POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

New Equivalent Static Load (ESL) creation procedure for complete vehicle

TESI MAGISTRALE IN MECHANICAL ENGINEERING – INGEGNERIA MECCANICA

AUTHOR: Luiz Felipe Faria Ricardo

ADVISOR: Federico Cheli, Michele Vignati

ACADEMIC YEAR: 2022-2023

1. Introduction

A significant part of the development time available is spent on various verification tests. Computer Aided Engineering (CAE) tools are used today in Research and Development (R&D) to reduce the number of physical tests using simulations instead of doing them.

In the past, the static torsional requirement was arguably the most important structural requirement, for several years it was used as an important reference. Today, body stiffness has taken that position; however, the requirement for electrical vehicles must be improved, thus becoming even more relevant, the reason being that the heavy and stiff battery pack has a big influence on the overall stiffness of the body.

This research will focus on understanding how forces affect the distortions of the structure and how the deformation patterns *i.e.* deformations of the body at various time steps that share similarities, can be used to simplify the large load history to a few single load cases that represent the general behavior of the structure and that can be used as a quality parameter for any vehicle development phase, as well as a tool to save a considerable amount of simulation time.

The outcome of this work will be the development of a simplified, but yet consistent, fast, and accurate method of determining the severity of the impact of the forces in the overall deformation of a vehicle, especially in the openings of the body, which will also serve as a quality parameter and have applications in durability and solidity.

2. State of the art

One of the most relevant examples of the Equivalent Static Load Method ESLM applied on a vehicle to reduce complexity of dynamic loads was a study performed at CEVT[1] in the 2020s and consisted in optimizing loads applied at 4 points, the 4 top mounts of the suspension system of the vehicle. The target of the optimization was to minimize the difference of the displacement measured at the diagonals in the openings in the vehicle such as the doors, tailgate, sunroof, and rear seat for a given time step where the dynamic load is responsible to generate the highest overall distortion in the openings.

Although this method succeeds in obtaining a simplified load that provides an accurate measure of the distortion in the openings of the vehicle as seen in Figure 1, it has some downfalls:

- It does not explain why such loads are representative of the given problem.
- It oversimplifies the high complexity of the forces on the vehicle, by reducing all force locations to only the 4 top mounts, neglecting lateral forces.
- It requires a complete dynamic simulation to use its results as target for the optimization problem, thus not being able to anticipate which loads would achieve accurate results beforehand.

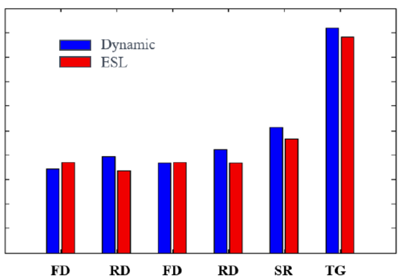

Figure 1: Comparing opening distortion (mm) from ESL with SEP from dynamic complete vehicle simulation for different opening.

3. Methodology

The vehicle used as reference for this work is the same used in the work mentioned in the *State-of-The-Art* chapter, which is a Lynk & Co 01, a 5-door compact crossover SUV and is the first model announced from the Chinese brand Lynk & Co, a brand created by CEVT.
A previous work performed at CEVT was able to show that the excitation between the wheel suspension (around 12 Hz) and the body response is quasi-static. This confirmation led to the approach employed in this work: dismembering each time step from the numerous dynamic load cases as equally numerous single static load cases, under the verified assumption of quasi-static response. The frequency gap can be verified in Figure 2.In this case, the wheel excitation is around 12 Hz, and the body modes which are affecting the distortion are between 25 and 60 Hz as a design choice, for sure reasonably away from the wheel excitation.

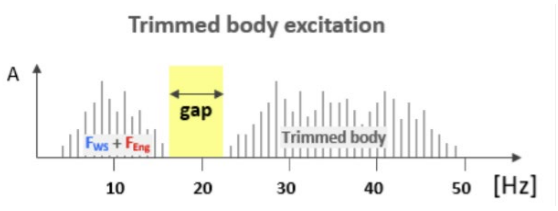

Figure 2: Frequency gap between the wheel suspension and trimmed body, indicating a quasi-static response between them.

3.1. Distortion in the body openings

It is fundamental to understand which openings are being analyzed, in Figure 3 the continuous colored lines represent the diagonals in the vehicle: Red diagonals are associated with left front and rear doors, black diagonals are associated with right front and rear doors, yellow diagonals are associated rear seat and tailgate, and green diagonals is associated with the sunroof. More diagonals could be used if other points of interest were considered, such as A or B pillar, however they opted out of this work, since would not greatly contribute to this work.

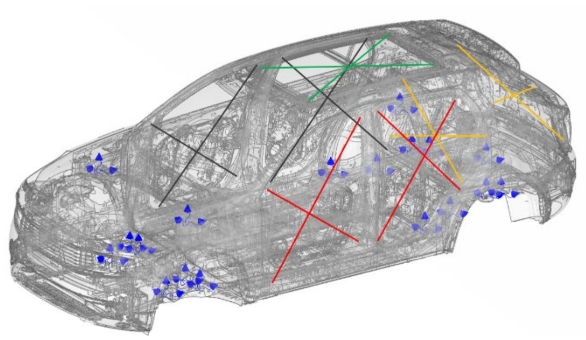

Figure 3: Diagonals associated with all openings (in continuous lines) and force locations in all three dimensions represented by blue vectors.

In total, 7 openings with a total of 14 diagonals and 22 force locations were considered.

3.2. Finite Elements and Multi-body

Given the complexity of extracting accurate measures for the forces applied in the vehicle, a already well stablished ADAMS model was implemented to obtain the forces applied in the vehicle, the limitation of this model was that the forces applied on the engine mounts were not as reliable, therefore they were not implemented in this analysis.
For the fully trimmed body, the FEM (finite element model) uses SHELL, SOLID, CBUSH, and BEAMS elements, containing around 6 million elements and 38 million DOF. A schematic relation between the FEM and the MBS model can be seen in Figure 4. Two simulations are performed: A Linear Static Analysis (SOL 101 on Nastran) for single load cases and Modal Transient Analysis (SOL 112 on Nastran) for time-varying load cases.

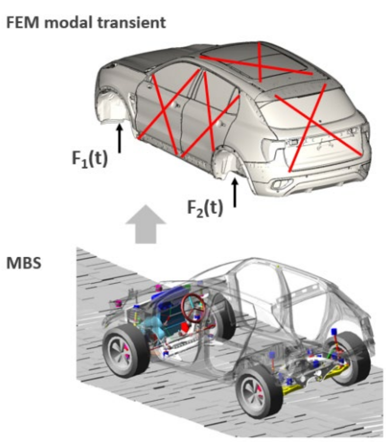

Figure 4: Top) Finite Element Model of the vehicle using as input the forces obtained from the MBS.

Bottom) ADAMS Model to obtain the desired forces since the road profile and the components and geometry of the vehicle are already known.

3.3. Distortion calculation

One of the most important procedures used in this work was to calculate the distortions on the aforementioned diagonals, this was also done in the method presented at the *state-of-the-art* chapter. The chosen method was the E-line method [2], which is used for squeak and rattle applications specially in the automotive industry in Sweden, such as CEVT and Volvo Cars.

The method consists of calculating the difference between each component of the distortion of each diagonal in a local coordinate system.

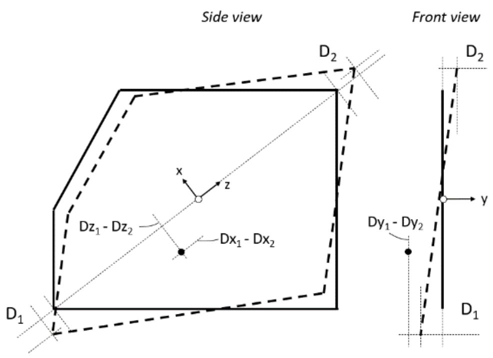

Figure 5: Measurements of distortions in a local coordinate system for all 3 degree of freedoms X,Y, and Z, accordingly to the E-line Method.

It can be seen that by plotting a dot (in the example, a black dot) from the center of the diagonal and adding the calculated values of D_{x1} - D_{x2}, $D_{y1} – D_{y2}$, and $D_{z1} – D_{z2}$, it is possible to visualize how the distortion generated from a load associated with a given time step.

Since the load history contains about 5000 time steps, a graphic visualization of these deformations for all time steps is performed. The reason for this visualization is to understand the behavior of the distortion at that specific diagonal.

The several points follow a distribution along time, this can be explained by a principal component analysis (PCA) where the 1st, 2nd, and 3rd principal directions are plot. Points with positive values when projected in the first direction axis are assigned a positive sign (+1) and the others are assigned a positive sign(-1).

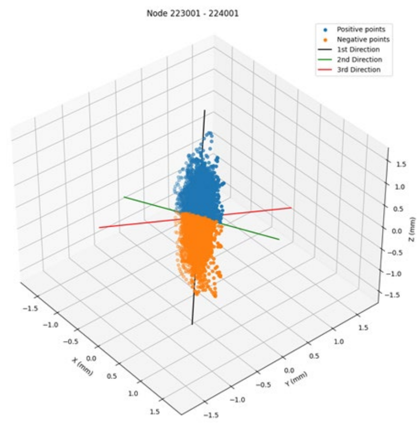

Figure 6: Schematic representation in 2D of a cloud of points for the distortion in the left front door. Positive points are the ones above the 2nd and 3rd principal directions and the other are negatives.

3.4. Statistical Evaluation Parameter (SEP)

Before introducing relevant topics, it is fundamental to understand the SEP, basically it is a way of sorting and filtering the overall distortions of the vehicle. We define the overall distortion as the sum of the absolute value of the distortion for all 14 diagonals for a given time step, as seen in Equation 1: Overall Distortion for a given time step.

Equation 1: Overall Distortion for a given time step

$$D_{total} = \sum_{n=1}^{14} abs(d_n)$$

Once we have measured D_{total} for all time steps, we can sort them and focus on a specific percentage of the highest distortions. The percentage of those highest distortions is called SEP. Which means that by choosing a low value of SEP we are looking at the highest overall distortions. The reason for using this tool is that it allows us to focus on the most critical scenarios, which are the ones where the vehicle is experiencing high distortions, a concern from a solidity point of view. A visual representation of using this tool can be seen in Figure 7.

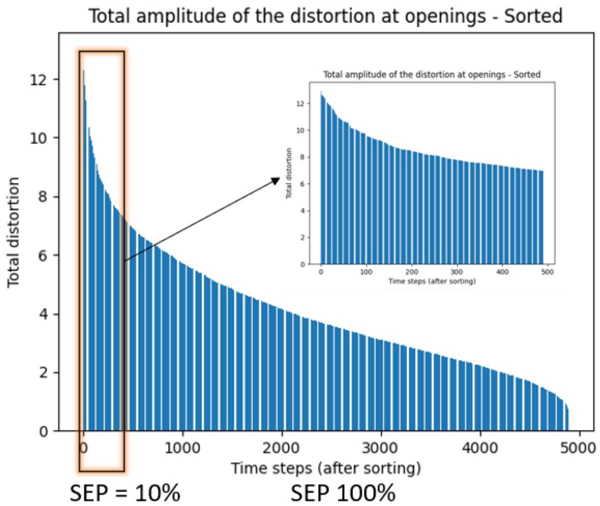

Figure 7: Overall Distortion after ranking the time steps with the highest ODs. Also showing a zoomed region when using SEP=10% to focus only on the time steps associated with the 10% highest ODs.

3.5. Distortion Patterns and DDP (Dominant Distortion Pattern)

For each diagonal, for a given time step, there will be a dot assigned either +1 or -1 according to the PCA analysis seen in Figure 6. We define then a vector of dimension (1 x N), called Distortion Pattern (DP), an example would be {+1, -1, +1, …, +1, +1, -1}$^{1 \times N}$, where N is the number of diagonals being analyzed. Each unique combination is called a Distortion Pattern. A DDP (Dominant Distortion Pattern) occurs when there is one distortion pattern that appears much more often than the other ones, for this work's purpose, this value will be set as 50% of all time steps being analyzed.

3.6. Vector Participation Plot of Distortion Patterns

VPA or Vector Participation Plot is a pie chart that summarizes the frequency of the appearance of each distortion pattern along the whole time history. It also simplifies the verification of a DDP, since a slice of the pie chart larger than 50% implies the existence of a DDP.

3.7. Force Analysis

Differently than the distortions, it should be pointed out that before the analysis, the mean value of the load history for each force location is subtracted from the load case itself, in order to remove constant forces that are irrelevant from a force pattern perspective.
The force Locations both in the front and rear of the vehicle can be seen in Figure 8 and Figure 9, note that due to the symmetry of the vehicle, only one side is presented in those figures.

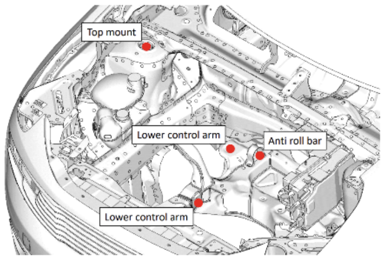

Figure 8: Force Locations in the front of the vehicle and the correspondent's name of the component where the force is being applied.

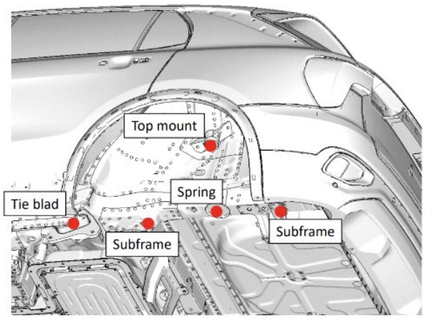

Figure 9:Force Locations in the rear of the vehicle and the correspondent's name of the component where the force is being applied.

3.7.1. Force Patterns

Similarly, as exploited in section 3.5 (Distortion Patterns and DDP) and on the PCA analysis as in Figure 6. The definition of the force patterns relies on assigning +1 and -1 values for the forces depending on their position relatively to the plane generated by the 2nd and 3rd principal direction.

3.7.2. Moment Analysis

The forces applied in the vehicle are also generating moments in the structure. By splitting the vehicle into front and rear and considering the moments generated on the force locations presented in Figure 8 and Figure 9. The moments are calculated between the force location and the center of gravity (COG) of the vehicle.

$$M_{front} = \sum_{i=1}^{24} F_y^i \cdot z_i + F_z^i \cdot y_i$$

$$M_{rear} = \sum_{j=1}^{30} F_y^j \cdot z_j + F_z^j \cdot y_j$$

$$M_{diff} = M_{front} - M_{rear}$$

When performing linear static analysis on specific time steps associated with the highest overall distortions it was verified that the behavior of the structure was very similar to a twist around X axis, therefore considering a methodology to understand the moment generated by those forces became a valid alternative.

4. Analysis and Results

4.1. Existence of the DDP and SEP influence

By looking at all time steps (SEP = 100%), applying the E-line method, plotting the points associated with those distortions, applying a Principal Component Analysis, applying the definition of Distortion Patterns and combining those results in a Distortion Pattern VPA in Figure 8, it becomes clear the presence of a DDP, since the largest slice of the chart is higher than 50%.

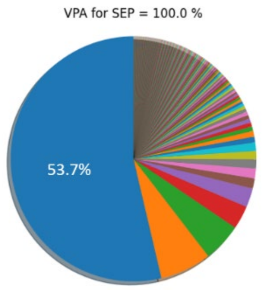

Figure 10: Distortion Pattern VPA for SEP=100%, which means that all time steps are being considered. It also shows that there is a clear dominant distortion pattern.

When choosing lower values of SEP, it is also concluded that the dominance of the already existent DDP increases as seen in Figure 11.

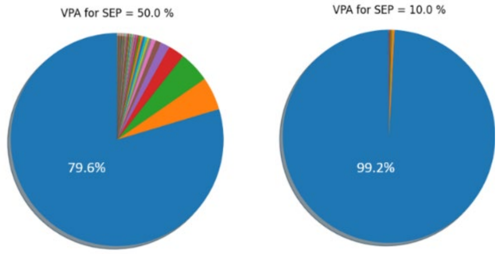

Figure 11: Effect of the decrease of the SEP on increasing the dominance of the DDP.

Based on the inference that low values of SEP will provide us the most critical scenarios (highest overall distortions) which are also mostly related with the DDP, a value of SEP equals to 10% will be vastly used throughout this work.

4.2. Force Patterns

Using the similar methodology as explained, the force patterns, on the other hand, demonstrated to have negligent correlation with the DDP and with the influence of SEP.

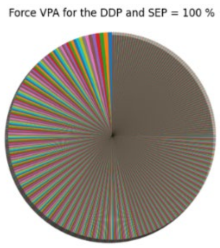

Figure 12: VPA for Force Patterns, showing that differently than for the Distortion Patterns, no clear force pattern can be derived from this chart.

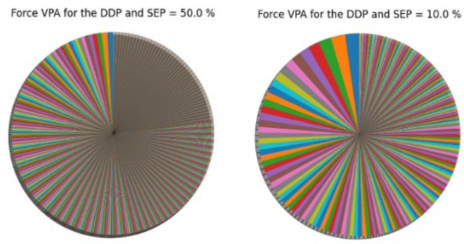

Figure 13: VPA for Force Patterns, showing that even by changing SEP, there remains no clear force pattern that could be derived from this chart.

Considering to use a force pattern to understand the relation with the DDP and the highest Overall Distortions seems to be not reasonable, therefore this approach will not be further used for this work.

4.3. Moment Analysis

The results obtained by analyzing the moment were much more interesting, in the sense that a clear relationship between the relative moment and the highest overall distortions was present, as seen in Figure 14. Thefore focusing on the relative moment will be the chosen approach for deriving some ESLs.

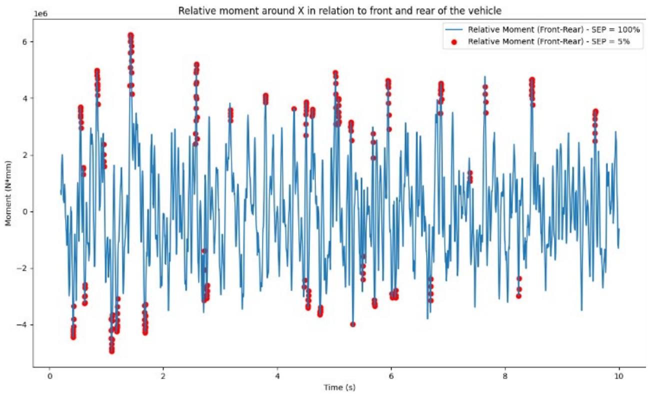

Figure 14: Relative moment around X for SEP equals to 100% and to 20%. The peaks of the relative moments are also coincidental with the highest Overall Distortions.

4.4. ESL

To obtain an ESL, the following procedure will be applied:

1. Calculate the relative moment for all time steps.
2. Apply an SEP = 5%.
3. Unify points around peaks to a single point, the criterion to choose which point to retain is based on the sum of the absolute forces on all force locations (to be more conservative in terms of durability).
4. Apply a threshold of 15% of the highest relative moments.
5. This should reduce the 5000 points to around 5 points, which are our ESLs.

The comparison of those 5 ESLs in respect to highest measured relative moments can be seen in Figure 15

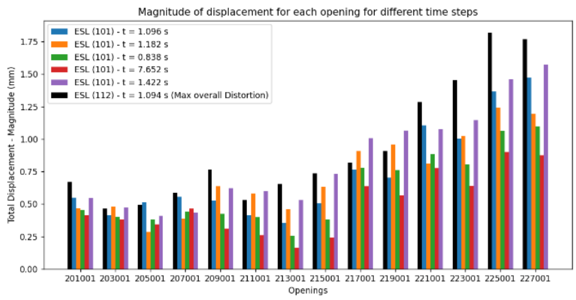

Figure 15: Comparison of the overall distortion between the 5 obtained ESLs using linear static analysis in respect to the highest measured overall distortion obtained from the modal transient analysis.

5. Conclusions

The proposed methodology answer and improves the key points presented in the state-of-the-art chapter: The reason for those loads generating the obtained distortions is due to a torsion of the structure around X-axis, there is no oversimplification of the force locations, since all of them are being considered and there is no need to run a simulation beforehand to anticipate which loads to use to obtain the highest overall distortions, ESLs can be obtained straight away from the load history after a short moment analysis with a python script, taking less than 5 minutes.

Two significative gains of this procedure are that by obtaining multiple ESLs that consider high forces there is a better understanding of localized stresses in the structure, very relevant from a durability point of view, besides that 5 ESLs can be run in parallel and are much less time consuming than a modal transient analysis, taking up to 95% less computational time.

6. Bibliography

[1] J. Weber, V. Jönsson, and M. Zaben, 'Squeak&Rattle-New Equivalent Static Load (ESL) based on Dynamic Distortion in all Body Openings from both Test and Simulation', 2020.

[2] J. Weber, P. Sabiniarz, C. Wickman, L. Lindqvist, and R. Söderberg, 'Squeak&rattle simulation at volvo car corporation using the e-line™ method', in *5th ANSA & μeta International Conference*, 2013.