Fast assembly predictions become more important in the vehicle development process. Design decisions are more and more based on virtual prototypes, as time-to-market and development costs must be reduced. The additional trend of mass customization forces engineers to design a higher number of variants on a lower number of platforms. The Finite Element (FE) method is widely used to predict the vibro-acoustic vehicle performance. FE models can only be applied in the low and medium frequency range, due to the model sizes and subsequent computational costs that grow with frequency. To partially overcome this practical limit, extensive work has been performed on substructuring and Component Mode Synthesis (CMS) techniques [1][2][3][4]. The degrees of freedom (DOFs) of each substructure are expressed in terms of a limited number of component modes; the component models are then synthesized. Recently, Automated Multilevel Substructuring (AMLS) [5][6] is being developed. A vehicle body is recursively divided into dozens of levels of in total thousands of substructures, based on the mathematical structure of the FE models, rather than on the physical composition of the system. Each substructure is separately solved and the results are synthesized.

When coupling multiple (levels of) reduced systems, the interface problem size becomes increasingly dominant. To further speed up the synthesis, the interface representation size between components must be reduced. This can be done by the condensation of the interface displacements as a linear combination of a limited set of interface basis functions ("waves"). As the required number of basis functions is typically much lower than the number of interface DOFs, faster assembly predictions are obtained. Previous papers have reported on the use of component modes to derive the interface basis functions [7][8]. When one couples a very stiff component with a very flexible component, an obvious choice is to derive the interface basis functions from the component modes of the stiff component [9]. For components with similar modal densities the component modes are typically less suitable. In the Wave-Based Substructuring (WBS) [10] approach applied in this paper, one performs a single computation of the full assembly model to obtain the interface basis functions. This allows to accurately capture the interface dynamics, and with modification analysis and optimization in mind, a single full computation is not a large burden: an optimization may consist of numerous iterations involving hundreds of FE runs, so that it is very valuable to speed up the iterations by reducing the size of the interface representation while maintaining the accuracy. Section 2 discusses the mathematical framework of the WBS approach, for the rigid and elastic coupling case. In Section 3, the accuracy of WBS is assessed for an academic case [10]: the modification of the elastic connection stiffness between two connected plates. In Section 4, two automotive
engineering cases are presented: WBS is applied to speed up the modification analysis of coupling stiffness of a windscreen in a vehicle body-in-white (BIW) and a trimmed body. The paper is concluded in Section 5.

2 Theory

Consider an FE substructure in an assembled system. The DOFs $x$ can be divided into interior DOFs $x_i$ and junction (coupling) DOFs $x_j$. The system matrices (for the undamped case) are then partitioned into submatrices:

$$
\begin{bmatrix}
M_{ii} & M_{ij} \\
M_{ji} & M_{jj}
\end{bmatrix}
\begin{bmatrix}
x_i \\
x_j
\end{bmatrix}
+ 
\begin{bmatrix}
K_{ii} & K_{ij} \\
K_{ji} & K_{jj}
\end{bmatrix}
\begin{bmatrix}
x_i \\
x_j
\end{bmatrix}
= 
\begin{bmatrix}
f_i \\
f_j
\end{bmatrix}
$$

(1)

In this formulation, all junction nodes have 6 DOFs. As described in [10], for a trimmed body. The paper is concluded in Section 5.

3 Academic Case: Plate Assembly

Consider the assembly of two steel plates in Figure 1. Plate 1 (left) has a trapezoidal shape, while plate 2 (right) is rectangular. The plates are connected along a line interface (21 junction nodes, i.e. 126 junction DOFs). Plate 2 makes an angle of $31^\circ$ with the X-Y plane. Plate 1 is slightly thicker (1 mm vs. 0.85 mm), but both plates have similar modal densities: 70 resp. 56 natural modes in the range 0-1000Hz. This example has been taken from [10], where 5 modification scenarios have been considered, using WBS for the rigid and the elastic case.

Figure 1: Plate assembly in LMS Virtual.Lab [12]

In this paper, the modification of the translational stiffness between reduced modal models in an elastic coupling case is considered. Reduced modal models are created from normal component mode solutions, by replacing the FE coordinates (441 nodes for plate 1, 434 for plate 2) with modal coordinates (76 and 70 component modes for plate 1 resp. plate 2) on a reduced DOF subset. A WBS assembly is created with a set of 48 interface basis functions (obtained from the normal modes solution of the nominal assembly model). As the number of basis functions is less than the number of junction DOFs (126), the WBS approach reduces the problem size. The nominal assembly has a translational stiffness $K_t = 1.0 \times 10^4$ N/m, and a rotational stiffness $K_r = 1.0$ N·m/рад. The value of $K_r$ is modified (with a factor $3 \times 10^{-2}$ to $3 \times 10^2$), while the rotational connection stiffness is kept constant. Wave-based substructuring is then used (with the nominal set of basis functions) to quickly re-assemble the reduced component models with a modified stiffness. In Figure 2, the WBS results are validated against the full FE assembly results (where the same modifications are applied to the full assembly model: conventional coupling, no component reduction) in the range 0-250Hz. Within the considered frequency range, average and worst-case values of relative eigenfrequency difference (left) and Modal Assurance Criterion (MAC) [13] are shown. The average results are very accurate in the entire modification range. Note that all eigenfrequency shifts are positive: the WBS
approach slightly reduces the interface flexibility by expressing the junction DOFs in terms of the basis functions, so that a small amount of stiffness is added to the system. The worst-case error on the eigenfrequency values is very limited with decreasing $K_t$, and always below 5% for increasing $K_t$. The minimal MAC value shows some drops due to mode switches that result from the modifications, but the average values are very accurate.

Figure 2: Two plates, elastically coupled: Effect of changing the translational stiffness $K_t$ (modification factor $3 \times 10^{-3}$ to $3 \times 10^2$). For the eigenfrequencies (top) and MAC (bottom), the average (solid) and worst-case (dashed) values are shown.

4 Industrial Application Cases

4.1 Windscreen-BIW Coupling

Figure 3 shows the first industrial application case: the coupling of a windscreen in a vehicle body-in-white (BIW). The connection between the windscreen and the vehicle BIW is realized with glue. The glue has been modeled using elastic springs defined between 149 pairs of nodes and for the translational DOFs only. A modification analysis is performed, multiplying the translational coupling stiffness with a factor ranging from 0.1 to 10. Such modifications have a substantial effect on the vehicle body dynamics. Figure 4 shows a MAC [13] comparison (top view) in LMS Virtual.Lab [12] between the nominal BIW+windscreen assembly modes and the modes obtained when the elastic coupling stiffness is multiplied with 10. The dynamics have changed significantly: the MAC clearly deviates from unity for a large number of modes.

Figure 3: BIW-Windscreen coupling.

Figure 4: MAC to compare the nominal BIW+windscreen modes with the modes obtained when the elastic coupling stiffness is multiplied with 10. Clearly the modification changes the dynamics.

It is assessed whether Wave-Based Substructuring can be used to obtain fast and accurate predictions in the above-mentioned modification range. 92 interface basis functions are obtained from the normal modes of the nominal BIW+windscreen assembly. As the number of basis functions is less than the number of junction DOFs (447), the WBS approach reduces the problem size. Figure 5 and Figure 6 compare the conventional assembly modes with the WBS predictions up to 150 Hz. Figure 5 shows that with a factor 0.1, the MAC diagonal is larger than 0.8 for all modes, and the frequency difference remains below 0.5%. Likewise, Figure 6 shows that with a factor 10, the MAC diagonal is larger than 0.85 for all modes, while the frequency difference never exceeds 0.3%. So despite drastic changes in coupling stiffness, it can be concluded that WBS can be used to accurately and quickly predict the BIW+windscreen assembly dynamics. This example shows that a WBS assembly
of reduced modal models can be used to efficiently perform sensitivity analyses to connector properties modifications. It gives very accurate results and, as reduced models are used, the analyses are very fast.

Figure 5: BIW-Windscreen case, translational stiffness modification with a factor 0.1: WBS vs. full FE results, in terms of frequency (top), relative eigenfrequency difference (middle) and MAC diagonal (bottom).

Figure 6: BIW-Windscreen case, translational stiffness modification with a factor 10: WBS vs. full FE results, in terms of frequency (top), relative eigenfrequency difference (middle) and MAC diagonal (bottom).

4.2 Windscreen-Trimmed Body Case

In a second industrial application case, Wave Based Substructuring has been applied to reduce the interface description of a windshield to trimmed body connection. This coupling has dynamic stiffness as shown in Figure 7 (defined in the range [10,150]Hz, and varying between 0.2 and 5 times the nominal stiffness value). Consider the acoustic cavity in Figure 8. The aim is to predict the Noise Transfer Function (NTF) between the structural input point (engine head mount) and a target pressure output point (front center microphone).

For the structural part, two assembly models are created:
- Conventional assembly of full FE body and windscreen. Acoustic Transfer Vectors (ATV) are used for the vibro-acoustic calculation [14];
- WBS assembly of reduced modal models of body and windscreen. Modal Acoustic Transfer Vectors (MATVs) are used for the vibro-acoustic calculation [14].

For a given frequency, direct forced response analysis [11] is used to compute structural responses (for the full model) or modal responses (for the WBS assembly). The structural responses are then projected onto the acoustic mesh, and LMS Virtual.Lab [12] Acoustics can then be used to predict the microphone sound pressures $p$ based on the LMS SYSNOISE [15] solver, using Equation (8a) for the full model and using Equation (8b) for the WBS assembly, so that the results can be compared.

$$p = \sum \{ATV\}^\dagger \{v\}$$  \hspace{1cm} (8a)

$$p = \sum \{MATV\}_w \{MRSP\}_w + \sum \{MATV\}_s \{MRSP\}_s$$  \hspace{1cm} (8b)

with $v$ the structural normal velocity and MRSP the structural modal responses (vector of the modal...
participation factors). Subscripts $tb$ and $ws$ denote trimmed body and windscreen, respectively. On an SGI Onyx3 workstation (1600 MHz MIPS R14000, 2GB memory), the structural solution for the conventional assembly requires 423s, and for the reduced WBS assembly it is obtained in 88s. The model considered here has a coarse mesh; for a refined mesh, the gain in time would be even more important. The calculation time of the full model rapidly increases with the model size, while it stays approximately in the same range for the reduced assembly.

OPTIMUS [16] is a commercial software package for process integration and design optimization. Using the process integration functionality, the above-mentioned computation process has been captured with the frequency as a variable. This allows to easily generate comparison results for discrete frequencies. Figure 9 compares the results for the full FE assembly structure with the results of the reduced WBS assembly structure, for the range of discrete frequencies 10, 11, 12..., 150Hz. It can be seen that the results are identical, as the curves are superimposed. It can be concluded that the reduced WBS assembly can be used to accurately and efficiently predict the full FE assembly results.

Figure 9: Coupling of windscreen in trimmed body: pressure response obtained with dynamic stiffness for the full FE assembly (thick, dashed) and the WBS assembly (thin, solid) – the curves clearly overlap. For comparison, the pressure response obtained with constant stiffness is also shown for the full FE assembly (thick, dotted) – clearly a different curve.

To underline the industrial relevance to accurately model the dynamic stiffness, the acoustic pressure has also been predicted at the same discrete frequency lines with a constant nominal coupling stiffness (in Figure 7, this corresponds to a factor 1 in the entire range). Figure 9 compares the constant stiffness curve (for the full FE model) with the dynamic stiffness curves (for the full FE model and the WBS reduced model). Clearly the effect of frequency dependent coupling properties is important to accurately predict the acoustic pressure in the range above 60 Hz.

5 Conclusions

A Wave-Based Substructuring (WBS) approach has been developed to enable fast vehicle body optimization. An efficient assembly formulation is obtained by writing the interface displacements as a linear combination of interface basis functions. As the required number of basis functions is typically much lower than the number of interface DOFs, faster assembly predictions are obtained. Interface basis functions are obtained from a single normal modes solution of the full assembly model. These basis functions accurately capture the dynamics of the interface in the assembly, so that the interface DOFs can be expressed accurately in terms of these basis functions. Performing a single full analysis may sound counter-intuitive, as substructuring and condensation methods were originally developed to prevent having to perform a complete assembly analysis. However, in a modification analysis and optimization framework, one might have to perform hundreds of iterations. It is then most critical to speed up the time required for a single iteration, so that a single full computation that allows doing so is not a large computational burden. The WBS approach has been worked out for the rigid and elastic coupling case, and can be applied to efficiently and accurately assemble FE components and/or reduced modal models of components.

As an academic test case, two plates with different shape and with similar modal densities have been assembled along a line interface using an elastic connection. Both substructures have been reduced, and the translational stiffness has been modified in a wide range. It has been shown that the WBS predictions are very accurate when compared to the full FE predictions. Two industrial scenarios have been considered: the coupling of a windscreen in a vehicle body in white using linear elastic stiffness, and the coupling of a windscreen in a vehicle trimmed body model using dynamic stiffness properties. Results from the different analyses showed that the WBS approach yields very efficient and accurate predictions of elastic coupling stiffness modifications, even when drastic modifications are applied. Comparison of the computation time showed the benefits of combining modal reduction and Wave-Based Substructuring. For these industrial cases, it has been shown that the WBS results compare well with full FE predictions in a wide modification range in terms of accuracy and CPU time. This proves the validity of WBS for performing accurate and efficient optimization within the considered modification range.
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