

Development of Evaluation Method for Automotive Outer Panel Surface Distortion Using Curvature Difference and Application to Body Design

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ABSTRACT

A quantitative evaluation method that correlates with human visual inspection is important in helping to predict outer panel surface distortion that may occur in the development phase of the automobile manufacturing process. This study proposes a quantitative evaluation method for distortion using curvature difference, in order to determine specifications through predictive simulations in the development phase. Curvature refers to the rate of change of the slope of a curved surface. The degree of distortion can be quantified by defining the difference in curvature between the standard shape and distorted areas as the curvature difference. The proposed method achieved reliable correlation between outer panel surface distortion and visual evaluation. Therefore, by incorporating curvature difference as one criterion in design phase simulations, it can be utilized as a consistent evaluation index from development to the manufacturing site. This paper reports the details and effectiveness of this evaluation method.

1. Introduction

Initiatives using digital development environments to shorten development periods and enhance quality and performance in automobile development are currently accelerating. In body development, these initiatives include defining specification requirements through design drawings, establishing control standards in the manufacturing process, and conducting simulations for a wide range of performance criteria such as rigidity, crash safety performance, strength, durability, and NVH (noise, vibration, harshness). Simulations have also been introduced to manufacturing processes such as press forming, welding, and painting, while developments in model-based development (MBD) and digital twin technology are further advancing simulation technology for body development. The authors previously developed a simulation technology capable of predicting outer panel surface distortion⁽¹⁾ by having design, manufacturing, and materials departments cooperate and handle factors related to outer panels in an integrated manner. However,

visual evaluation is a key element of distortion inspection at manufacturing sites, and the remaining issue was that dimension-based prediction results from simulations did not match on-site visual judgments in some cases. This made it necessary to develop a method capable of quantitatively evaluating distortion without relying on visual evaluation, and to incorporate that method into simulations.

Human vision is sensitive to disturbances in surface smoothness and continuity, as well as discontinuous and sudden changes in curvature. For example, the sense of incongruity when the reflection of light changes in an unnatural manner, or when a continuous image bends, is due to the sudden change in curvature that negatively impacts the smoothness perceived by humans^{(2), (3)}. Especially on glossy surfaces such as automotive outer panels, even slight unevenness can change the reflection of light, greatly impacting visual evaluation. Past methods for quantification and evaluation of distortion are listed below, but each faces challenges, and they have not been put to practical use in Honda body development.

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- (1) Evaluation based on dimensional differences through non-contact 3D measurement⁽⁴⁾⁻⁽⁶⁾

While this method is able to capture fine surface waviness with high precision, correlation between visual evaluation of light waviness and bending by the human eye and evaluation by non-contact 3D measurement has not been demonstrated, making it a challenge to set distortion amounts that match visual evaluation.

- (2) Evaluation using curvature^{(7),(8)}

Similar to the evaluation method in (1) above, the distribution of surface distortion is quantitatively evaluated by measuring the 3D shape of the outer panel surface and calculating the surface curvature and changes in the curvature. However, due to their design, the design surfaces representing the final product shapes described in the product drawings addressed in this paper inherently have large curvatures or changes in curvature. Therefore, small changes in the curvature due to outer panel surface distortion become buried in the curvature of the original design surface, making it a challenge to extract only the curvature of distorted areas as extreme values.

- (3) Line-scan measurement using a profiler

Differences in the height of the surface over a certain measurement length are continuously measured using contact or non-contact surface profilers, and utilized to quantify the surface distortion. However, measurement as a surface is not possible, making it a challenge to evaluate wide areas such as actual panels.

Therefore, the goal of this study was to develop a new quantitative evaluation method in which the prediction results of outer panel surface distortion simulations match on-site visual evaluation.

2. Development Goals

To evaluate outer panel surface distortion, it is necessary to establish criteria to serve as judgment standards, and this calls for quantification of outer panel surface distortion. This paper focuses on a quantification method that examines the difference in curvature between the design surface and the outer panel surface after deformation in the body manufacturing process. The reason that humans are able to visually perceive distortion is that the reflection changes unnaturally, the result of a sudden change in curvature partway along a smooth transition in curvature. Therefore, it was thought that areas with distortion could be effectively extracted by identifying the difference between the original curvature and the curvature that contains distortion. First, human visual evaluation was correlated with the calculated curvature difference values for actual vehicle outer panels. Next, the design specifications were investigated in simulations, using the quantitative index established based on this correlation as criteria. Lastly, validity was verified by comparison with actual vehicles manufactured using design specifications that are effective against distortion.

3. Method for Quantification of Outer Panel Surface Distortion

The principle of using curvature difference to quantify outer panel surface distortion is described below. When a certain curve on the xy coordinate plane is represented as $y = f(x)$, the x direction curvature κ is defined by Eq. (1). Labelling the curvature of the design surface as κ_1 and the curvature of the surface that contains distortion as κ_2 , the difference between the two given by Eq. (2) is defined as the curvature difference $\Delta\kappa$.

$$\kappa = \frac{f''(x)}{(1+f'(x)^2)^{3/2}} \quad (1)$$

$$\Delta\kappa = \kappa_1 - \kappa_2 \quad (2)$$

Figure 1 shows an example using a simple curve. Figure 1(a) is the curve intended by the design, and Fig. 1(b) is a curve distorted in one area compared to the design curve. The two curves are nearly indistinguishable on the graphs. Next, Fig. 1(c) and (d) respectively show the curvature distribution of both curves, and here too, the presence of distortion cannot be determined from the curvature distributions. However, when the difference in curvature distribution is obtained and plotted as shown in Fig. 1(e), the extreme value of the difference in curvature distribution appears at the distortion location. If it can be demonstrated that the calculated curvature difference results and human visual evaluation are correlated, this would enable quantitative evaluation.

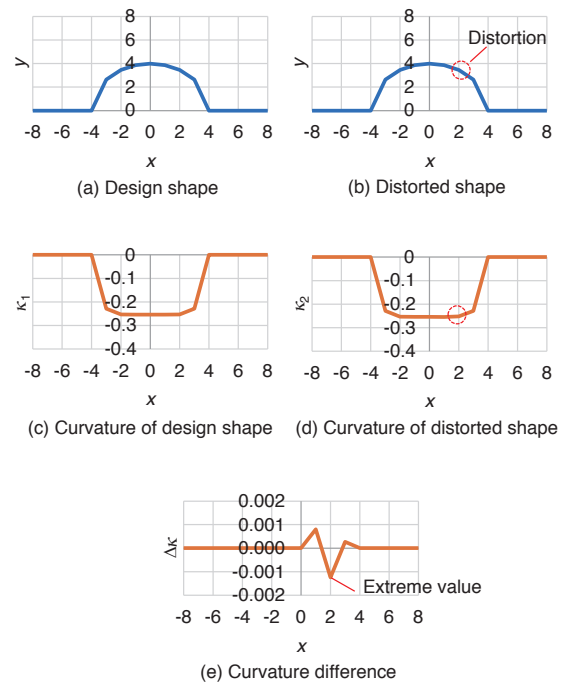


Fig. 1 Example of distortion extraction using curvature difference

4. Proof of Principle Using Actual Vehicles

4.1. Method for Calculating Curvature Difference Using Actual Vehicle Measurement Data

The curvature difference of the outer panels of actual vehicles was calculated to investigate the correlation between quantitative values based on the curvature difference of outer panel surface distortion and visual evaluation. This paper used optical scanning by GOM GmbH (measurement device: ATOS 5X) to measure the 3D shape data of actual vehicles. The data was output as random mesh data with an average mesh size of 1 mm. Figure 2 shows the curvature difference calculation flow. To calculate curvature difference from the outer panel shape data, the overall process was divided into four steps.

•Step 1: Acquisition of 3D mesh data

The panel surface to evaluate distortion was arranged parallel to the xy -plane as data on an xyz -axis 3D coordinate system, and the design data was converted from CAD data to mesh data.

Optical scanning measurement data was used as the 3D data of the actual vehicles.

•Step 2: Conversion to equal-interval mesh data

x and y coordinates were spaced at equal intervals on the random mesh data, and linear interpolation was performed for the z coordinates corresponding to those xy coordinates.

•Step 3: Calculation of curvature difference

The first and second derivatives in the x -direction of the design and measurement data were calculated using the central difference method, and the curvature κ_1 of the design data in the x -direction and the curvature κ_2 of the measurement data in the x direction were calculated. Finally, the difference between curvature κ_1 and curvature κ_2 was obtained and used as the curvature difference $\Delta\kappa$.

As described hereafter in Section 4.2., this paper focused on the roof panel, roof side, and side sill to confirm the correlation between visual evaluation and curvature difference. Therefore, the longitudinal direction of each area was aligned with the x -axis, and in consideration of past situations where distortion appeared, evaluation was performed only for the x -direction.

•Step 4: Mapping of curvature difference

The calculated curvature difference values were visualized by mapping to the mesh data coordinates set in step 2. In order to intuitively grasp the tendencies of the

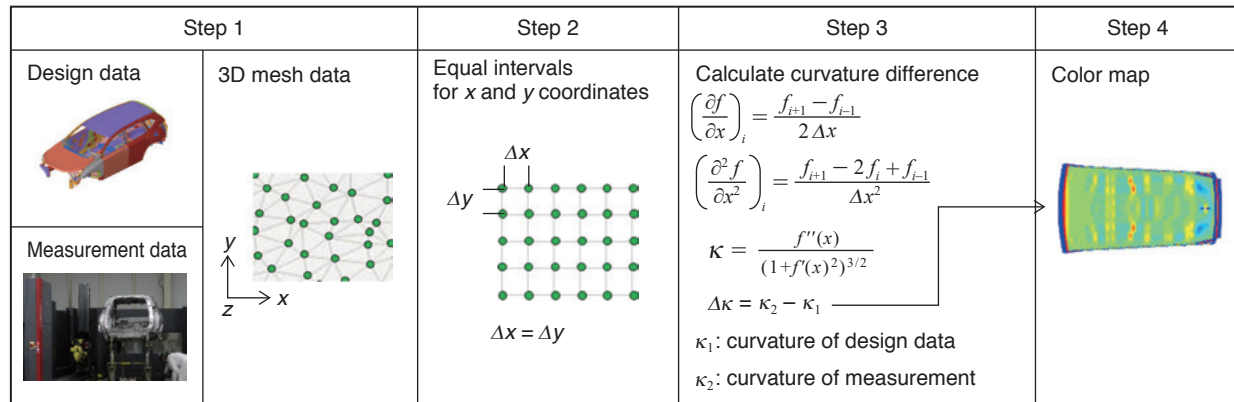


Fig. 2 Curvature difference calculation flow

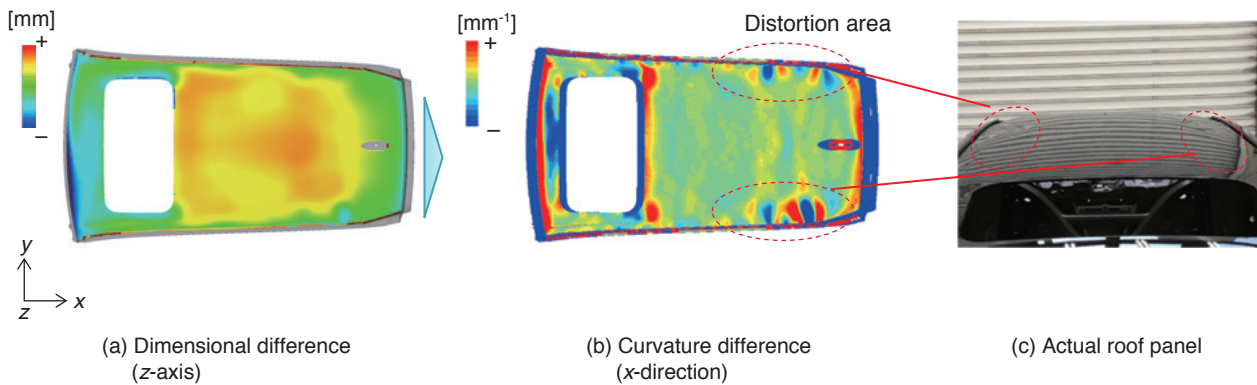


Fig. 3 Example of dimensional difference and curvature difference in measurement data

deformation, the signs of the curvature difference were defined as positive in the convex direction and negative in the concave direction relative to human vision, and displayed using a color map.

Figure 3 shows the results of calculating and color mapping the dimensional difference and curvature difference of an actual roof panel. The displacement in the z-axis positive direction at the center of the roof panel can be confirmed in (a), but there are cases where areas with large dimensional difference may not be visually recognized as distortion. This is because while the dimensional difference indicates the displacement between the design and measurement data, local deformation and waviness resulting in visual unnaturalness also exist as small displacement, and that small displacement becomes buried, making it a challenge to capture. In contrast, the waviness at the roof edges is clearly extracted in the curvature difference (b), and was confirmed to be consistent with the distortion areas in the photograph (c). This showed that curvature difference is highly correlated with visual evaluation, and is an effective evaluation index close to visual inspection.

4.2. Verification of Correlation between Visual Evaluation and Curvature Difference

To confirm the correlation between visual evaluation and curvature difference, verification was conducted using five sample vehicles prepared with varying degrees of distortion. The prepared vehicle types included two sedans and three SUVs with large outer panel areas prone to distortion. For visual evaluation, the points where the curvature difference values are extreme values were extracted in advance for the three areas of the roof panel, roof side, and side sill, as shown in the examples in Fig. 4. Those points were visually scored using the 10-point scale shown in Table 1, and a score of 6 or more was defined as borderline acceptable for

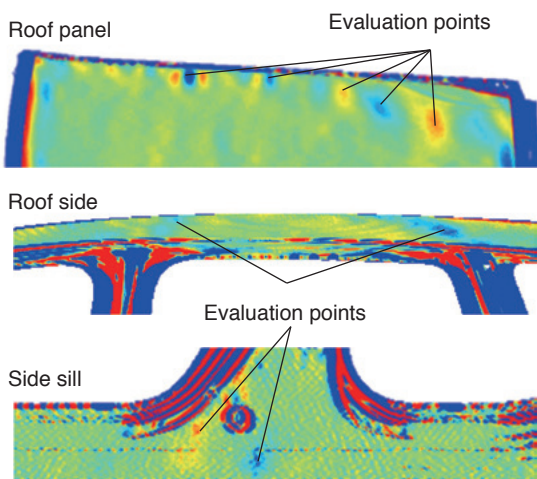


Fig. 4 Example images of visual evaluation points

Table 1 Visual evaluation scores

Score	Judgement	Reactions
10	EXCELLENT	No distortion
9	VERY GOOD	Undetectable even by experts
8	GOOD	Detectable by experts
7	ACCEPTABLE	Recognized but acceptable by experts
6	BORDERLINE	Acceptable but noticeable if customers pay attention
5	UNACCEPTABLE	Detectable by customers
4	UNACCEPTABLE	Complaint
3	POOR	Strong complaint
2	VERY POOR	Repair request
1	N/A	Rejection

a mass-produced product. Evaluation was conducted in an inspection environment with fluorescent lights arranged at equal intervals to facilitate detection of distortion by changes in light reflection. 55 expert inspectors scored the extracted points, and the average value was used as the score. These scores were compared with the curvature difference values at each point to confirm the correlation.

Figures 5, 6, and 7 show the respective confirmation results for the roof panel, roof side, and side sill. The vertical axis of the graphs represents the visual evaluation, and the horizontal axis represents the curvature difference. The relationship between the average value of the visual evaluation scores and the curvature difference at the points shown in Fig. 4 is plotted for each vehicle type. Regarding the side sill in Fig. 7, the sedan models use resin garnish parts, so these were not evaluated, and only the SUV plots are shown.

The results clearly show a tendency in which the lower the visual evaluation score, the greater the absolute value of the curvature difference for any outer panel area, confirming the expected correlation. The acceptable criteria range differed for each of the roof panel, roof side, and side sill, which is thought to be due to differences in the curvature of the design for each area. When the curvature of the design surface is small, that is to say a smoother surface, it is easier to visually detect distortion even if the curvature difference is small. Conversely, when the curvature of the design surface is large, it may be a challenge to visually detect distortion even in case of a large curvature difference. Based on this result, human vision and a quantitative index of distortion in actual vehicles can be correlated by setting the range of curvature difference resulting in a visual evaluation score of 6 points or more as the criteria for distortion. These criteria enable comparison using simulations, as well as investigation of potential factors in the event of issues, and accurate predictions when making design changes.

These criteria were established to cover the outer panels of a wide range of existing models, and are considered capable of accommodating even the development of new models. However, efforts are needed to further enhance accuracy by accumulating more detailed data in preparation for the appearance of greatly differing designs as bodies evolve going forward.

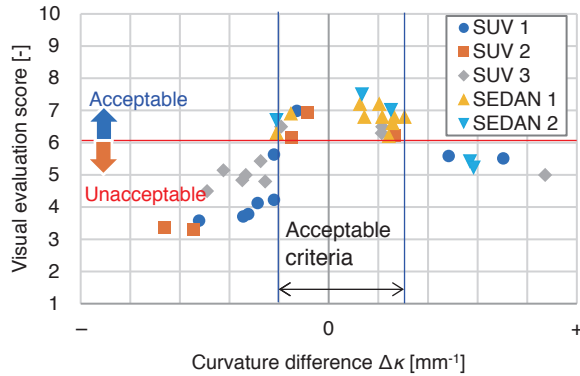


Fig. 5 Correlation between visual evaluation scores and curvature difference of roof panel

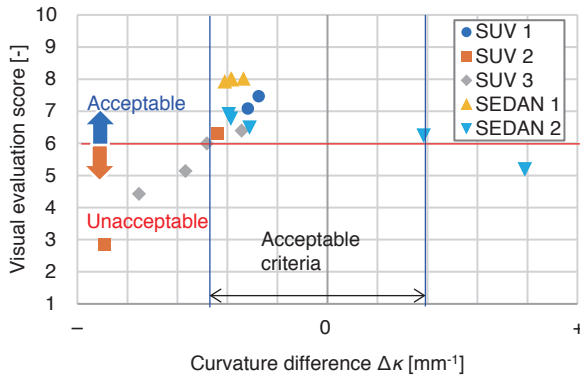


Fig. 6 Correlation between visual evaluation scores and curvature difference of roof side

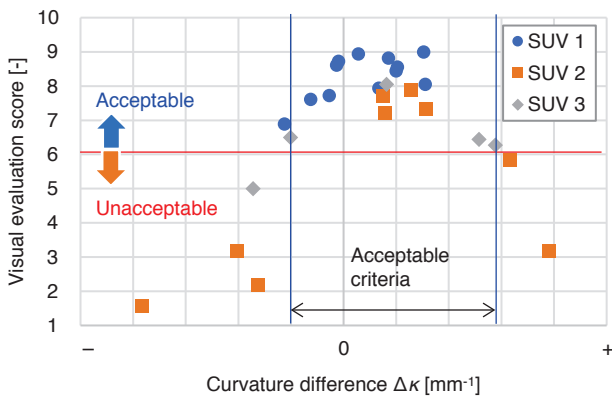


Fig. 7 Correlation between visual evaluation scores and curvature difference of side sill

5. Application to Simulation

Figure 8 shows an example of the design process for reducing distortion in the roof of the 2022 model year CR-V. The roof edges have spot welds between the body frame and the roof panel, making these locations relatively susceptible to distortion. Figure 8(a) and (b) compare the results of curvature difference calculated by predictive simulations of outer panel surface distortion based on two design proposals: a first design and a resistance-enhanced design. In the first design (a), welding of the weld flanges resulted in displacement and distortion in the visible area of the roof, and the curvature difference in the red areas did not meet the acceptable criteria. As the design for enhancing resistance (b), the dimensions of the two cross-sectional shapes of the visible surface and the vertical face were considered within the range that does not negatively impact other design requirements such as press formability, functionality, and aesthetics. For the visible surface, the curvature was reduced and the rigidity was increased. For the vertical face, a two-step shape was established and the dimensions were set so that deformation in welding does not easily extend to the design surface. As a result, the curvature difference values were confirmed to be within the acceptable criteria.

Figure 9 shows the curvature difference measurement results for the actual vehicle roof. The design with enhanced distortion resistance (b) was confirmed to fall within the acceptable criteria range.

The above results show that by quantifying distortion using curvature difference, it is possible to demonstrate congruity between predictive simulations of outer panel surface distortion in the design phase and the actual body.

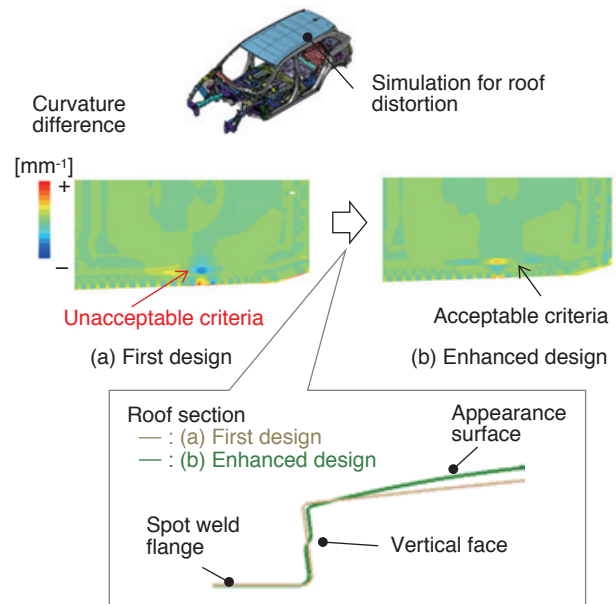


Fig. 8 Design process to reduce distortion in roof

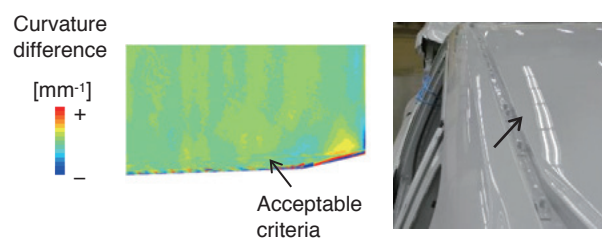


Fig. 9 Measurement of actual roof curvature difference

6. Conclusion

Curvature difference was used to establish a quantitative index correlated with human vision in order to achieve a quantitative evaluation method for distortion, which is needed to develop simulation technology for body outer panel surface distortion. Establishment of a calculation process that enables the calculation of differences in curvature between actual measurements and simulation mesh data made it possible to verify specifications using simulation data. This calculation process can be used together with predictive simulations of outer panel surface distortion in actual development sites, and will enable the development of technology for enhancing the efficiency of vehicle body development.

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