A database framework for industrial vehicle body concept modelling

D. MUNDO¹, A. MARESSA², N. RIZZO¹, S. DONDE³, W. DESMET²

¹ Department of Mechanical Engineering, University of Calabria - 87036 Rende, ITALY
e-mail: d.mundo@unical.it - http://www.unical.it/portale

² Department of Mechanical Engineering, Katholieke Universiteit Leuven, Division PMA, B-3001, Leuven, BELGIUM
e-mail: wim.desmet@mech.kuleuven.be - http://www.kul.be

³ LMS International, Interleuvenlaan 68, B-3001 Leuven, BELGIUM
e-mail: stijn.donders@lmsintl.com - http://www.lmsintl.com

Abstract: Nowadays, in automotive industry the prediction of the static and dynamic behavior of a vehicle body is essential already in the initial phases of the design process in order to shorten the Time To Market through the early identification of issues and the application of proper countermeasures. The NVH (Noise, Vibration and Harshness) behavior of a vehicle Finite Element (FE) model is typically analyzed and optimized by using Computer Aided Engineering (CAE) technologies, which require a detailed model, often unavailable in the concept phase of the vehicle design process. The aim of the research presented here is to provide the designer with an efficient methodology that enables the optimization of the NVH behavior of a concept vehicle body through structural modifications. A concept joint modification approach is proposed, based on the idea of building a database of joints, which consists of reduced FE models of structural variants of the original joint. By applying the Waves-Based Substructuring (WBS) technology, the database can be used for the optimal concept design of vehicle bodies. The proposed approach is illustrated through two case-studies, where a simple and an industrial model are analyzed to prove the feasibility of the concept joint database.

Key-Words: Vehicle Body, Concept Design, Finite Element Method, Automotive Joints, Sub-structuring

1 Introduction

Especially in this period of crisis, the modern automotive market, in which an increasing interaction with customers and a high competitive pressure are present, requires that more and more efficient design methodologies are developed to create and launch in a short time innovative, satisfactory and low cost manufactured products [1]. In order to achieve such a goal, researchers have developed a series of techniques, based on CAE methods, that allow to obtain a numerical model for the prediction of several vehicle performance attributes, such as safety, crashworthiness, NVH, acoustics, environmental impact, etc [2]. Such a virtual philosophy of the vehicle design engineering process has led to innovative technologies and methods, with the aim of assisting and helping in all the stages of the realization of a product, from the concept design phase to the sale. The concept phase is a highly strategic step in the vehicle development for all automotive manufacturers [3-6]. The aim is to develop simulation methods that can help improving the vehicle design from an early stage onwards, so that the vehicle designer can rely on efficient methods for NVH optimization, usable since the concept phases, when the CAD model is not yet frozen and countermeasures can be taken at lower costs.

In the field of NVH predictions, several concept modelling approaches have been proposed, among which methods based on predecessor FE models [7] and methods from scratch [8] are included. In this paper an innovative concept modification approach is presented, in which the early design choices are supported by a database of structural elements, consisting of variants of the original FE model that are created as to preserve the mesh-compatibility at each interface. The focus of this paper is on the joints of a vehicle body, but the proposed approach can be extended to other structural elements (beams, panels, etc…).

The goal of making such a concept database useful for the NVH optimization of a vehicle body is pursued by building further on two starting blocks...
reported previously in the state of the art: the Beam and Joint Concept Modeling approach [7] and the Wave-Based Substructuring Technique (WBS) [9]. The Beam and Joint Concept Modeling approach is used to make a concept model consisting of beam elements and joint matrices. It results in efficient models for the use in the concept phase, but in the joint property calculation, there are some inaccuracies introduced by “end effects”, since the loose ends of isolated joints, used in the calculation of the joint matrices, have different mechanical properties than a joint included in the assembly model. In order to take into account the local behavior of the joint’s end-sections, the Beam and Joint Concept Modeling method can be combined with the WBS approach. This is a substructuring technique, which consists in dividing the main structure in substructures, calculating some particular functions, called waves, to the interface between various components based on modal displacements. By using such functions, a ‘wave connection’ is made between the substructures, where a limited number of non-physical (scalar) degrees of freedom (DOFs) are used instead of physical contour nodes.

In the research presented here WBS is used to enable a compact and accurate formulation of the connections between concept joints, which are statically reduced variants of the original joint and collected in a joint database, and the rest of the original vehicle FE model.

The outline of the paper is as follows. In Section 2 the numerical methods used for creating the concept joint model and connecting it to the rest of the structure, i.e. the WBS technique and the Guyan Reduction [10] respectively, and their combination are summarized. In Section 3 the proposed concept modification approach is illustrated by analyzing a case study, in which one joint of a simple FE model is used to create a database of joint variants.

In Section 4 the feasibility of the database concept is investigated on an industrial automotive application case. By using a Chrysler Neon FE application model, aimed at the conceptual modeling of four joints, the robustness of the nominal waves with respect to the joint modifications, is analysed through a dynamic comparison between each variant concept model and the corresponding detailed model.

2 Theory: Numerical Methods

2.1 Guyan Reduction

Guyan reduction is used to compute a static superelement that contains stiffness relations between the end points of the joint (i.e. the beam center nodes). Guyan reduction involves partitioning the stiffness matrix into the connection DOFs and the internal DOFs, and applying a static reduction to the connection DOFs [10]. The matrix equation can then be solved to find the displacements of the DOF subset of interest (i.e. the beam center node DOFs). Using the same transformation, also the mass matrix can then be reduced.

2.2 Wave-Based Substructuring (WBS)

In substructuring, the aim is to develop a reduced modal model of a structure, by representing the physical DOFs of each substructure into a reduced number of so-called generalized coordinates. Different methods have been reported [11-13], in which the general coordinates consist of the substructure’s natural modes (under some boundary condition) and static enrichment vectors (to accurately represent the local flexibility at the connection interface). Traditionally one has to obtain an enrichment vector for each interface DOF with the other substructures, which becomes prohibitively costly for complex industrial models with extensive (line) connections (e.g. weather strips, spot welds between floor and body ...).

To address this, a Wave-Based Substructuring has been developed [14], in which the deformation of the coupling interface is written as a combination of a set of basis deformations called "waves". Connections between substructures (normally defined in terms of interface DOFs) are replaced by connections between waves that impose the continuity of the displacements and forces. Often one can use (much) less waves as the number of physical interface DOFs, which results in a smaller-sized assembly definition. This also greatly facilitates the reduction procedure for (large) components of interest (since a much lower number of static enrichment vectors needs to be calculated). Local modifications on components in FE representation can then be quickly processed to predict the updated structural performance in terms of structural modes and response.

2.3 Combining Guyan Reduction and WBS

The innovation in this paper is to use the “waves” boundary condition (from WBS) in the reduction procedure of the vehicle joints, in order to improve the accuracy of the joint estimation. The procedure is as follows:

- Define a beam and joint layout for a structure
- Calculate a limited number of global modes at the physical end nodes of the joints.
- From these global modes, calculate the
wave boundary conditions at the joint end sections. Effectively, one writes the physical interface DOFs of the joint as a linear combination of a few wave DOFs.

• Perform a Guyan reduction on the wave DOFs. This not only yields a very small matrix model of the joints, but (since the waves contain global dynamics information) this also increases the accuracy of the joint matrix to be used on a global vehicle body modification level.

• The reduced joints are then connected into the remainder of the vehicle along these wave DOFs connections.

A database framework can then be obtained, by defining joint variants, applying the same Guyan-WBS reduction procedure to these joint variants (using the original waves from the nominal body model), and inserting the modified joints into the vehicle body.

3 Academic Case

In this section an academic case study is analysed to illustrate the proposed concept modification approach. A joint of a simple FE model is isolated from the rest of the structure and a series of variants is generated. A concept joint database is created and tested by connecting each joint variant, statically reduced, to the surrounding FE elements through a number of waves that are previously computed on the original model.

3.1 Model description

Fig. 1 shows the FE model of an open structure, consisting of eight thin-walled beam-members, modelled by 4-node shell elements (Nastran CQUAD4 elements) that have a uniform thickness of 1 mm and typical steel material properties. The central joint, i.e. joint B in fig. 1, is isolated from the surrounding four beams by duplicating the interface nodes (white lines in the same figure). Twelve waves, computed through a modal analysis of the entire structure, connect each end-section of the joint to twelve scalar points that are used for the static reduction of the joint. A number of waves equal to 12 has been selected through a sensitivity analysis, which showed that increasing further the number of waves wouldn’t improve significantly the accuracy of the concept model in the frequency range of interest A concept model, schematically represented in fig. 2, is thus built, where the equivalent stiffness and mass matrices of the joint are wave-connected to the rest of the structure.

3.3 Concept database for the central joint B

A set of model variants is created by replacing the original FE model of joint B with a joint variant. Joint variants are created as to guarantee mesh compatibility at interface with beams. Two different types of structural modifications are operated:

• A uniform increase of the original thickness of the joint walls from +10% up to +500%;
• The insertion of a plate inside the central joint, which is expected to stiffen the joint and to modify the modal shapes at the joint-beam interfaces.

In order to assess the impact of the joint modifications on the global modes of the structure, the variant models and the nominal one are compared in terms of natural frequencies. The
results are summarized in Fig. 3, where a 500% increase of the thickness can be observed as the modification with the highest impact.

For each variant, a concept model is created where the modified joint is statically reduced and connected to the rest of the structure by using the original waves. The concept models are compared with the corresponding detailed models, i.e. the models where the nominal joint is replaced by the detailed FE model of the joint variant, with the aim of analyzing the approximations involved by the use of the waves computed on the nominal model. The results are summarized in Fig. 4, where the percentage errors on the estimation of the first eighteen natural frequencies are shown. A systematic over-estimation of frequencies can be appreciated, which is due to the “stiffening effect” involved by the use of a limited number of waves.

4 Industrial case

Fig. 5 shows the FE model of a vehicle Body in White (BIW), formed by panels that are modelled with linear shell elements and assembled by means of spot weld connections. In order to prove the feasibility of a concept joint database in an industrial context, four joints, labelled in fig. 5 as Joint A, Joint B, Joint 2A and Joint 2B, are analyzed in this work. The four joints are the right and left A-pillar and B-pillar to roof joints and are symmetrical with respect to the longitudinal direction of the vehicle body. Such a choice is suggested by the consideration that, in the vehicle design engineering process, realistic modifications are typically symmetric, since the body performance on left/right side in terms of static strength, dynamic vibrations and mode shapes, as well as crashworthiness, is typically desired to be the same.

A total of fourteen cross sections are identified at the interface between each joint and the surrounding beam-members. In each of them, twelve waves are calculated through a modal analysis of the vehicle body. A structural modification of the four joints is made by increasing the thickness of all panels by 50%. The influence of this variation is assessed through a dynamic comparison between the variant model (full FE model with the four joints variants) and the nominal vehicle FE model. Fig. 6 shows the differences between the two models in terms of global frequencies in the range 0-50 Hz, where six global modes are observed. The maximum
percentage difference between the two models is +3.29%, which proves that the proposed model modification, even if local, has a significant impact on the dynamic behavior of the full vehicle.

Fig. 6: Variations of the global frequencies of the vehicle body in the range 0-50 Hz due to the modification of the four joints

A concept model of the vehicle is created, with the four joint variants statically reduced and connected to the rest of the body by using the nominal waves. The concept model is finally compared with the modified detailed model in the same frequency range 0-50 Hz. The results are shown in Fig. 7, where a maximum error of +0.22% can be observed for the second global frequency of the full vehicle body.

Fig. 7: Comparison between the variant concept model and the corresponding detailed model in terms of global frequencies in the range 0-50 Hz

5 Conclusion
A methodology for the concept design of vehicle bodies has been presented in this paper. The main motivation was to check whether a ‘wave connection’ could be used to deal with the ‘end effects’ in the reduced beam and joint modeling approach. Subsequently, the feasibility of a ‘database concept’ that can be used for the conceptual modelling of automotive bodies (consisting of beams and joints, possibly with wave connection layers) has been investigated through dynamic simulations.

When applying the WBS technique in an early concept design stage, a problem arises from the fact that it relies on the computation of the waves, which is typically done by performing a modal analysis of the entire vehicle body structure – which unfortunately is not always available in an early design stage, or is moreover a time consuming step. In this work the error made when connecting variant joints with the waves calculated on the original model has been quantified and it has been demonstrated that a database of concept joints can be used in the concept design phase a new vehicle, starting from an existing one.

The feasibility of the database concept has been verified on a simple model with only three joints and eight beams. An industrial case study has been analyzed as well to demonstrate the proposed approach.

Future developments could be oriented to the identification of a set of joint physical parameters useful for the automatic generation of model variants, and to the identification of a range of variability of these parameters. The proposed approach has been tested only for joints replacement, but it can be applied also for the replacement of other substructures, such as beams and panels.

Acknowledgements

We kindly acknowledge IWT Vlaanderen for their support of the project IWT-090408 “CHASING”. Furthermore, we kindly acknowledge the European Commission for their support of the Marie Curie FP6 RTN “Smart Structures” (from which Mr. Antonio Maressa holds a Research Training Grant, http://www.smart-structures.eu) and the FP7 ITN “VECOM” (http://www.vecom.org/).

References:


