ON THE PROFILE INTENSIVE BIW DESIGN AND OPTIMIZATION –THE FRONT MODULE CASE STUDY-

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ABSTRACT

The European automotive industry is known world-wide as the technically most advanced and innovative. Based on the competitiveness of global market, it is an emerging challenge and puts forward the need of flexibility for automobile OEMs and the product's ability to meet the demands of the continuously changing customer's behaviour. Therefore flexible processes have to be implemented during the design process of a BiW in order to achieve a flexible and modular product.
In this paper profile intensive design of a front module has been developed under the prism of lightweight design. Profile intensive design offers to the manufacturer higher levels of flexibility and ability to adapt to the market needs efficiently and more quickly. Evaluation of the proposed design has been made through Design of Experiments. Finally Response Surface Method has been used for predicting the response of the front module when design variables are being changed.

Keywords: body in white, optimization, lightweight.

1 INTRODUCTION

The economical use of energy and other limited resources and the protection of the environment will be one of the main influencing cornerstones of tomorrow's mobility. Intensive efforts in the automotive industry focus on further reduction of CO_2 emissions and higher energy efficiency in all phases of vehicle life cycles. EU have set the target in $130 gCO_2/km$ for a class A car until 2014 and $95 gCO_2/km$ until 2020 (EU Press Release. 2012). Reduction of fuel consumption and CO_2 emissions can be achieved primarily by power train or vehicle technology related measures. Consequently, development of lightweight design plays a major role for further fuel consumption reduction.

Moreover third markets are growing fast, changing the trade flows. As a result OEMs have to further increase their flexibility in order to meet customers' needs. It is clear more than ever that a lot of challenges are emerging towards automotive industry which will lead to change of vehicle design. Integral design which is the main trend cannot follow the diverse consumers' environment. Previous design optimization approach cannot be adopted in order to achieve further weight reduction and in extent reduce vehicle emissions. Lightweight design philosophy has to be implemented and not only

in terms of conceptual design of a vehicle but also in manufacturing and material design of an automobile.

As a result modular and lightweight design can be used to confront the future challenges. A modular architecture presents a one-to-one correspondence between modules and functions and specifies de-coupled interfaces between components (Pandremenos et al. 2009). This way, a high degree of customization can be achieved, satisfying different needs (Chryssolouris et al. 2008). On the other hand weight reduction can help the automotive industry to meet the environmental target. Powertrain developments can help a lot in this direction with more efficient engines but Body in White (BiW) possesses 30% of the vehicle weight (Zhang et al. 2007). Weight reduction of 100kg reduces fuel consumption about 0.3-0.4l/100km.

However, modular and lightweight design will bring changes to the whole production line as new materials may be used to reduce weight (lightweight material design) and consequently new joining technologies have to be developed (Nunez 2009). Moreover modularity may affect the production line in terms of that rescheduling may be needed or even definition of new modules and as a result new sub-assembly lines.

In this paper, a profile intensive BiW design of the front module is presented. Front side rail, rear side rail and shotgun have been re-designed to be manufactured from a progressive and simple roll forming process, processes which can lead to a high degree of flexibility. The study focuses on front module but it can be extended to the rest of the modules. Moreover, Design of Experiments (DoE) has been coupled with Response Surface Method (RSM) in order to reduce weight and to improve torsional stiffness.

2   DESIGN PROCESS

A profile intensive BiW design methodology is being proposed. For evaluation of this methodology, the front module of Fiat Stilo has been selected. Front module is one of the most important modules that should be taken in account during lightweight design because on it, the engine is installed, which has a fixed weight and it is not a design variable during BiW design. The majority of the automotive parts are produced from deep-drawing or casting processes. However these processes do not guarantee flexibility of design because for a simple change, modification of tooling is required, thus most of the times lead to a product that cannot meet the customer's needs. However, processes such as roll forming and extrusion can deliver parts which lead to a scalable product. In order to substitute and simultaneously respect the design philosophy of Fiat Stilo BiW, a design 'template' has been developed. This design template, Figure 3, gathers all the design characteristics such as dimensions, joining interface planes etc. As a result, the changes will be occurred in BiW's design will not cause any design interference.
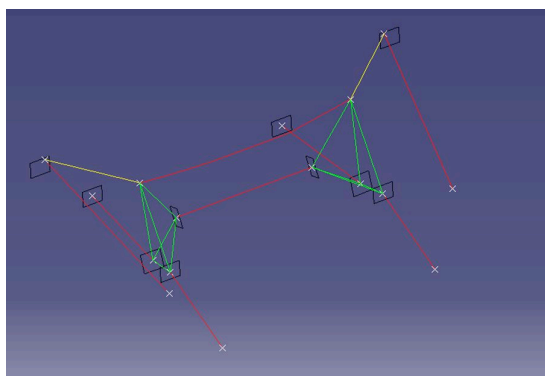

Figure 1: Design Template

The proposed design includes re-design of some parts in respect of the roll forming and flexible roll forming processes. The final target is to reduce the weight of the front module, and increase torsional stiffness. ANSYS Workbench has been used for setting benchmark values in order evaluate the profile design. The two characteristics which have been measured are torsional stiffness and front module's weight. Torsional stiffness has been measured as it is described in (Tebby et al. 2010).. For the measurement of front module mass, CATIA V5R18 Measure module has been used and a constant thickness of 1.2mm of steel has been selected as material.

Table 1: Fiat Stilo Benchmark Values

Weight (only Front Module measured)	42.18 kg
Torsional Stiffness	14833 Nm/deg

Under these assumptions, front side rail (fsr), rear side rail (rsr) and shotgun have been re-designed in order to be manufactured from cold roll forming process (fsr and rsr) and flexible roll forming (shotgun). Cold roll forming processes has been selected due to the cost advantages towards hot stamping which is on average 40-60 % cheaper. The reason for this is the fast production cycle for each cold formed part. The U profile has been selected for the parts. As a result, numerous joining points on the flanges can be provided for the connection of the front with the floor module. Moreover, flanges in the front side rail provide freedom to the selection of engine mounting points. After the design completion, an evaluation has been conducted and the results can be seen in Table 2.

Table 2: Comparison of Stilo and Profile Front Module

	Fiat Stilo Front Module	Profile Front Module	Difference
Weight (only Front Module measured)	42.18 kg	36.62 kg	-13.18%
Torsional Stiffness	14833 Nm/deg	15248 Nm/deg	+2.7%

3   DESIGN OF EXPERIMENTS

Conducting a set of experiments using orthogonal arrays allows the effects of several parameters to be determined efficiently (Phadke 1989) in relevance to a defined response. In the current work, the L_9 orthogonal array has been used. The statistically designed experiments are simulation runs, changing each time specific design variables, implemented using FE calculations. The variables and the ranges are shown in Figure 5 and Table 3 respectively.

Table 3: L_9 Virtual Experiments

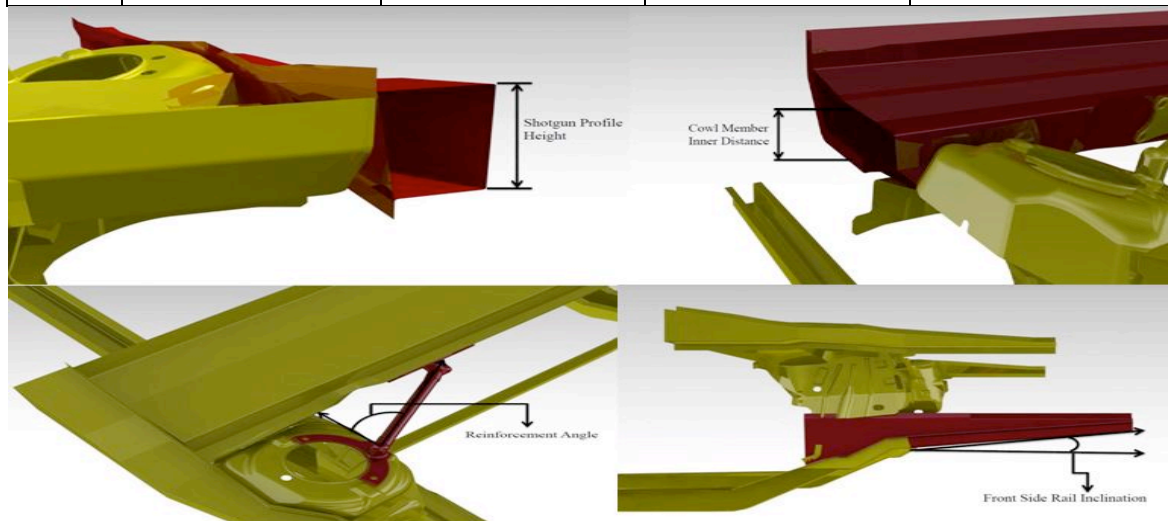| Expt. No.	A. Shotgun Profile Height	B. Reinforcement Angle	C. Front Side Inclination	D. Cowl Member Inner Distance
1	Level 1	Level 1	Level 1	Level 1
2	Level 1	Level 2	Level 2	Level 2
3	Level 1	Level 3	Level 3	Level 3
4	Level 2	Level 1	Level 2	Level 3
5	Level 2	Level 2	Level 3	Level 1
6	Level 2	Level 3	Level 1	Level 2
7	Level 3	Level 1	Level 3	Level 2
8	Level 3	Level 2	Level 1	Level 3
9	Level 3	Level 3	Level 2	Level 1

Figure 2: Design Variables

Table 4: Design of Experiments Variables and Ranges

Design Variables	Units	Range	Level
A. Shotgun Profile Height	mm	115-145	15
B. Reinforcement Angle	deg	62-68	3
C. Front Side Rail Inclination	deg	6-12	3
D. Cowl Member Inner Distance	mm	60-100	20

On every virtual experiment, the ratio weight of front module to torsional stiffness has been measured. This way the two important characteristics can be linked in one response value. Analysis of means (ANOM) used to calculate the optimum value of each variable. The objective was to reduce the response ratio, therefore, the "smaller the better" analysis was performed in order for the effect of each variable on the response ratio to be obtained. The signal to noise ratios for each experiment and for each level have been calculated (Peace 1992):

$$\eta = -10 \log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{1}$$
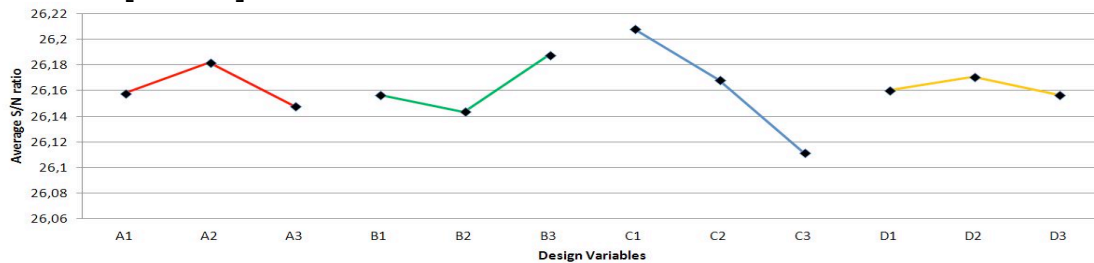

Figure 3: Response graph for each design variable

From the response graph in Figure 3 the maximum value of each design variable corresponds to the selected optimum value from the designated range. Table 4 shows the optimum combination in order for the bigger torsional stiffness value and simultaneously smaller weight value to be achieved.

Table 5: Optimum Combination of the Design Variables

Design Variables	Optimum Design Variables
Shotgun Profile Height	A2 (130mm)
Reinforcement Angle	B3 (68 deg)
Front Side Inclination	C1 (6 deg)
Cowl Member Inner Distance	D2 (80mm)

The optimum combination is translated to 36.909 kg of front module and a BiW torsional stiffness of 15604 Nm/deg. Moreover, the analysis of variance for the S/N ratio has been carried out as indicated in Phadke (1989), in order for the effect of each design variable in the response ratio to be determined. The results can be seen in Figure 4.
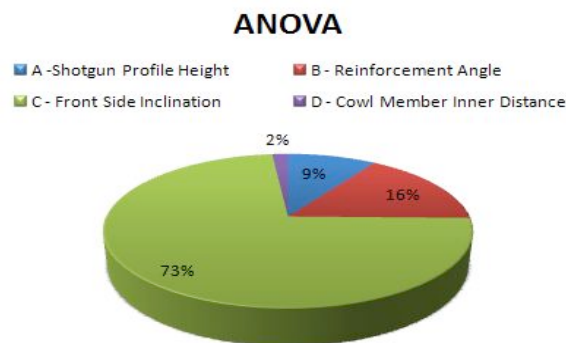

Figure 4: Analysis of Variance of the Experiments

4   RESPONSE SURFACE METHOD

In the frame of this work, a second degree polynomial model has been developed in order to examine the behaviour of the response around the discrete optimum which DoE has identified. With the second degree model it can be identified if the DoE's optimum is global or if there is another optimum, which cannot be identified with DoE due to the fact this method can only indicate results relative to the picked levels of each variable. Therefore new virtual experiments have been conducted.   The variables with the bigger influence to the response, according to ANOVA, had been chosen to be altered around the discrete optimum, which has been identified through DoE, while the rest are kept constant.

Table 6: Response Surface Method Experiments

Expt. No.	1	2	3	4	5	6	7	8	9	10	11	12
Reinforcement Angle	66	66	66	66	67	67	67	67	68	68	68	68
Front Side Inclination	6	7	8	9	6	7	8	9	6	7	8	9

The above experiments were used to develop a second order prediction model of the weight/torsional stiffness ratio. The regression coefficients of the second order polynomial equation have been calculated using regression techniques through Matlab.
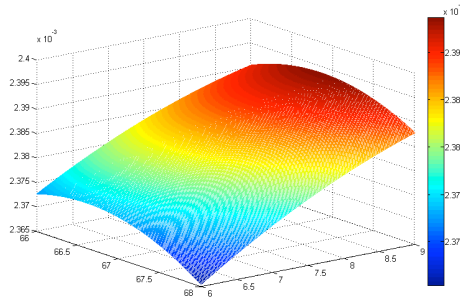

Figure 5: Response Surface Plot

The results showed that in this case the DoE optimum with the RSM optimum coincide. Finally the designer can use the representative second order polynomial equation (1) to take quick decisions at an early stage of the design process regarding the two most influential design variables.

$$y= -0.0000044525x_1^2 -0.00000086833333x_2^2 +0.000000783x_1x_2 +0.000588293749999x_1 -0.00032831033333x_2 -0.017141580833140$$

(2)

5   RESULTS

In this work, the front module of an integral designed BiW, had been re-designed under the prism of lightweight and flexibility. The followed workflow is described in Figure 6. Lightweight has been addressed at the level of conceptual lightweight design using an optimization strategy coupling DoE and RSM. Flexibility has been addressed through the manufacturing approach of the parts. Roll forming has been selected as a manufacturing process, as it is cheaper and more flexible than the hot stamping or deep-drawing. It has been achieved a 13.12% weight reduction in the front module and a 2.7% increase in the torsional stiffness of the whole BiW. With the optimization process , weight was kept almost the same (0.7% increase), and the torsional stiffness was further increased by 2.3%. A RSM has been conducted around the discrete DoE optimum to investigate if it is global or local. The result showed that DoE optimum and RSM optimum coincide.
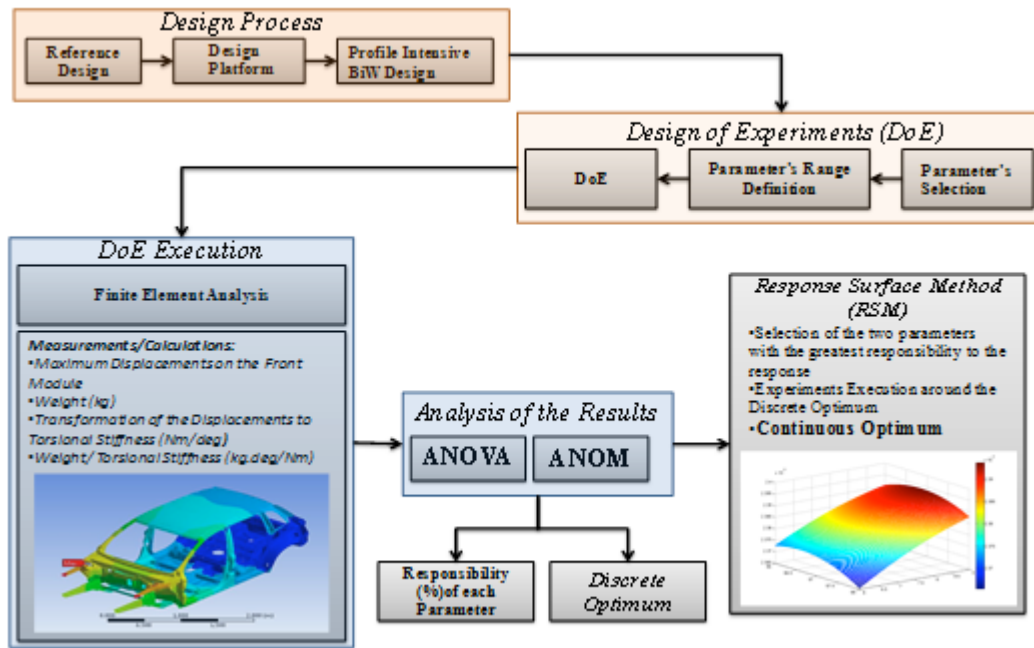
Figure 6: Design and Optimization Workflow

6   DISCUSSION: FURTHER RESEARCH

It is clear that a holistic approach to the design of cars has to be adopted in order to face the environmental and customer's behaviour challenges. Lightweight design and modularity can both help as concepts towards the solution. The work which has been conducted here, should be extend in the rest modules of the car in order to have a complete assessment of the profile design. Work for further research could be to use a multi-material concept for the BiW. Moreover, the impact of a multi-material approach to the production line should be examined. Finally, design maps with the influence of certain design variables to BiW quality characteristics can be developed and used from the designer as a tool to take early-stage decisions during the design process.

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