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# An efficient procedure for spot welds optimization in automotive structures

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## ABSTRACT

In the automobile industry, two structural parts are often joined using welding spots. Both the number and their locations are critical parameters for designers and manufacturers, since the dynamic behavior of the whole structure largely depends on them. Moreover, the number of spot welds and their positions is also an important consideration for reducing manufacturing costs. In this paper, we propose to compare three energy criteria for spot weld optimization in the context of large automotive models. We assume that an over-populated spot welding distribution is given and that this nominal model satisfies the design objectives.

The proposed iterative procedure then attempts to eliminate spot welds while preserving as far as possible the nominal structural behavior based both eigenfrequency and static criteria. Since the number of spots can be very large, the efficiency of the criteria which are used to remove them is a crucial point. Three energy criteria are used and compared on an industrial application in automotive context (1,000,000 degrees of freedom and 5000 spot welds).

## 1. INTRODUCTION

Resistance Spot Welds (RSW) are widely used in automotive industry, mainly to join thin metal sheets in order to obtain the so-called body-in-white of the car. A survey of the effects of spot welds on the dynamic behavior of vehicles has been presented in ref. [1], including both experimental and numerical aspects as well as optimization strategies to define a compromise between acceptable modal behavior of the body-in-white and the number of RSW, which should be as small as possible to reduce manufacturing costs.

Thanks to the growth of computers calculation power, a full body-in-white modal analysis can now be performed in relatively short time, and optimization on such a complex structure can be investigated. The analysis which is proposed here deals with spot weld optimization both in terms of number and position. The objective is to detect, among a large number of resistance spot welds, which of them can be removed while the behavior of the structure remains almost the same. In this paper we will focus on a full body-in-white finite element model of a PSA Peugeot-Citroën car (1,000,000 degrees of freedom), whose components are joined using 5800 RSW. The objective is to remove as many RSW as possible while insuring that the first three eigenfrequencies do not vary more than 5% of the original value. Of course, this should be done with an efficient optimization procedure in order to reduce the calculation costs as much as possible. We propose an efficient approach based on energy criteria which allow a large number of RSW to be eliminated RSW at each optimization step.

Let us consider the typical behavior of a given feature of the model versus the number of eliminated RSW. This feature could typically be the frequency error of an eigenmode of the modified structure (with missing RSW) which has been matched to a homologous target mode of the nominal model. If the original structure includes a large number of RSW, removing them based on a minimum energy criterion and considering the value of this feature (typically a matched eigenfrequency) versus the number of eliminated weld spots leads to the typical behavior illustrated in figure 1:

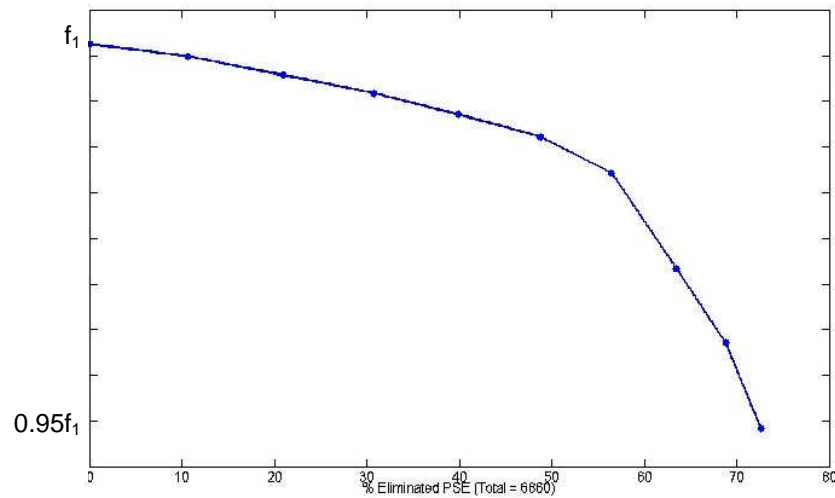


Figure 1 : Typical evolution of eigenfrequency versus % of eliminated RSW

Earlier formulations of the optimization algorithm were based on the removal of one RSW at a time. Unfortunately, this kind of approach obviously results in a very high calculation cost. This cost can be reduced, in particular at the beginning of the procedure when the cost function is almost insensitive to spot weld removal. The basic idea here is to find a method that allows one to reach the end of this “insensitive” zone in a small number of iterations, using a criterion that would indicate the “insensitive” spot welds. Ideally, the number of spot welds to be removed at a given iteration would be a function of their energy distributions.

In order to evaluate the efficiency of the proposed procedure, it is necessary to test it on a complex structure, for which the unsensitive zone described above is large. This structure will be described in section 2. Then, the optimization procedure will be presented in section 3, while the section 4 will describe the chosen energy criteria for the selection of the RSW to remove. Finally, section 5 will present and discuss the results.

## 2. FINITE ELEMENT MODEL

The structure which will be presented here is a body-in-white finite element model of the car. The mesh has about 1,000,000 degrees of freedom.

Modal analysis of the structure up to 75 Hz takes 45 minutes on the computer which has been used in this study (MSC/NASTRAN 2004 on a PC Xeon 3.6 GHz, 2 Gb RAM). This frequency range includes 3 global modes, the first torsion mode at a given frequency  $f_1$  is presented in figure 2. The two other modes that will be considered here are flexural ones, corresponding to  $1.69 f_1$  and  $1.77 f_1$ .

The initial mesh that is considered here has been reinforced by adding spot welds to the original structure in order to dispose of a large number of candidate RSW. In all, 6660 RSW are located on the structure grouped along 572 interfaces. In this study, each of the RSW is described with the simplified model shown in figure 3: the shell elements of the two structural parts are linked to two master nodes 101 and 102 with MPC elements, while the two master nodes are linked together with CBUSH elements.

In the following, we will denote:

- $K_0$  and  $M_0$  the stiffness and mass matrices of the original (reinforced) structure.
- $\lambda_v^0$  and  $\gamma_v^0$  the eigenvalues and eigenvectors of mode  $v$  of the original (reinforced) structure.

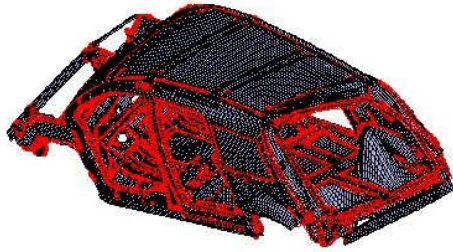


Figure 2: FE Model of body-in-white (torsion mode)

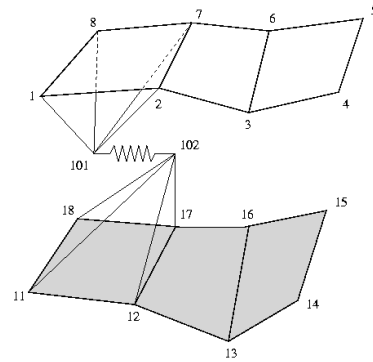


Figure 3: Finite Element Model of a spot weld

### 3. OPTIMIZATION PROCEDURE

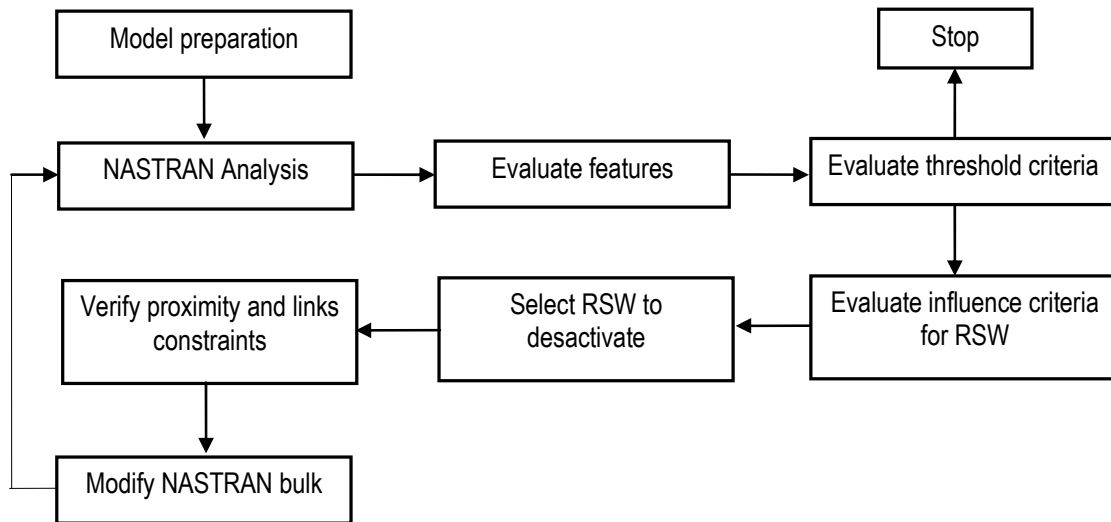


Figure 4: Optimization procedure

Figure 4 describes the optimization procedure that will be used to progressively remove the RSW from the model. After the model preparation (reinforcement of the structure, characterization of each RSW by its membership to a given identified interface which is characterized by an ordered list of weld spots), a modal (and/or static) Nastran analysis is performed to evaluate the target model features. In this step, a correlation analysis is required in order to identify the modes of interest, using the Modal Assurance Criteria (MAC). Eigenvectors are considered to be matched if the corresponding MAC is above 0.7). Then, an evaluation of threshold criterion is performed, in order to determine if the iterative process has to be stopped or not. The next step is the evaluation of influence criteria of each RSW on the cost function based on the target features, using one of the three criteria that will be described in the next section. This evaluation allows one to detect the candidate RSW that are likely to be removed of the structure. Then, before removing the spot welds of the model, two topological constraints must be satisfied: a proximity constraint and a minimal interface constraint. The proximity constraint is illustrated in figure 5, for which the value of the constraint is 6. In this case, two candidate RSW in a given interface (and at a given iteration) must be separated by 6 remaining ones. A proximity constraint of 0 will authorize two consecutive spot welds to be removed at a given iteration. This constraint is closely linked to the ability or failure of the procedure to take into account coupling between effects of removed RSW at a given iteration. The interface constraint consists of verifying the integrity of each interface: each interface comprises a given number of RSW at the beginning of the procedure, and if the algorithm can reduce the number of weld spots for this interface, it is not authorized to completely remove all

the interface RSW. In the present study, the RSW at the two ends of the interface are systematically preserved. Then, the Nastran command file is modified by removing RSW which have been selected and which verify the constraints. Finally, the optimization loop goes back to the analysis to re-evaluate the current state of the target features.

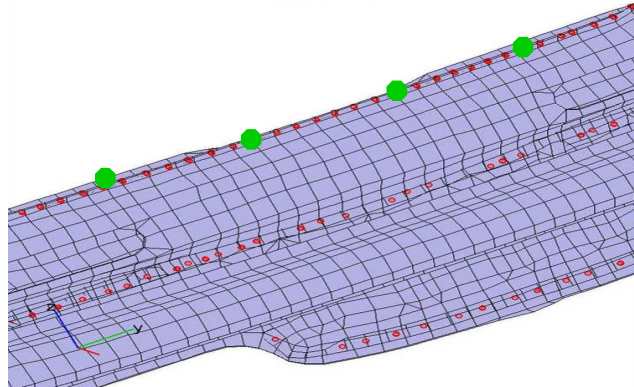


Figure 5: Candidate RSW for proximity constraint equals 6

The procedure which is presented here has two specificities compared to the earlier formulations of this optimization problem. The first one is that the number of RSW which can be removed at a given iteration is unknown: as many RSW as possible are removed such as their total contribution to a given energy of the structure is lower than a threshold value will be eventually removed at a given iteration. The second specificity is that the proposed criteria are unable to take into account coupling between parameters (they should give information about the influence of a given RSW on feature while all other ones still exist, even if in fact many RSW are removed at a given iteration): this specificity imposes that a proximity constraint should be used during analysis.

#### 4. ENERGY INFLUENCE CRITERIAS FOR CANDIDATE WELD SPOTS DETERMINATION

In the optimization procedure described above, the critical point is the choice of the influence criteria for each spot weld. Three categories of criteria could be chosen:

- Criteria based on interface forces: these criteria are the least expensive to evaluate but there is no simple link between these forces and the evolution of the model features used here. All coupling effects are included in the criteria.
- Criteria based on energies: these criteria are relatively inexpensive to evaluate and there exists simple relationships between values of criteria and eigenvalue shifts. However, coupling effects are not taken into account.
- Criteria based on *a posteriori* evaluation: these criteria are quite expensive to evaluate but give the exact influence of each parameter. This is considered to be the reference calculation.

In this paper we will focus on energy criteria. Three of them have been implemented in AESOP, the optimization and model updating development platform of the FEMTO-ST Institute, and they will be described in this section.

##### 4.1 Criterion 1: elastic energy in RSW

The first imaginable criterion is undoubtedly the more physical of all those described in this paper: it is the elastic energy of each spot weld. Denoting  $K^{e,i}$  the element stiffness matrix of RSW number  $i$ , the element elastic energy considered here can have several expressions, corresponding to the contribution of considered element to the total elastic energy:

- Modal analysis (eigenshape  $y_v$ , eigenvalue  $\lambda_v$ )  $E_i^1 = y_v^T K^{e,i} y_v / \lambda_v$  (1)

- Static analysis (static response  $x$ )  $E_i^1 = x^T K^{e,i} x / x^T K x$  (2)

- FRF analysis (frequency response  $y$ )  $E_i^1 = y^T K^{e,i} y / y^T K y$  (3)

The normalization operation is done using the total energy of the structure. In this paper we will focus on the first expression, corresponding to a modal analysis. This criterion is very closely linked to eigenvalues shifts, inducing good performances when the features of the problem take into account only eigenvalues variations and not eigenshapes modifications.

Using this first criterion, all spot welds are sorted using their elastic energy  $E_i^1$ , in ascending order, and the candidate RSW to elimination will be selected using the following relationship:

$$\text{Select RSW 1 to n such as } \sum_{i=1}^n E_i^1 < \text{tol} \propto \Delta\lambda \quad (4)$$

#### 4.2 Criterion 2: elastic energy in RSW and adjacent shell elements

In some cases, in particular when the stiffness of a given RSW is higher than the one of the adjacent shell elements, the above criteria does not capture the correct behavior of the structure, since the elastic energy of the considered spot weld can be very small while the surrounding shell elements have a large elastic energy, it implies that removing this RSW will yield a significant change in the considered feature.

This is why the second considered criterion will be the same as the previous one, completed by the elastic energy of surrounding shell elements:

$$E_i^2 = E_i^1 + \frac{\sum E_i^{\text{shell}}}{\sum V_i^{\text{shell}}} V^{\text{sh tot}} \quad (5)$$

In which  $E_i^{\text{shell}}$  is the elastic energy of shell elements surrounding spot weld  $i$ ,  $V_i^{\text{shell}}$  the total volume of surrounding shell elements, and  $V^{\text{sh tot}}$  the total volume of shell elements surrounding all considered RSW. This normalization is necessary to avoid artificial variations of indicator due to size elements.

Using this second criterion, all spot welds are sorted using their elastic energy  $E_i^2$ , in ascending order, and the candidate RSW to elimination will be selected using the following relationship:

$$\text{Select RSW 1 to n such as } \sum_{i=1}^n E_i^2 < \text{tol} \propto \Delta\lambda \quad (6)$$

#### 4.3 Criterion 3: Hypersensitivity indicator

The third considered criterion is based on work presented in refs [2] and [3], which has been called a "hypersensitivity indicator". For the problem presented here, two stiffness matrices can be defined:  $K_0$  is the stiffness matrix in nominal case (with all RSW), and  $K_1$  is the stiffness matrix corresponding to the structure with some removed RSW. In the present case, no change appears in mass matrix when RSW are removed. The indicator is then based on the residual modal force:

$$\Delta F_v = (K_1 - K_0) y_v \quad (7)$$

which is then transformed into a residual modal displacement:

$$R_v = K^{-1} \Delta F_v \quad (8)$$

Finally, this displacement is used to evaluate a kinetic energy in order to have global information and to link it to variations in the eigenvectors:

$$H_v = R_v^T M_1 R_v \quad (9)$$

Then, it can be shown (ref. [3]) that this is closely related to the features shifts, starting from a modal decomposition of initial shape  $y_v$  on the modal basis of modified structure (with removed RSW)  $y_v^1$ :

$$y_v = \sum_{\tau} \alpha_v^{\tau} y_{\tau}^1 \quad (10)$$

The  $\alpha_v^{\tau}$  factors are the projections of  $y_v$  on modal basis  $y_{\tau}^1$ , which can be seen as a measure of difference between the two considered bases: if the structural modifications are small,  $\alpha_v^j \approx \delta_j^j$  in which  $\delta_j^j$  is the Kronecker symbol. Then,  $H_v$  can be expressed as:

$$H_v = (\alpha_v^v)^2 \left( \frac{\lambda_v^1 - \lambda_v}{\lambda_v^1} \right)^2 + \sum_{\tau \neq v} (\alpha_v^{\tau})^2 \left( 1 - \frac{\lambda_v}{\lambda_{\tau}^1} \right)^2 \quad (11)$$

in which  $\lambda_v^1$  is the  $v$ -th eigenvalue of the modified structure.

This indicator provides a single value for the structure, and then it is decomposed in element contribution to the total energy, and also includes a normalization to avoid artificial variations of indicator due to size elements, to finally obtain the criterion 3:

$$E_i^3 = \frac{R_v^T M^{i,e} R_v}{\sum V_i^{\text{shell}}} V^{\text{sh tot}} \quad (12)$$

Using this third criterion, all spot welds are sorted using their elastic energy  $E_i^3$ , in ascending order, and the candidate RSW to elimination will be selected using the following relationship:

$$\text{Select RSW 1 to n such as } \sum_{i=1}^n E_i^3 < \text{tol} \propto (\Delta\lambda)^2 \quad (13)$$

The calculation cost for the estimation of criteria 3 is higher than the one required for the two first ones, but the objective is to obtain a lower global calculation cost thanks to a larger selection of RSW to eliminate at each iteration. The difficulty here is to determine the value of tolerance which should be used in this case: it is of the order of  $(\Delta\lambda)^2$  only in when changes in deflection shapes are very small.

## 5. RESULTS

### 5.1 Criterion 1: elastic energy in RSW

Results of the analysis using the first criterion are illustrated in figure 6. In this case, a proximity constraint of 2, with a threshold value of 0.025 has been used. It can be seen that according to eq. (4), only two iterations are required to reach the maximum eigenfrequency shift of 5%, allowing one to eliminate 45.6% of the RSW. The third iteration, corresponding to 60% of removed RSW, corresponds to the end of the “unsensitive” zone, for which the shifts are too large, up to 8.6%. The required calculation cost for this analysis is 3 hours.

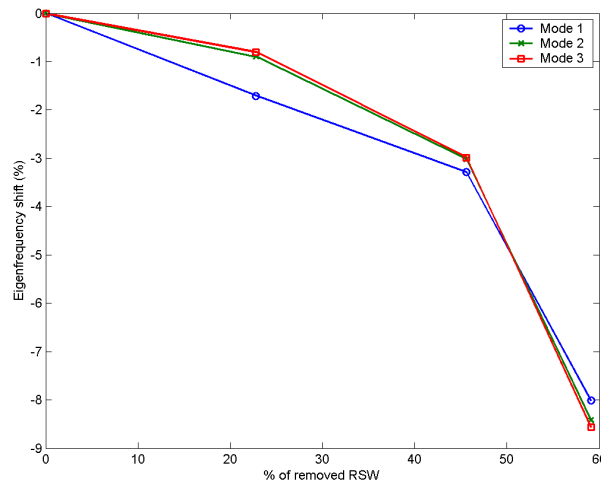


Figure 6: results of optimization for criterion 1

### 5.2 Criterion 2: elastic energy in RSW and adjacent shell elements

Results of the analysis using the second criterion are illustrated in figure 7. In this case, a proximity constraint of 2, with a threshold value of 0.025 has been used (same parameters as in case 1). One can observe that a given threshold value corresponds to a lower frequency shift, since the energy includes not only the RSW but also the adjacent shell elements, which means that lower RSW are selected at a given iteration. This results in a better final result, since the third iteration leads to shifts just below 5%. The fourth iteration, which corresponds to a removing of 70% of RSW induces large changes in deflection shapes: in this situation modes 1 and 3 are no longer correlated enough to be automatically matched.

The final results are the best ones that have been obtained in this study, corresponding to removing of 60% of RSW while keeping the matched eigenfrequency shifts below 5%. The required computational time is 4 hours (about 1 hour per iteration).

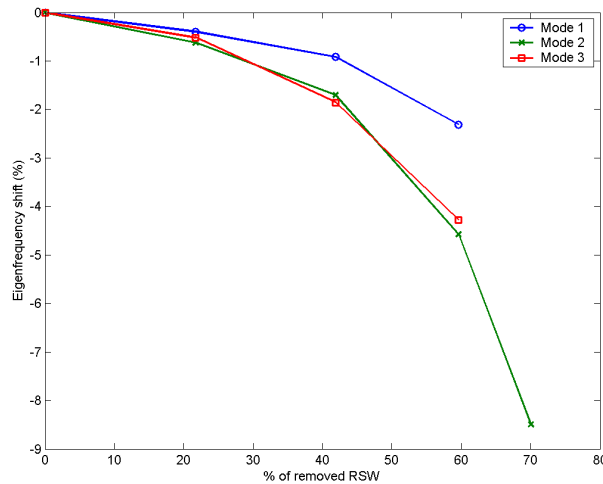


Figure 7: results of optimization for criterion 2

### 5.3 Criterion 3: Hypersensitivity indicator

Results of the analysis using the third criterion are illustrated in figure 8. In this case, a proximity constraint of 2, with a threshold value of 0.05 has been used. In order to be competitive compared to the other runs, this indicator should be able to remove at a given iteration more RSW than the two first indicators, since the required calculation cost is higher, due to the static resolution of the problem (eq.8). In this case, the threshold is reached at the second iteration, for which 40% of RSW have been removed. The results are not as good as the ones obtained using the first two indicators, since they were able to remove more than 40% of RSW while keeping the total eigenfrequency shift under 5%. Moreover, the required calculation cost is much higher than in the two other cases (5 hours).



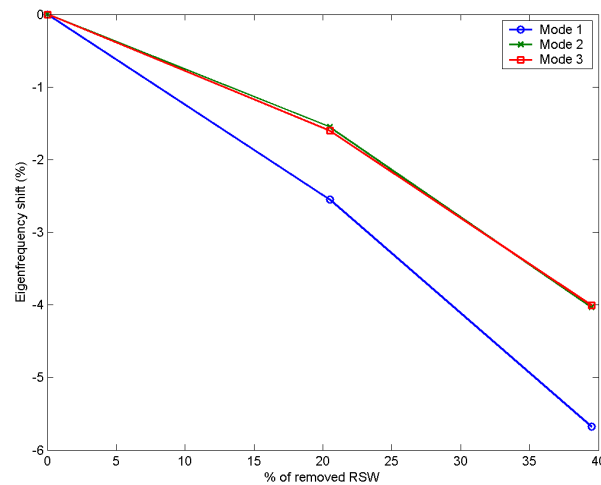


Figure 8: results of optimization for criterion 3

## 6. CONCLUSION

Three energy criteria for the suboptimal design of RSW in large automotive structures have been presented in this paper. All of them are based on the elastic energy of spot welds and if they are used in parallel with a proximity constraint, they allow one to select hundreds of RSW to eliminate at a given iteration. Gains in calculation time with respect to a weld-by-weld elimination approach are thus very large. The third criterion is based on modal residual force, and gives similar results, even if the calculation time is higher than for the two first criteria, and the efficiency is a bit lower. The hypersensitivity approach does not seem to provide any real advantages in this case.

The next steps that could be taken into account for RSW optimization are the following ones:

- Understanding the behaviour of indicators (in particular indicator 3) to be able to specify the best value of tolerance to reach in a few iterations the end of the insensitive zone
- Based on a knowledge of global energy transfer in each RSW interface, the algorithm should be able to adaptively add or remove spot welds
- Based on the know-how of manufacturer, include specific constraints such as the *a posteriori* distribution of RSW changes
- Based on the know-how of the designer, include new constraints such as static responses, energy dissipation, transient behaviours
- Perform a robustness analysis in order to obtain information about uncertainties in optimized model and to be able to choose the most robust solution among several sub-optimal cases.

## Acknowledgement

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