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Influence of bolted items on modal analysis performed on a car body

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When performing Modal Analysis testing on a BIP (Body-in-Prime), some bolted items are included to better take into account their influence on body stiffness. However, their contribution to the stiffness is not relevant in the frequency range accessible for modal analysis (usually up to 70 Hz on a BIP). On the other hand, these bolted items increase the dispersion between results obtained for nominally identical test objects. The question which arises is whether the items should be included in the BIP definition to perform modal analysis and, in this case, which is their influence on the results? MIMO (Multi-Input-Multi-Output) measurements were carried out over three, nominally identical, BIPs. Several configurations were measured for each BIP, starting from the complete body the bolted items were progressively removed. A version of LMS PolyMAX method was programmed by Matlab to analyze the measured data. Conclusions about bolted items influence are drawn based on the study of stabilization diagrams and modal parameters. The poles selection by the stabilization diagrams is one of PolyMAX method keys. The method understanding obtained from programming allows studying the ins and outs of poles selection. Polynomial order plays an important role in physical poles identification, especially for closely spaced modes. Results are shown to highlight its relevance.

1 Introduction

A Body In White (BIW) is the automobile designing (or manufacturing) stage where the car body is formed by assembled metal sheets, and the main components as chassis, powertrain, doors, etc. are not still mounted. A Body In Prime (BIP) is plainly a BIW containing the front and the rear window.

The designers aim of performing modal analysis on BIPs is avoiding resonances in the frequency range excited by the engine when idling (below 40 Hz). Experimental Modal Analysis (EMA) data is used to update the finite element models. These models allow to redesign car bodies.

In Volvo Cars, BIPs are often studied including some bolted items which are not isolated and add stiffness to the structure. During GPDS project, interest about the influence of the bolted items on modal analysis results was aroused. Three items had potential to be decisive in the results: the Grill Over-hanging Reinforcement (GOR), the Radiator Beam (RB) and the Tunnel Brace (TB). The three bolted items can be observed in Fig. 1:

Figure 1: Bolted items:
Grill Over-hanging Reinforcement (polygon), *Radiator Beam* (dash-line) and *Tunnel Brace* (ellipse)

Apparently, the influence of the bolted items is related to the coupling between their local modes and the body ones. Coupling phenomenon hinders the work of modal analysis algorithms, lowering the results consistency and increasing the dispersion between nominally identical BIPs.

One the one hand, bolted items effect has been studied in terms of dispersion by measuring 3 vehicle BIPs. On the other hand, four BIP configurations were measured (on each BIP) in order to analyze how body modes are modified when bolted items are included/excluded:

- Standard BIP (bolted items on).
- Standard BIP without GOR.
- Standard BIP without GOR and RB.
- Standard BIP without GOR, RB and TB (bolted items off).

Additionally, a Matlab program, named MACOL (Modal Analysis COLomo), was developed to analyze measurements data. MACOL follows the well-known PolyMAX method, which was presented by its authors in [1]. The program development has provided a valuable insight of the method, highlighting the dependence of the modal parameters on the polynomial order selected in stabilization diagrams. This effect is quantified in the paper.

The paper reports the results extracted from the multi-input-multi-output (MIMO) modal testing performed on 12 car bodies (3 BIP $\times 4$ configurations). The dispersion of the resonance frequencies, between the 3 BIPs, has been determined for each configuration to investigate the relevance of bolted items on the results consistency. Moreover, MAC values (for a single BIP) have been calculated between consecutive configurations, i.e. configurations differing on a single item.

2 Modal parameters dependence on polynomial order

The polynomial order (p) plays an important role in modes identification, especially for closely spaced modes. The results dependence on the polynomial order is introduced in PolyMAX method by the right matrix-fraction model [2]. This model expresses the Frequency Response Functions (FRFs) matrix ($[H(f)]$) as the division of two matrices ($[A(f)]$ and $[B(f)]$) which are built-up by polynomials in z-domain, as shown in Eq. (1) and (2):

$$[H(f)]_{N_o \times N_i} = [B(f)]_{N_o \times N_i}[A(f)]^{-1}_{N_i \times N_i} \quad (1)$$

$$< H_o(f) >_{1\times N_i} = \frac{\sum_{r=0}^{p} < \beta_{or} > z^r(f)}{\sum_{r=0}^{p}[\alpha_r]z^r(f)} \quad (2)$$

Eq. (2) illustrates the o^{th} row of the FRFs matrix. N_i and N_o represent, respectively, the number of inputs and outputs of the modal test. The polynomial coefficients are α_r and β_{or}. The calculation of the denominator coefficients (α) allow calculating system poles, which are necessary to construct the stabilization diagrams. In Table 1, the notation of MACOL stabilization diagrams is shown:

Table 1: Stability borders of damping ratios (η) and modal participation factors ($< L >$)

$\Delta\eta_r < 5\%$	$\Delta \lVert < L_r > \rVert < 2\%$	Symbol
no	no	square
yes	no	diamond
no	yes	triangle
yes	yes	cross

During the study of modal analysis results, two different situations were observed when identifying modes from stabilization diagrams. On the one hand, modes easy to identify appear as stable poles for the most of the polynomial orders (vertical line of crosses). On the other hand, modes affected by coupling are hard to identify because there are few stable poles to select (few crosses appear in between squares, diamonds or triangles). From now onwards, those modes which are not clearly identifiable are referred as "unclear modes".

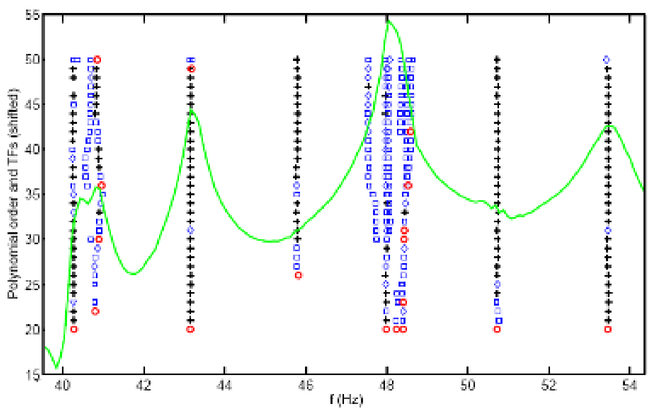

Figure 2: "Easy-to-identify" and "unclear" modes

The selection of a stable pole for identifying an unclear mode can still be done but its reliability is doubtful. A discontinuity of stable poles appears for these modes. From one stable pole to the next one, poles unstable in damping factor or/and modal participation factor are found. The discontinuity entitles that the extracted modal parameters are significantly different depending on the polynomial order selected. Fig. 2 shows some examples of "easy-to-identify" (40.26, 43.15, 45.79, 50.74, 53.46 Hz) and "unclear" modes (47.53, 47.98, 48.50 Hz).

Easy-to-identify modes are likely to show more consistent results than those considered as unclear modes. Therefore, both type of modes have been investigated and compared. Tables 2 and 3 provide an example of the modal parameters comparison done between an easy-to-identify mode and unclear one from figure 2. These tables show the modal parameters for 4 different polynomial orders (p). The last line contains the maximum variance ($\Delta(\%)$) between the polynomial orders used.

Table 2: Poles selection dependence on polynomial order for an easy-to-identify mode

p	f_r	$\eta_r(\%)$	$< L_r >$
22	43.15	0.443	-0.283;-0.073+0.001i
24	43.15	0.431	-0.276;-0.069-0.001i
39	43.15	0.440	0.258;0.067+0.003i
58	43.15	0.432	0.249;0.065+0.003i
	$\Delta = 0.00\%$	$\Delta = 2.71\%$	$\Delta = 12.00\%$

Table 3: Poles selection dependence on polynomial order for an unclear mode

p	f_r	$\eta_r(\%)$	$< L_r >$
24	47.99	0.249	0.086+0.007i;0.241
29	47.99	0.242	0.083+0.021i;0.226
38	47.99	0.210	0.072+0.028i;0.204
51	47.97	0.218	0.060-0.007i;0.199
	$\Delta = 0.04\%$	$\Delta = 12.45\%$	$\Delta = 19.97\%$

Results are revealing. High accuracy in modes frequency is observed for both cases. Damping factors show different behavior in each case. In the easy-to-identify mode case, damping factors estimation is very consistent. Whereas for the unclear mode, the maximum variation is over the double of the limit set for consecutive polynomial orders, 5%. Although the difference is not extreme, it should be take into account when considering results.

Modal participation factors are not reliable in both cases. Its stability criterion for consecutive poles is 2%. A relative difference five times over the limit proves the lack of consistency. This result implies that the consistency of mode shapes (ψ_r) estimation is low, according to the modal model used in PolyMAX [3], shown in Eq. (3):

$$H_{oi}^{synt}(f) = \sum_{r=1}^{n} \left(\frac{\psi_{or} L_{ir}^T}{j2\pi f - \lambda_r} + \frac{\psi_{or}^* L_{ir}^H}{j2\pi f - \lambda_r^*} \right) - \frac{LR_{oi}}{(2\pi f)^2} + UR_{oi} \quad (3)$$

These results have been obtained using MACOL software. Therefore, they cannot be extrapolated to LMS PolyMAX although both programs are based on the same method.

3 Bolted items results

3.1 Dispersion between BIPs

The standard deviation (σ) has been the variable chosen to quantify the dispersion of the resonance frequencies between BIPs. The standard deviation of the resonance frequency (between the 3 BIP) has been calculated for each body mode and configuration. Two points has been analyzed from the standard deviations:

3.1.1 Coupling phenomenon relation to dispersion

Results show that unclear modes, the ones mainly affected by coupling, do not have a higher standard deviation than the other ones. Indeed, their standard deviation (0.05-0.25 Hz) is low in comparison to the standard deviation average over all body modes (0.47 Hz). In addition some easy-to-identify modes have a high standard deviation as for instance the mode at 50.74 Hz in Fig. 2.

3.1.2 Dispersion introduced by the bolted items

Table 4 presents the average standard deviation obtained for all the configurations measured. It is of significance that the standard deviation does not increase when bolted items are added. However, it has been observed that the standard deviation relative to the resonance frequencies is around 1% for all configurations. This could prove that the dispersion (in terms of resonance frequencies) added by the bolted items is very low.

Table 4: Averaged standard deviation introduced by the bolted items

Std wo GOR&RB&TB	0.54 Hz
Std wo GOR&RB	0.53 Hz
Std wo GOR	0.46 Hz
Std configuration	0.43 Hz

3.2 Bolted items influence on body modes

The study of the bolted items influence on body modes has been run over all configurations for one of the BIPs. The aim of this study is defining the effect of each bolted item on the body modes. This is done by establishing the relation between the mode shapes of consecutive configurations, i.e. configurations differing on a single item. MAC values has been used to determine the mode shapes correlation, so they constitute the best indicator possible to illustrate bolted items influence.

One must keep on mind that different structures are compared, therefore points which do not belong to both configurations are not taken into account to calculate MACs. However, "usual" MACs cannot be expected because having attached an extra-item does influence a mode shape due to the mass and damping modification introduced by the extra-item. Therefore, it is hard to find MAC values over 90% even if a couple of mode shapes resemble.

Relations between mode shapes has been classified and shown in the so-called modes evolution diagram (Fig.4), developed by the author.

- **High correlation** ($MAC > 60\%$): Modes highly correlated are joined by arrows.
- **Weak correlation** ($40\% < MAC < 60\%$): Modes slightly correlated are joined by dotted arrows. The original mode, the one of the structure before the bolted item is added, suffers a strong modification.
- **New mode** ($MAC < 40\%$): Modes not correlated to the ones from previous configuration. They are circled.
- **Swapped mode**: The modes order is modified due to a bolted item inclusion. They are surrounded by a polygon.
- **Unclear mode**: Hard-to-identify modes. They are marked by a sloping arrow.

The modes evolution diagram facilitates the analysis of the results. In the following sections the influence of each bolted item is analyzed:

3.2.1 Tunnel brace influence

The Tunnel brace (TB) is the bolted item less important. The modes evolution diagram highlights a higher contribution of the other items.

Figure 3: Tunnel Brace

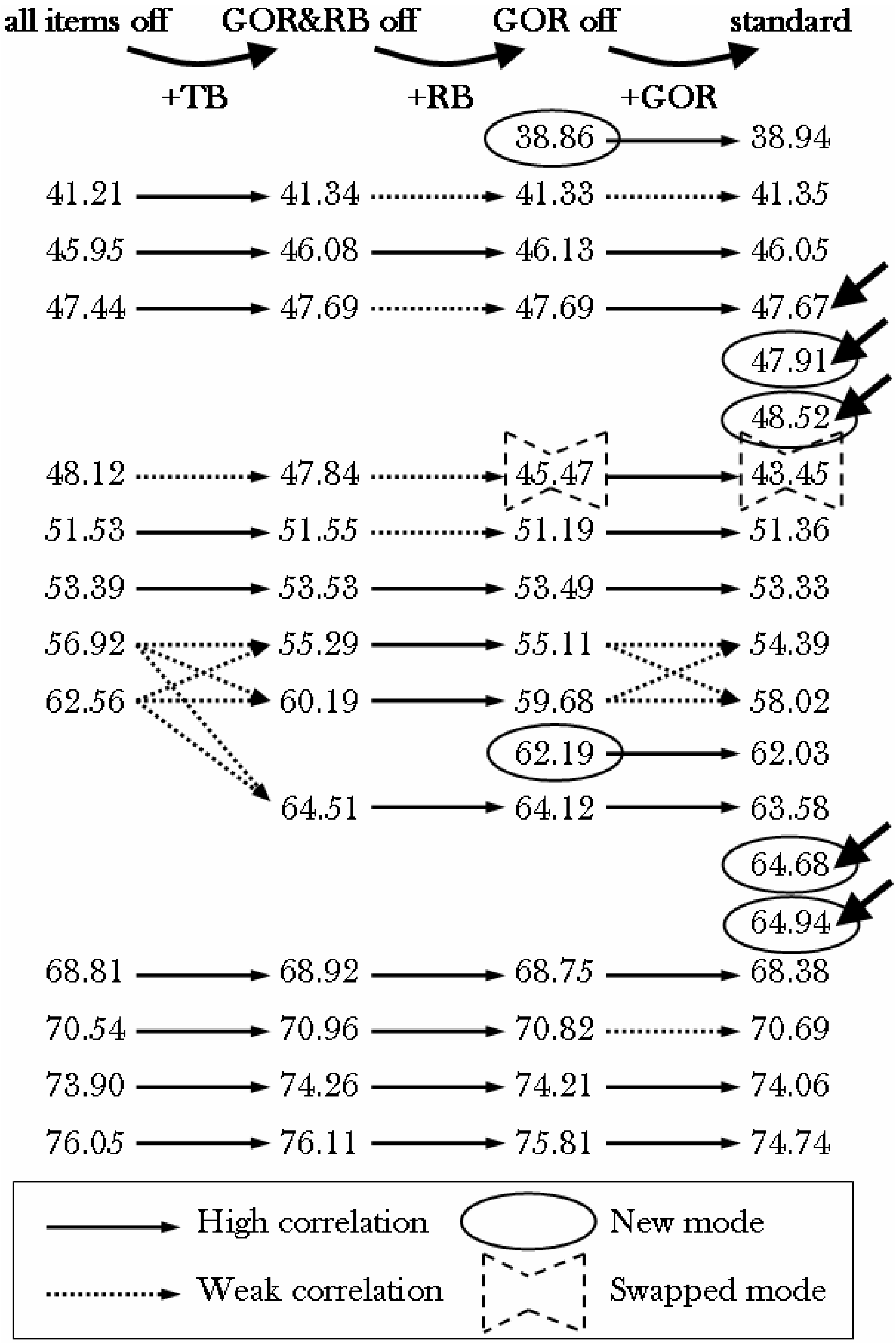

Figure 4: Modes evolution diagram

Only three body modes, from the "all items off" configuration, are modified when TB is set on. Two body modes (56.92, 62.56 Hz) experience coupling with a TB self-mode, yielding three body modes in the "GOR&RB off" configuration.

3.2.2 Radiator beam influence

Two modes (38.86, 62.19 Hz) appear when the Radiator Beam (RB) is added. They are not correlated to any of the modes for the "GOR&RB off" configuration. In this case bolted item local modes are not close (in frequency) to body modes. Therefore coupling phenomenon does not occur.

Figure 5: Radiator Beam

3.2.3 Grill over-hanging reinforcement influence

The GOR is definitely the most influencing bolted item. Its heavier weight and its position might be the cause.

The addition of the GOR introduces four new body modes, probably GOR local modes. It is also a matter of size, the bigger the bolted item is, the earlier its local modes are found in frequency. Therefore, when a bigger bolted item is joined to the body, more new modes are found in the resulting structure. Additionally, four modes from the configuration without GOR are strongly modified.

Figure 6: Grill Over-hanging Reinforcement (GOR)

4 Conclusions

The polynomial order has a significant influence on mode shapes and modal participation factors magnitude. A difference of 20% can be achieved when selecting a mode from two different stable poles. When considering unclear modes, there are also important differences in damping ratios.

No relation has been found between coupling phenomenon and the dispersion of the resonance frequencies. Therefore, it has been concluded that bolted items do not add dispersion to the estimation of the resonance frequencies.

Stabilization diagrams observation, together with the study of the polynomial order influence, has discovered the key role of unclear modes in the inconsistency of modal analysis results. Avoiding them would probably improve the results accuracy, especially for the mode shapes estimation.

The modes evolution diagram provides a straight answer to the origin of unclear modes. Its observation has shown that four of the five unclear modes appear when GOR is set on. The other unclear mode, at 47.67 Hz, cannot be avoided as it comes from one of the modes of the plain body. Nevertheless, this mode is not unclear when GOR is not on, as there is not coupling between itself and the modes introduced by the GOR.

Hence, GOR exclusion is suggested for further Modal Analysis tests on BIPs in order to improve results consistency. Exclusion of both, tunnel brace (TB) and radiator beam (RB), is considered unnecessary.

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