An Application of Shape Similarity Recognition Using PCA based Dimensional Compression

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1 Introduction

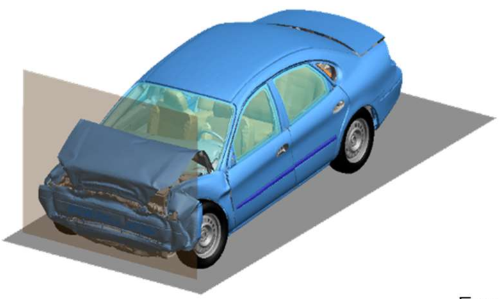
In recent years, the demand for faster product development has been increasing year after year. In addition, as requirements and their levels become more sophisticated, data-driven development that makes use of past data is attracting attention.

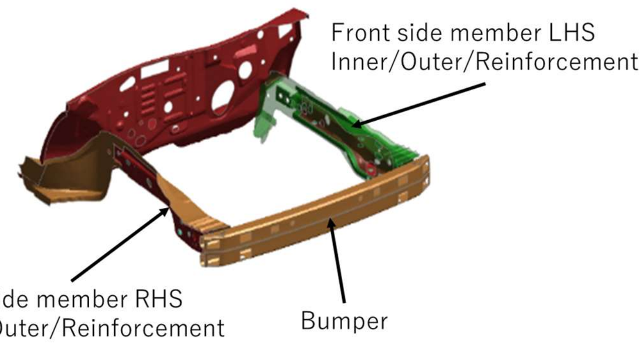
Compared to experiments, simulations are characterized by the ease of retaining data that can be used for analysis, but this creates the problem of handling huge amounts of result data. In order to overcome this challenge, we propose a method to detect similar behaviors based on the distance in the modal space obtained from the animation results of past calculations with a reduced dimension reduction technique (1).

2 Problem definition

In this study, the Ford Taurus model developed by the U.S. Collision Safety Analysis Center (2) was used, and the load case was a full-flat frontal crash. The load case is shown in Figure 1(a). In the development of a vehicle structure, the geometry of the vehicle is important to improve its performance. In this study, the thickness of 8 parts has been varied as shown in Table 1.

Version control was conducted when making changes to the design. The first calculation is version 1 (V01), and each time the model is modified after that, the version is incremented one by one.





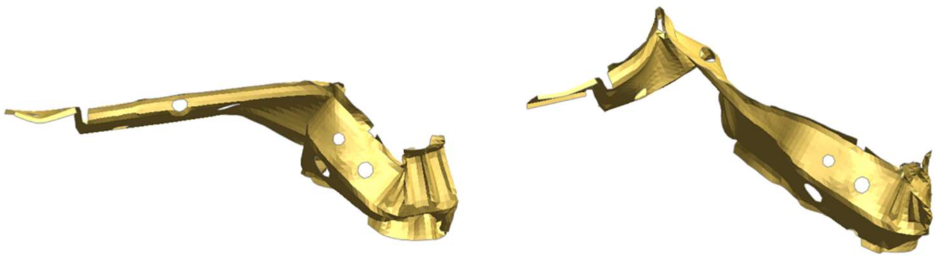
(a) Vehicle model in full-width frontal crash (b) Parts modified in this study

Fig.1: The model used in this study

Part Name	V01	V02	V03	V04	V05	V06	V07	V08	V09	V10	V11	V12	V13	V14	V15	V16	V17	V18	V19	V20
Outer L	1.8	1.8	1.7	1.6	1.8	1.7	1.7	2.1	2.0	2.2	1.6	1.5	2.2	2.2	1.8	1.8	1.6	1.9	2.2	1.6
Inner L	2.3	2.3	2.4	1.4	1.6	2.1	1.6	2.3	2.1	1.6	1.9	2.4	2.4	2.2	2.2	2.3	2.3	2.4	1.8	2.0
Reinforce-L	2.0	2.3	2.5	2.3	2.5	2.1	2.5	2.2	2.4	2.3	2.6	2.9	2.4	2.9	2.0	1.9	2.7	2.5	2.6	2.9
Outer R	1.9	2.1	2.3	1.8	1.5	2.3	1.6	1.8	1.5	1.4	2.1	2.3	2.4	1.9	2.1	1.9	2.0	2.1	1.7	1.5
Inner R	1.8	2.2	2.3	2.3	2.4	2.4	2.1	2.2	1.8	1.6	1.5	2.2	1.8	1.9	1.7	2.1	1.4	2.3	2.1	2.0
Reinforce-R	2.1	2.4	2.1	2.3	2.8	2.3	2.6	2.6	2.8	2.9	2.8	2.0	2.5	2.7	2.4	2.3	2.8	2.9	2.5	2.1
Bumper	1.0	1.0	1.1	1.7	1.4	1.6	0.9	1.5	0.8	1.1	1.2	1.6	1.7	0.9	1.3	0.7	1.0	0.9	1.3	1.0
Firewall	0.9	1.1	1.0	0.9	0.7	1.2	0.6	1.2	0.9	0.7	0.9	0.9	1.0	1.0	1.1	0.8	0.8	1.1	0.8	0.8

Table 1: Design table (thickness of the part [mm])

In the course of structural modification during the development of the vehicle structure, an undesired change in the deformation mode of the front side member during a collision is assumed, as shown in Figure 2, to verify whether the proposed method can detect similar cases easily in previous versions of the vehicle.



(a) Favorable deformation mode (b) Unfavorable deformation mode

Fig.2: Deformation modes of the front side member on the left hand side

2.1 Proposed Approach

2.1.1 Shape Feature Extraction by Mode Decomposition

Assuming the mean and variance of the nodal coordinates obtained from n times of calculations are calculated at a specific time of a two-dimensional transient phenomenon.

The mean value μ_{x_i}, μ_{y_i}, and covariance σ_{x_i, y_j} can be obtained as equations (1)-(3), where x coordinate of node ID i is $x_{i(k)}$ and y coordinate of node ID j is $y_{j(k)}$ in run ID k.

$$\mu_{x_i} = \frac{1}{n}\sum_{k=1}^{n} x_{i(k)} \tag{1}$$

$$\mu_{y_j} = \frac{1}{n}\sum_{k=1}^{n} y_{j(k)} \tag{2}$$

$$\sigma_{x_i, y_j} = \frac{1}{n}\sum_{k=1}^{n}\left(x_{i(k)} - \mu_{x_i}\right)\left(y_{j(k)} - \mu_{y_j}\right) \tag{3}$$

Extending the above discussion to three dimensions, the variance and covariance of the coordinate components (x, y, z) of all m nodes, in addition to the mean value, are calculated separately and summarized as the variance-covariance matrix C given in Equation (4). This aggregates information on the mean of the nodal coordinates of the structure at a given time, the variation of individual nodes, and the correlation between the nodal variations.

$$C = \begin{bmatrix} \sigma_{x1,x1} & \sigma_{y1,x1} & \sigma_{z1,x1} & & & & \\ \sigma_{x1,y1} & \sigma_{y1,y1} & \sigma_{z1,y1} & \cdots & & & \\ \sigma_{x1,z1} & \sigma_{y1,z1} & \sigma_{z1,z1} & & & & \\ & \vdots & & \ddots & & \vdots & \\ \sigma_{x1,xm} & \sigma_{y1,xm} & \sigma_{z1,xm} & & \sigma_{xm,xm} & \sigma_{ym,xm} & \sigma_{zm,xm} \\ \sigma_{x1,ym} & \sigma_{y1,ym} & \sigma_{z1,ym} & \cdots & \sigma_{xm,ym} & \sigma_{ym,ym} & \sigma_{zm,ym} \\ \sigma_{x1,zm} & \sigma_{y1,zm} & \sigma_{z1,zm} & & \sigma_{xm,zm} & \sigma_{ym,zm} & \sigma_{zm,zm} \end{bmatrix} \tag{4}$$

Eigenvalues and eigenvectors are obtained by solving an eigenvalue problem on the covariance matrix. The eigenvalues are represented as the standard deviations and indicate the size of the spread of variation in a 3m-dimensional space, while the eigenvectors indicate the directions of the scatter. The nodal group of each result can be represented as a linear superposition of eigenvectors, and each result is represented as a point in the eigenmode space defined by the eigenvectors [3] [4].
Figure 3 shows the result of projecting a set of calculation results into the mode1-mode2 space. If the result to be used as the reference for comparison is k_1 and the result to be compared is k_2, the discrepancy of the shapes can be measured as the distance d_{mode} in the modal space.

$$d_{mode} = \sqrt{(m1_{k2} - m1_{k1})^2 + (m2_{k2} - m2_{k1})^2} \tag{5}$$

When d_{mode} is small, two shapes can be said to be similar, and when d_{mode} is great, two shapes are considered to be divergent. When considering a certain transient response, the same structure is expected to have similar shapes at the same time, so the point cloud is expected to be dense to some extent. However, if a design change causes a difference in behavior, new points will diverge from the group on the plot, and the d_{mode} value will increase. This method enables engineers to evaluate how much each member deviates from or is similar to the previously calculated results by calculating d_{mode} value.

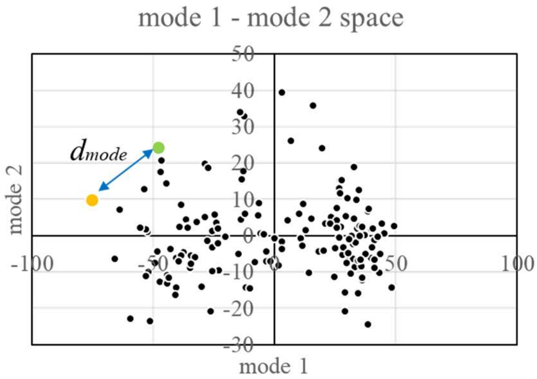


Fig.3: A cloud plot of simulations on the modal space

2.1.2 Feature extraction of shapes by modal decomposition

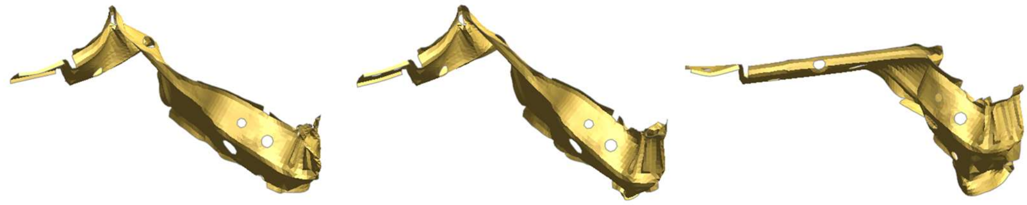
Given the calculation results of V01-V19 for the engine room with design changes, a new calculation of V20 is performed, and the behavior shown in Figure 2(b) is observed. Figure 4 shows the results of a modal space search for the geometry of all model versions at each time using this proposed method with the target side member's part ID and target time as inputs. The columns indicate each version of the model and the rows indicate the time step.

time[s]	V01	V02	V03	V04	V05	V06	V07	V08	V09	V10	V11	V12	V13	V14	V15	V16	V17	V18	V19	V20
0	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
0.01	0.16	0.16	0.16	0.15	0.16	0.16	0.16	0.15	0.16	0.16	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.16	0.16
0.02	0.16	0.17	0.17	0.15	0.17	0.17	0.16	0.15	0.17	0.17	0.15	0.17	0.15	0.17	0.17	0.17	0.17	0.17	0.16	0.16
0.03	0.17	0.22	0.17	0.12	0.16	0.20	0.16	0.15	0.10	0.12	0.22	0.20	0.14	0.10	0.24	0.14	0.18	0.11	0.13	0.24
0.04	0.13	0.26	0.14	0.10	0.15	0.47	0.15	0.14	0.20	0.13	0.55	0.23	0.12	0.17	0.49	0.21	0.15	0.10	0.09	0.66
0.05	0.17	0.30	0.17	0.24	0.26	0.65	0.30	0.19	0.18	0.19	0.69	0.30	0.20	0.18	0.65	0.26	0.14	0.16	0.20	0.82
0.06	0.22	0.31	0.23	0.24	0.28	0.65	0.34	0.21	0.17	0.21	0.68	0.32	0.19	0.16	0.66	0.21	0.12	0.18	0.19	0.77
0.07	0.23	0.32	0.24	0.25	0.28	0.63	0.35	0.20	0.17	0.22	0.65	0.33	0.19	0.16	0.65	0.21	0.12	0.18	0.20	0.75
0.08	0.23	0.32	0.24	0.25	0.28	0.62	0.36	0.19	0.18	0.23	0.64	0.34	0.19	0.16	0.64	0.21	0.11	0.16	0.21	0.75
0.09	0.23	0.32	0.24	0.25	0.28	0.62	0.36	0.18	0.18	0.23	0.66	0.34	0.19	0.16	0.64	0.20	0.11	0.15	0.21	0.77
0.1	0.22	0.32	0.23	0.24	0.28	0.64	0.36	0.17	0.16	0.19	0.72	0.34	0.17	0.12	0.66	0.19	0.10	0.11	0.19	0.82
0.11	0.19	0.33	0.21	0.23	0.28	0.72	0.36	0.17	0.13	0.16	0.85	0.39	0.20	0.08	0.73	0.16	0.10	0.07	0.15	0.93
0.12	0.18	0.35	0.18	0.25	0.28	0.85	0.38	0.17	0.14	0.15	0.91	0.54	0.18	0.09	0.80	0.17	0.11	0.06	0.13	1.00

Fig.4: The similarity scale of the part of interest through the development

The numerical values in each cell in Figure 4 represent the shape similarity calculated based on the distance in the modal space on a scale of 0 to 1, where 1.00 indicates that the shapes are identical to each other. Variation of similarity score is also observed within the same run. This indicates that the part is moving from the initial shape to the final deformed state by collision events. The analysis results suggest that V06, V11, and V15 are similar, and V11 is most similar to V20.

Figure 5(a) and (b) show the results of the shape comparison of V11 and V20 at the final timestep, and Figure 5(c) shows V18, which has the lowest similarity, as a reference. As shown in the figure, the shape obtained using this method, Figure 5(b), captures the characteristics of the side member behavior of the referenced V20 quite well, thus demonstrating the validity of this methodology.



(a) V20 (reference) (b) V11 (c) V18

Fig.5: Search results using the proposed method

3 Summary

In this paper, a distance-based shape similarity retrieval method in the modal space is demonstrated with the side-member deformation mode in automotive crashworthiness analysis. The method uses all the nodes of the part and recognizes the shape as a mode, so there is no need to pre-install sensors such as search tags or to use special tools such as parametric CAD.

This method becomes most effective when version control and documentation are fully maintained on the simulation data management system in the product development process. In the case presented in this paper, an unwanted change of mode occurred due to the change from V19 to V20. However, using this method, enabled us to find out quickly that a similar situation had already occurred in V06, V11, and V15 in the past.

If the analysis of the causes of past cases and countermeasures are documented in conjunction with model version information, it becomes possible to avoid reinventing the wheel and focus only on effective countermeasures by referring to them.

As the demands for reducing development time and man-hours grow, it will become increasingly important to quickly identify problems using anomaly detection technology [(1)] and to make effective use of past knowledge using methods to search for similar behavior.

4 Acknowledgment

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5 Literature

[1] M. Okamura, Anomaly Detection Method of Body Deformation Shape in Vehicle Frontal Collision Using Eigen Mode Decomposition, 34th Computational Mechanics Conference, 2021

[2] National Crash Analysis Center: Finite Element Model Archive, http://www.ncac.gwu.edu/vml/models.html

[3] R. Brown, M. Bloomfield, C. Thole, L. Nikitina, “Analysis of the Scatter of a Deploying Airbag”, 12th International LS-DYNA® Users Conference, 2012

[4] D. Borsotto et al.: “Improving robustness of Chevrolet Silverado with exemplary design adaptations based on identified scatter sources”, 10th European LS-DYNA Conference, 2015