Title:
Quality Appearance Evaluation of Automotive Bodies: Effect of Flexible Parts Tolerances on Final Product's Surface Quality

Authors:
Ali Hashemian, a.hashemian@hsu.ac.ir, Hakim Sabzevari University
Behnam Moetakef Imani, imani@um.ac.ir, Ferdowsi University of Mashhad

Keywords:
Tolerance Analysis, Quality Appearance Evaluation, Finite Element Analysis, Surface Interrogation, Statistical Analysis

DOI: 10.14733/cadconfP.2015.112-116

Introduction:
Part tolerances have a crucial effect on the quality of products. In vehicle design, tolerance analysis is of central importance in quality appearance evaluation of automotive bodies and significantly taken into consideration by manufacturers. The relationship between input tolerances and assembly errors is analysed aiming at visualizing the quality of products and conducting quality audits based on statistical tolerance data. This paper evaluates the surface quality of a car's roof as one of the key quality characteristics in vehicle design (Fig. 1). Compared to previous research in the area of quality appearance evaluation of automotive bodies, which are based on the assumption of part rigidity [7-9], the current research proposes to include part flexibilities in the analysis. The rigid body analysis cannot account for part deformations and, therefore, some quality appearance issues will not be revealed. Some notable differences of rigid and non-rigid body analyses of sheet metal assemblies are represented in Tab. 1.

The presented methodology of this paper is classified into three main modules: finite element analysis, surface fitting and interrogation, and statistical analysis. The results of this study shows that input tolerances have a considerable effect on the surface quality of the final assembled product.

As illustrated in Fig. 1, the assembly process of the roof is the last stage of this body assembly and, therefore, all accumulated deviations from the previous stations should be defined as input tolerances. For simplification, it is presumed that the deviation of left and right side bodies from their nominal positions is the only input variation of the analysis. Since the main frame is much stiffer than the roof, this deviation will affect the roof shape and create some quality appearance issues in the final product.

Finite Element Analysis of Assembly Process:
Finite element analysis is one of the main steps in variation analysis of flexible sheet metal systems which aims at modelling the assembly process as close to reality as possible. Generally, the assembly process of sheet metal parts can be divided into four main steps: (1) locating the parts in desirable assembly position using fixtures; (2) clamping the components and moving the welding guns towards each other to close the gap between parts; (3) joining parts together by resistance spot-welding process; and (4) releasing the guns and clamps so that the assembly springs back. The process is schematically demonstrated in Fig. 2.

Fig. 3(a) demonstrates the example assembly of car body in ANSYS environment. The figure only shows those parts that have the most effect on the surface variation of the roof. Other components are excluded from the model and replaced with appropriate constraints in order to increase the analysis speed.

In this model, all body panels are produced by thin steel sheets with the thickness of 0.7mm and meshed by shell elements with Young's modulus and Poisson's ratio of 210GPa and 0.3, respectively. Clamps and welding guns, which are not shown in the figure, are generated with solid elements and assumed to be rigid since their stiffness is considerably larger than panels. If an initial inward deviation of 5 mm is applied to side bodies, it will result in a deformation contour as represented in Fig. 3(b) (dimensions are in millimetres).

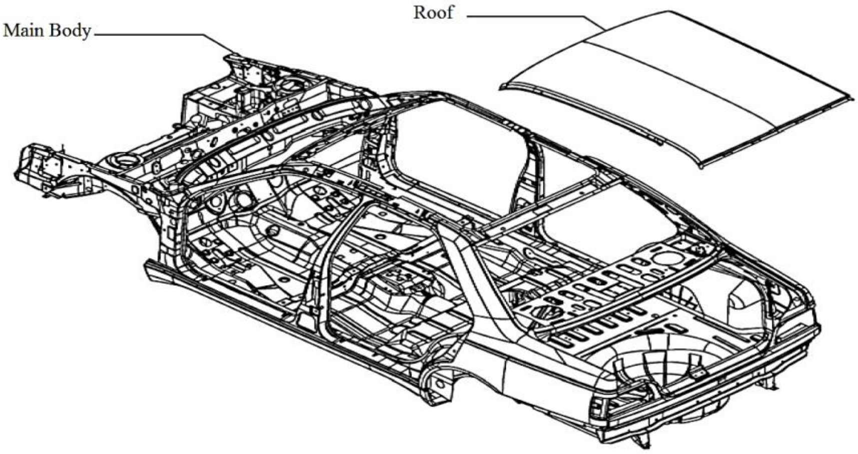

Fig. 1: Main car body components and roof before assembly, courtesy of IKKCO.

	Rigid body analysis	*Non-rigid body analysis*	*Remarks*
Reality simulation	Cannot represent actual assembly process	Is closer to reality and represents variations occurred during process	Sheet metal components are flexible and may deform during the assembly process
Relationship between variables	Geometric or kinematic formulation	Finite element analysis (FEA)	Some variables cannot be revealed in rigid-body analysis
Assembly force	No force is applied	Need to apply clamping forces	Applying assembly force causes part deformation

Tab. 1: Differences of rigid and non-rigid body analysis of sheet metal assemblies.

<u>Surface Interrogation:</u>
Surface interrogation is of principal importance for CAD applications. Wherever free-form surfaces are used, they often need to be analysed with respect to different aspects such as visual pleasantness, technical smoothness, geometric constraints or surface intrinsic properties. Surfaces in automobile design also need to be smooth and have nice reflection characteristics.

In this section, the parametric CAD model of the deformed roof will be generated from the FEA results. Based on surface quality analysis methods represented in [1, 3, 5], this paper proposes the quantitative and qualitative surface analysis approaches. The quantitative methods are related to differential geometry surface features like curvature distribution and fairness criterion. These features can then be used to statistically evaluate the surface variation and conduct quality audits of the final product. On the other hand, the qualitative approach refers to visualizing surface characteristics by means of highlight bands and reflection lines. The next topics of this section will represent more details regarding the above-mentioned methods.

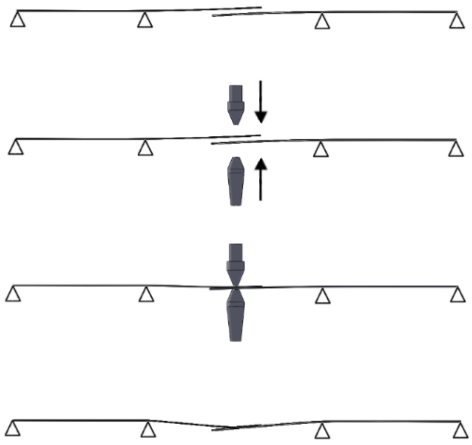

Fig. 2: Assembly process of compliant sheet metal parts [4].

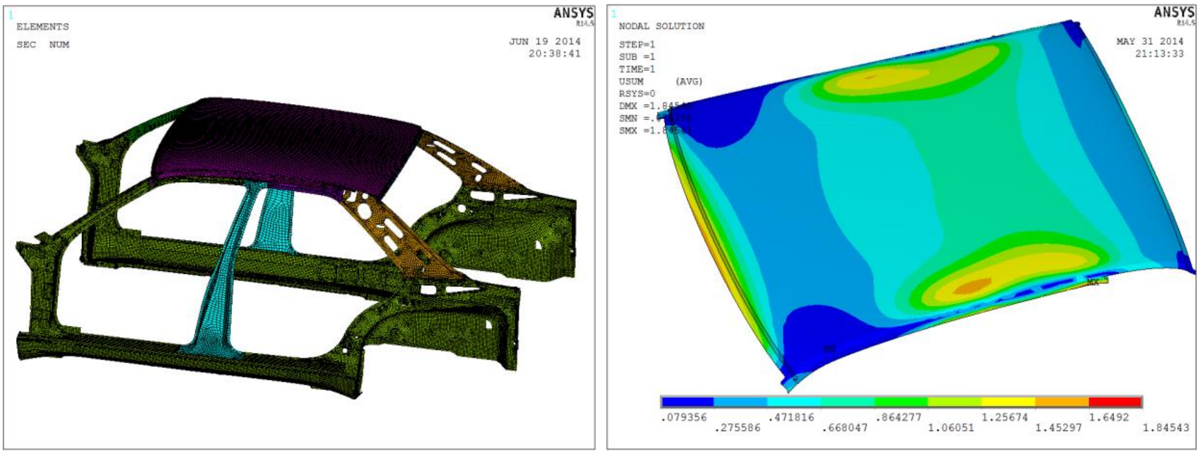

Fig. 3: (a) Example assembly of car body in ANSYS environment (b) Roof's deformation contour as a result of side bodies' deviation.

Curvature Distribution and Fairness Criterion

The first step in surface quality evaluation is to find a parametric CAD formulation for the surface. Automotive bodies are mainly designed by Bézier and B-spline surfaces which are common in many computer design applications. Generally, a B-spline surface of degree (p, q) with a bidirectional net of $(n+1) \times (m+1)$ control points defined as $S(u,v) = \sum_{i=0}^{n} \sum_{j=0}^{m} N_{i,p}(u) N_{j,q}(v) P_{ij}$ has infinite number of curvatures in different directions. The maximum (κ_1) and minimum (κ_2) of those values are principal curvatures of the surface and can be calculated as the roots of the following determinant [2]:

$$\begin{vmatrix} L - \kappa E & M - \kappa F \\ M - \kappa F & N - \kappa G \end{vmatrix} = 0 \tag{1}$$

where $= \boldsymbol{S}_u . \boldsymbol{S}_u$, $F = \boldsymbol{S}_u . \boldsymbol{S}_v$, $G = \boldsymbol{S}_v . \boldsymbol{S}_v$, $L = \boldsymbol{S}_{uu} . \boldsymbol{n}$, $M = \boldsymbol{S}_{uv} . \boldsymbol{n}$, $N = \boldsymbol{S}_{vv} . \boldsymbol{n}$ and $\boldsymbol{n} = \frac{S_u \times S_v}{\|S_u \times S_v\|}$.

Calculating fairness criterion is one of helpful quantitative approaches in surface interrogation. This method can represent a global value for the entire surface or local values for every desired portion of the surface. Since variation of curvature is usually of importance for designers, it is suggested in [6] to use the derivative of curvatures with respect to principal directions ($\boldsymbol{e}_1$ and $\boldsymbol{e}_2$) as follows.

$$I = \iint \left[\left(\frac{\partial \kappa_1}{\partial \boldsymbol{e}_1} \right)^2 + \left(\frac{\partial \kappa_2}{\partial \boldsymbol{e}_2} \right)^2 \right] dA \tag{2}$$

The above integral can also be used to minimize the variation of the surface and, therefore, it is referred to as minimum variation surface (MVS) criterion [6]. This fairness metric equals to zero for spheres, cones, cylinders, tori, and planes which are intrinsically fair. The MVS fairness factor for the nominal and deformed roof is calculated as 4.2×10^{-6} and 6.5×10^{-3}, respectively. The factor grows dramatically as a result of surface deformation. This calculation, however, is global and represents the fairness factor for the entire surface i.e. the integration interval is $0 \le u, v \le 1$. In order for the MVS factor to make more sense as a surface interrogation approach, it should be determined locally for smaller regions of the surface rather than being calculated globally for the entire surface. It helps find those regions in which there are surface deviations and classify regions based on their local fairness factor.

Highlight Bands

Compared to the aforementioned quantitative approaches to surface interrogation, qualitative methods are more natural and easier to comprehend. By simulating the effect of a realistic lighting environment, a simplified reflection or so-called highlight line can be introduced and expanded into the concept of highlight bands. The highlight band is interpreted as the imprint of a cylindrical light source on the surface and defined as the collection of all surface points for which the extended surface normal passes through the light source. The shape of this imprint is, therefore, governed by the surface variation.

The highlight bands for the nominal and deformed roof of current case study are compared in Fig. 4. For this purpose, a set of 15 cylindrical light sources with a radius of $r = 20\text{mm}$ are located equally-spaced at the height of 700mm above the surface. All light sources have a 20° rotation with respect to the longer edges of the roof. The figure also illustrates, by means of colour intensity, the areas of the deformed roof at which the local MVS factor is extremely larger than the others. The maximum local MVS value for the deformed roof is 1.68×10^{-6} while it is 2.92×10^{-8} for the same region in the nominal surface. It is inferred that the fairness metric in the deformed roof is maximum at the middle of the longer edges where the highlight bands show some irregularities. The results are also well consistent with finite element simulation.

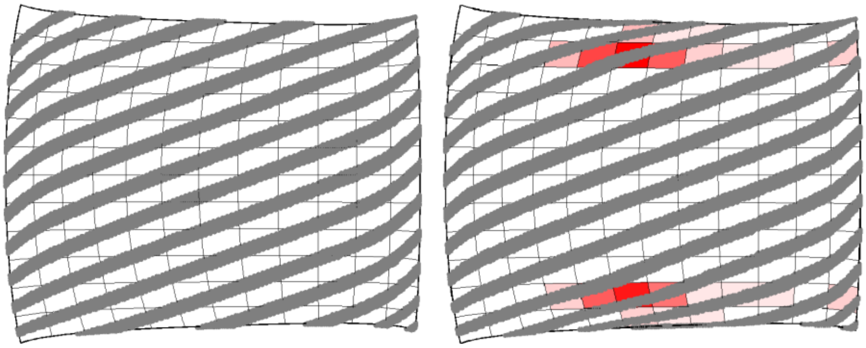

Fig. 4: Highlight bands of nominal (left) and deformed (right) roof.

Statistical Analysis:

In the current research, the quality appearance of the roof is evaluated by local MVS fairness criterion. Hence, the assembly's feature of interest can be defined as the maximum local MVS value for the deformed surface while the initial deviation of side bodies from their nominal position is the input random variable. Based on the experimental data obtained from the assembly line, both left and right bodies have a same deviation between 2 and 5mm. It should be noted that this is a $\boldsymbol{3\sigma}$ variation limit and, in mass production, almost 70 percent of values are located within the range $\boldsymbol{\mu \pm \sigma}$.

The statistical specifications of the assembly's quality appearance metric i.e. the maximum local MVS of the deformed roof is calculated probability analysis and tabulated in

Tab. **2**. The result of this analysis is also benchmarked against Monte Carlo simulation of the assembly process of 10,000 vehicles. For this purpose, a routine is written in MATLAB software which creates random input values for side bodies' deviation, calls ANSYS automatically to apply finite element analysis and calculates the fairness criterion of the deformed roof. The results show that the developed methodology of this paper is in a great accordance with Monte Carlo simulation.

	Mean (μ)	*Standard deviation* (σ)	*Skewness* (γ_1)	*Kurtosis* (β_2)
Statistical analysis	0.6174×10^{-6}	0.1982×10^{-6}	0.4839	3.3140
Monte Carlo simulation	0.6168×10^{-6}	0.1970×10^{-6}	0.4852	3.3131

Tab. 2: Statistical specifications of assembly's quality factor.

Once the statistical specifications are calculated, the Pearson system indicates that the assembly's quality appearance metric has a beta distribution. The distribution is, in this case, very close to a normal distribution with a slight skewness to the right (in a normal distribution $\gamma_1 = 0$ and $\beta_2 = 3$). Using the statistical distribution of the quality appearance metric, designers could assess the effect of input tolerances to the final assembly variation. It is also possible to define an acceptance limit for the maximum MVS value and find those assemblies which violate the limits.

Conclusions:
In this research, the quality appearance of automotive bodies is evaluated as a function of parts' or subassemblies' tolerances. The paper proposes to use a fairness criterion in order to determine the surface quality of body panels. In comparison to previous research works in the area of aesthetical assessment of automotive bodies, which are based on the assumption of part rigidity, the current research proposes to include part flexibilities in the analysis. As a case study, the surface quality of a car's roof, which is one of the key quality characteristics in vehicle design, is statistically evaluated in this research. The results of this quality appearance evaluation shows that input parts' or subassemblies' deviation have a significant effect on the surface quality of the final assembly.

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