These subsystems are particularly relevant in the overall modal analysis. The finite element model of the structure was constructed using predominantly 2D elements of the Quad type, interconnected by their respective nodes at points where welded joints exist. The other subsystems were also fully constructed, either through meshing (block, piston, CVT) or representation with corresponding elements, such as CBUSH and CELAS (bearings, ball joints, springs). For example, the transmission model utilized both forms of representation. The shock absorber model was constructed in a similar manner, with the stiffness and damping properties considered in the order of magnitude according to Kanchwala (2017). These properties can be adjusted either through the elastic modulus of the spring elements' material or by using CBUSH created in the damper's rod.

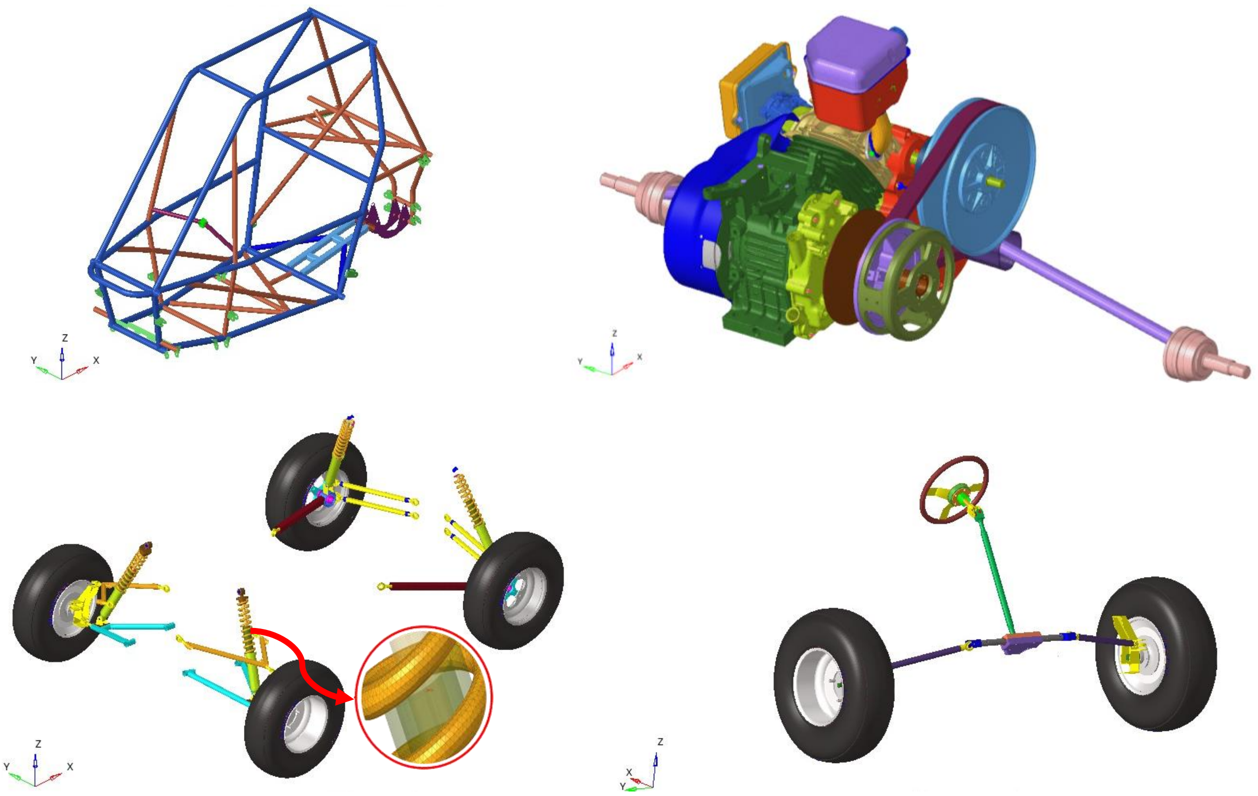


Figure 3. Subsystems FE Model.

2.1.2 Model building simplifications

Due to the existence of components with complex geometries, simplifications were made to the geometry of the vehicle components that exhibited this characteristic, reducing the occurrence of elements with quality errors (warpage, aspect ratio, and Jacobian). An example of this is the prototype's tire model, which, being a component with a variable profile and extrusions along its length, was simplified. However, it was still possible to include the internal components, such as belts and wires, as shown in Figure 4.

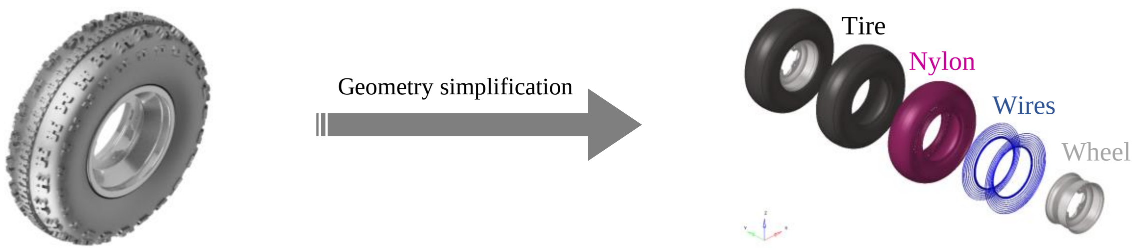


Figure 4. Example of tire geometry simplification for finite element model construction.

Another example of CAD geometry simplification performed for the construction of the finite element model is the fuel tank. Due to variations such as curvatures, ribs, and indentations, a simplified model with a box-like shape was created, but with properties, such as mass, equivalent to the real component, as shown in Figure 5.

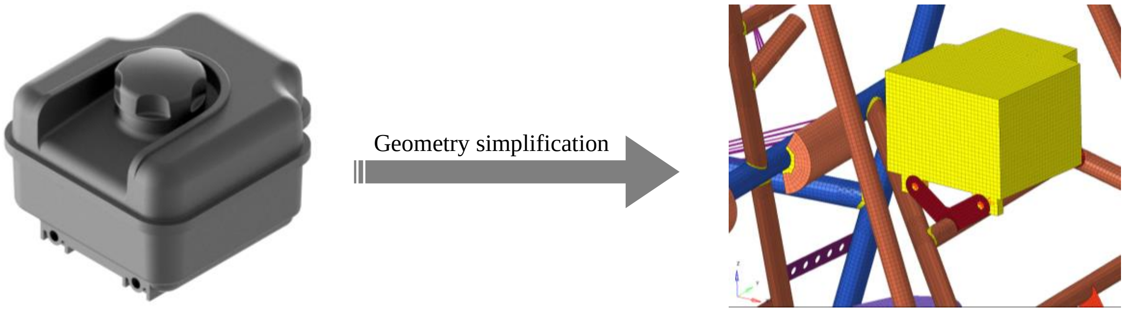


Figure 5. Example of fuel tank geometry simplification.

2.1.3 Mass distribuition

With the purpose of appropriately representing the mass distribution of the subsystems, for components whose shape was less influential, mass elements (CONM2) were defined at locations approximating the component's center of gravity. Thus, it was necessary to construct the finite element model of these components to obtain the position of their respective geometric centers. An example of this is the representation of the pilot's mass, which involved indicating the densities of different parts of the human body, as shown in Table 2. Therefore, the finite element model of a pilot with a height of 1.8m and weight of 78kg was constructed so that their respective center of gravity could be obtained and inserted to represent them, as shown in Figure 6.

Table 2. Density values for different parts of the human body. Winter (2004)

Segment	**Density (kg/m^3)**
Hand	1.16
Forearm	1.13
Upper Arm	1.07
Foot	1.10
Leg	1.09
Tight	1.05
Trunk	1.03
Head and Neck	1.11

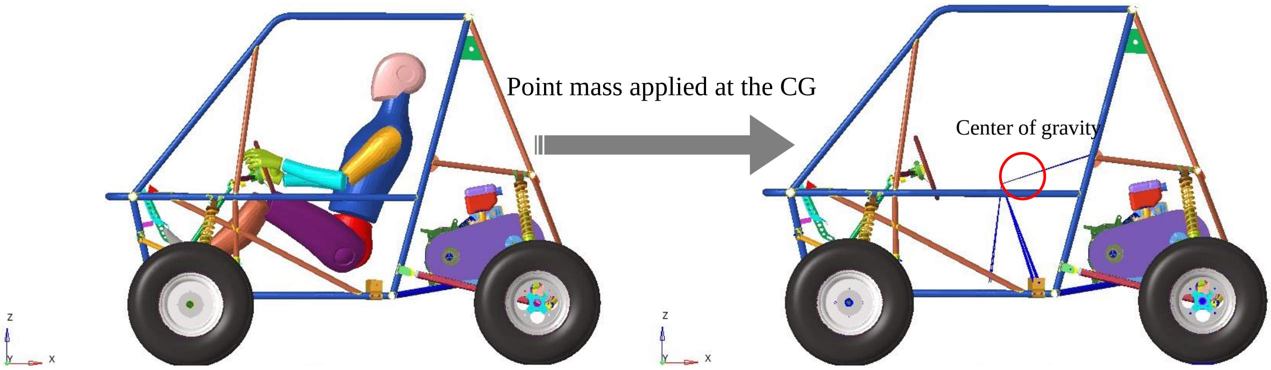


Figure 6. Representation of the pilot's mass with the estimated CG (Center of Gravity).

Similarly, other components such as the battery, master cylinders, calipers, and brake discs had their masses represented by CONM2 elements (placed at their centers of gravity) and connected to the Roll Cage bracket points through RBE3 elements. Figure 7 shows examples of this type of mass distribution for the battery and brake system actuators of the vehicle.

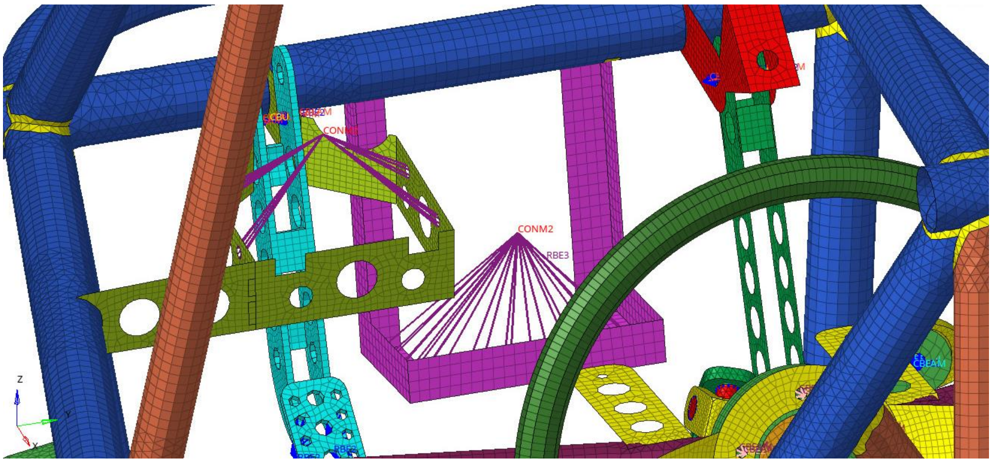
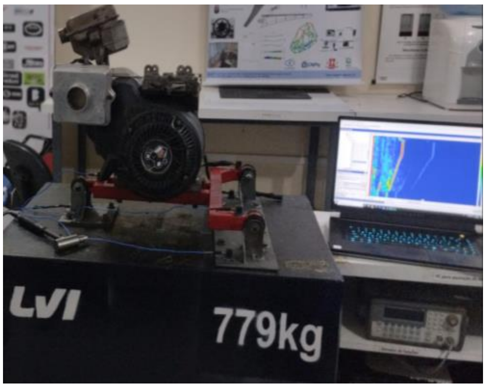


Figure 7. Representation of the masses of other components using CONM2 and RBE3.

2.2 Experimental engine test on bench

According to Panza (2015), order tracking is an experimental technique that can provide valuable information about vibrations and acoustic signals generated in the powertrain components of a vehicle, related to the engine's rotational speed, particularly the engine frequency. This analysis allows visualizing peaks of magnitude in the spectrum aligned with order spectrum lines and enables the identification of operating conditions and the frequency range of interest where noise emissions predominate.

The engine tested was a Briggs and Stratton 10Hp Series 20 used in BAJA SAE competitions. A gradual acceleration sweep (run-up) was performed from minimum to maximum engine rotation, over a duration of 15 seconds, to obtain the engine acceleration values by RPM. The test was performed on bench, as shown in Figure 8 (a), with unloaded engine, using three triaxial accelerometers (PCB 356A16) positioned and connected to a data acquisitor system (Simcenter SCADAS Mobile). The results were post-processed using LMS Testlab v2021.2 and Matlab R2019A. The RMS of all signal and the waterfall shown the main orders excitation are showed in the Figure 8 (b).

(a) 

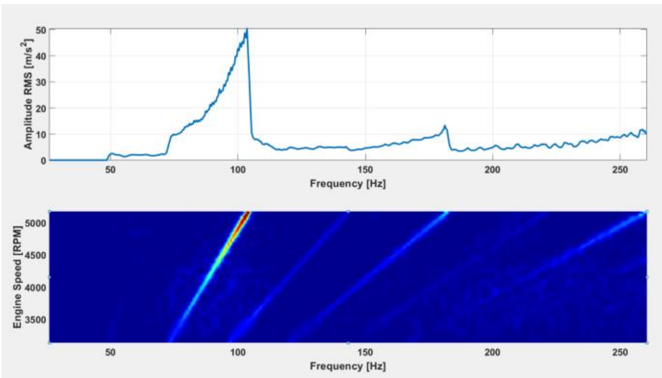
(b) 

Figure 8. (a) Experimental setup, (b) run-up engine curves.

Furthermore, based on engine bench results the frequency range analysis was defined from 0Hz to 150Hz. On the vehicle the engine works under variated load that should reduce the RPM and the frequency range.

3. RESULTS

3.1 Modal map

Using Altair® Optistruct®, a modal analysis was performed up to 150Hz (range based on test). As shown in Figure 9, the simulation results have been organized by the main components modes by distributing scatter frequency and the engine experimental excitation curve placed on second axle.

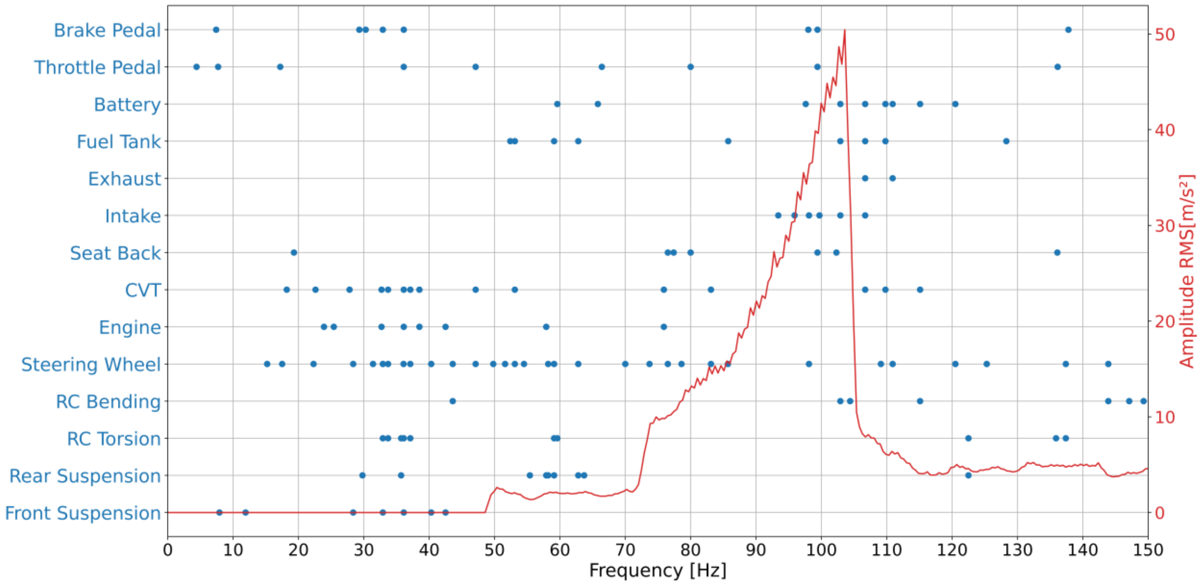


Figure 9. Modal map of the vehicle main components.

This modal mapping allow evaluates the modes at different frequencies, as well the modal couplings (when the modes of different components assume the closer frequencies). The modes positions are also compares with the experimental engine excitation curve.

The results show from 80Hz to 105Hz modes of the steering wheel, the air intake, and the fuel tank as high potential resonance frequencies. A broad alignment combining the engine, CVT, steering wheel, roll cage torsion, suspensions, and pedals also suggests a harmful frequency range of the vehicle from 30 Hz to 40 Hz.

3.2 Main frequency response functions (FRF's)

In addition to the modal analysis, the FRF from the vibration source to the tactile pilot locations (the steering wheel, seat, and pedals) must be performed in order to identify the vibration risks. Then, using the modal frequency response calculation through Altair Optistruct® and the Altair HyperGraph® the FRF was organized by the main sources (suspensions and engine) versus tactile points (steering wheel, seat back, and throttle pedal), as shown in Figure 10.

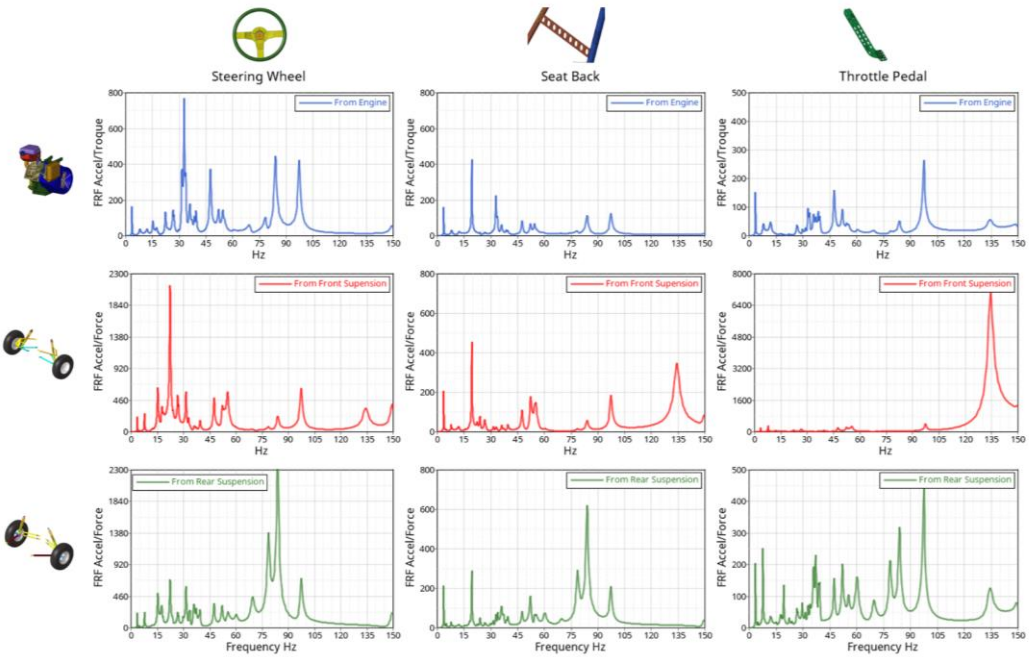


Figure 10. Main Frequency Response Functions (FRF's).

The FRF's results allows established a clearer relationship between the curves amplitude and the modes listed on the modal map. In this way, one can observe, between the steering wheel and the front suspension FRF a higher sensitivity at 22Hz or at 100Hz on throttle pedal/engine FRF response.

4. CONCLUSIONS

With the results of this study, up to this point, it was possible to identify the frequency ranges of the vehicle subsystem modes through the modal map. Additionally, it highlighted by the FRF the components sensitivity from the engine and suspensions to the steering wheel, seat back, and throttle pedal.

The modal map results demonstrate that the engine experimental excitation, ranging from 80Hz to 105Hz, overlaps various modes of the steering wheel, the air intake, and the fuel tank, all of which have a significant potential for resonance. Another important conclusion is the broad alignment combining the engine, CVT, steering wheel, roll cage torsion, suspensions, and pedals from 30 Hz to 40 Hz. However, the modes outside the engine excitation curve may be essential, because other vibration sources, such as the road, are not included in this study.

The steering wheel is more responsive to front suspension excitations than to engine and rear suspension excitations, according to the transfer functions. The seat back responds to various excitation sources with a generally balanced behavior, while the amplitude changed depending on the sources, the amplitude acceleration frequency values stayed relatively constant.

Constructing the complete vehicle model using finite element analysis proved to be a crucial factor in vehicle development, as it not only allowed the observation of the main component modes and their interactions but also enabled the assessment of the sensitivity of the vehicle's main components to excitation sources.

5. FUTURE WORK

As a suggestion for future work, it is valuable to consider characterizing the excitation from different road surfaces and velocities, given the broad frequency range in which the modes of various vehicle components are present.

Furthermore, adjusting the finite element model based on local measurements (inertances) of tactile points and FRF's between the main systems such as the engine, gearbox, and front and rear suspensions is recommended. This adjustment will not only observe sensitivity but also make the simulation response more precise.

Another relevant aspect that can be included in future work is the comparison between experimental modal analysis and the finite element model calibrated through the Modal Assurance Criterion (MAC). Additionally, analyzing the relationships between the torsional static stiffness and torsional modes of the vehicle structure and the complete vehicle should be considered.

6. ACKNOWLEDGEMENTS

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Another initiative that deserves our full gratitude was the loan of sensors and equipment for engine measurements on the test bench, provided by the NVH team of Stellantis LATAM. This support made the entire development of this research possible.

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