Reverse Engineering and CAE*

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Existing CAE is based on CAD data and is mainly applied to design and development. Product-based CAE to acquire data from actual products and implement CAE based on the derived data is being actively studied now. The present paper describes the important points in using reverse engineering that acquires data using noncontact 3D measuring instruments and generates CAD and CAE models based on the derived data. The present paper furthermore introduces the uniquely developed automatic surfacing tool, Clay Galaxy, for use in reverse engineering. The effectiveness of reverse engineering and Product-based CAE is also explained.

Key Words: Reverse Engineering, CAE, CAD, Automatic Surfacing, STL, FEM, Noncontact 3D Shape Measuring Systems

1. CAD- and Product-Based CAE

Product development by 3D CAD has been established in many manufacturing industries. As a result, CAD-based CAE, which uses 3D line, surface and volume data generated by 3D CAD, is generally accepted at this time at the beginning of the 21st century. There are, however, many aspects where human resources must be used, even when CAD cleanup technology is fully utilized, such as the necessity of adjusting CAD for use in CAE.

Analysis software and computing hardware are also developing steadily. The accuracy of analysis has dramatically improved in the past 10 years. The development period has been reduced to 3 or 4 months for many automobiles and household electrical appliances. The conventional development style of manufacturing prototypes following analysis and developing products using actual products and CAE simultaneously is no longer appropriate for this very short development time. Future product development requires the use of digital prototyping where main product models are created using only the results of CAE analysis. This method still needs further enhancement of analysis accuracy and shortening of the analysis period.

In terms of analysis accuracy, vibration analysis, stress endurance analysis and impact analysis are satisfactory to some extent with regard to the absolute deformation such as deformation of major parts of a product.

However, further improvements are necessary with regard to detailed deformation modes and acceleration, and the strain and stress of individual parts. This is because the users require such a high level of analysis accuracy where intrinsic errors of finite elements are significant. The other reason is the difference in deformation mode and characteristics between analysis models and actual cars arising from different shapes and material characteristics. This means that for CAE to continually develop in the 21st century, the shape and material characteristics of actual cars must be precisely reflected in the finite element models, or the establishment of Product-based CAE.

Speaking of car development, the national safety regulations must be met, but it is also important to demonstrate the impact absorbing characteristics to protect occupants and pedestrians for the differentiation of products and the assertion of advantage over competitors. Impact characteristics of interior equipment and exterior plastic parts (bumpers, headlights, etc.) must be precisely reproduced. To analyze plastic parts precisely, the shape of an actual machine must be precisely represented to reproduce deformation mode. A shape model faithful to the actual machine must be generated based on Product-based CAE.

The recent dissemination of mobile phones and digital cameras has provided opportunities for people in general to use precision equipment. The new function of impact endurance is now an important design theme. CAE technology required for precision digital household electrical appliances calls for high accuracy different in nature from that of cars. In this case also, Product-based CAE by reverse engineering is no less effective than the conventional CAD-based CAE. (Fig. 1)

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2. Usefulness of Digital Prototyping

In the actual development and design activity, a design to satisfy regulations and product requirements without prototyping is required against the background of the above-mentioned shortened development period. This necessitates the practical application of prototyping by CAE (hereafter called “digital prototyping”). Digital prototyping requires that both mesh generation, a preparatory stage for analysis, and mesh modification to execute a parameter study must be finished in a short time period of, say, one week. Considering the current high-performance and sophisticated general-purpose CAE systems, this requirement is only met by inputting as much manpower as required, making it doubtful whether digital prototyping is the best solution for all manufacturers. Analysis specialists also find it difficult to conduct a necessary and sufficient analysis in time that satisfies the requirements of the designers.

Mesh generation and its preparatory stage of CAD editing, which are important in reducing the total job time, can be performed effectively by using an auto-mesh generator or its fully automatic batch processing system. Many defects of discontinuity and duplication exist in the CAD data prepared by designers because the data are not intended to be used as analytical CAD data or simply because of lack of time. These defects constitute the most critical impediments to the use of an auto-mesh generator.

A number of healing software programs are available to correct the defects present in the CAD data prepared by designers but these programs are not meant for exclusive use in CAE. These programs are highly functional to include, for example, a function to correct errors of CAD data down to approximately 1/100 mm. They are thus not suitable for use in automatic mesh generating batch systems; a program with specially designed accuracy and functions must be developed. Such a program should not be designed to correct all defects on CAD but correct them after generating a mesh to prevent the algorithm from becoming complicated. The quality of a mesh depends on the level of the relevant CAD data, and thus the generation ratio should not be unduly increased but the defects to be corrected later should be as few as possible. This is because manual correction by engineers cannot be spared however skillfully the algorithm is refined.

Problems encountered in mesh generation and the batch system are described below using our Clay Divider and Clay Divider Manager as examples.

The CAE tool Clay Divider has a virtual geometry function called Virtual Zone. A mesh is generated fully automatically in the virtual zone (Fig. 2), where two or more surface data are healed under certain conditions to treat them as a single virtual surface dataset. Face angle, CAD edge tolerance and other conditions are added to the

Fig. 1 CAD data created with reverse engineering

Fig. 2 Two distinct surfaces A and B are assumed to be a single surface using the tolerance between edges and face angle as the parameters.

virtual zone. Given these conditions, the virtual zone is defined inclusive of the defects absorbed. A mesh is automatically generated in the virtual zone, and the resultant mesh is free from the effect of CAD defects. The virtual zone is a virtual geometry and does not modify or alter the original CAD data. A mesh is automatically generated by absorbing the defects while maintaining the CAD originality. The idea of virtual geometry facilitates the automatic generation of meshes and significantly reduces the time period required for product development.

The Clay Divider Manager is a tool for continuous automatic process or batch process with parameters input in advance. The new tool allows the user to successively process the specified series of files including the creation of virtual zones through to the automatic generation of meshes simply by entering and executing (Fig. 3) the file names to be processed, conditions for the virtual zones and mesh generation standards on the spread sheet displayed on the GUI screen (Figs. 4 and 5).

The batch processing function of the Clay Divider Manager is not limited to mesh generation. It is used to convert CAD data to any other type of CAD data, and detect and automatically correct errors affecting mesh quality peculiar to certain analysis solvers (e.g. length of a specified element affecting time step). The combined use of these tools allows the user to automatically generate and correct an analysis model of a car comprising a great number of parts, thereby contributing to significant shortening

Fig. 3 Image of Screen on Clay Divider Manager

Fig. 4 Images of input files

Fig. 5 Image of output file

of the development period and the resultant cut in manpower cost.

To enhance perfection of the batch system, the result of analysis made with the meshes generated by this system is compared with the result of analysis conducted by skilled analyzers in the past. If any difference emerges, the mesh pattern of the batch system is improved to make the difference minimal.

In some cases, 3D CAD data may not have been created, or they are not available within the company because the development is outsourced. Even in these cases, Product-based CAE can be effectively used: 3D CAD data are created by reverse engineering of the product, and meshes are generated with the batch function. By following this course of automation, appreciation of the usefulness of digital prototyping is expected.

3. Reverse Engineering

Reverse engineering generally means to clarify the structure, specifications, purposes, components, and element technologies of software or hardware. In the field

Fig. 6 Reverse engineering data series

of software programs, for example, reverse engineering is negatively defined as an act to reversely analyze software, including elucidation of the relation among modules and analysis of basic specifications of a system. However, reverse engineering is used not only in a negative sense of reverse analysis and copying of other makers' products, but also in a positive sense of analysis of own products to facilitate product development. This understanding directly leads to the concept of Product-based CAE proposed by us. Thanks to the recent development

of rapid prototyping technologies, prototypes of parts, if products are not yet possible, are produced without necessarily manufacturing dies once 3D CAD is completed. Product-based CAE is basically different from the existing CAD-based CAE which generates CAE meshes after generating CAD. The usefulness of CAE will be further enhanced by developing and applying Product-based CAE typically represented by reverse engineering. The Product-based CAE backed by reverse engineering creates highly accurate 3D data and promises effective utilization of CAE in the development and design activity. Product-based CAE technology will become a future technology indispensable to all manufacturers.

The data derived from reverse engineering are, like those derived from CAE, effectively used in the inspection and quality control activity. The data are used, for example, for checking differences between design and finished products in terms of radius shape, plate thickness, the amount of springback after pressing, etc. The important points for using reverse engineering are (1) selection of a measurement method according to purpose, (2) acquisition of accurate measurement data using adequate filters, (3) efficient surfacing and concrete techniques, and (4) generation of data on shape and analysis models according to purpose (Fig. 6).

3.1 Selection of measurement method according to purpose

3.1.1 Purpose of measurement The measured point groups and STL data are used in two ways: (1) analyze own and other products (design) and (2) confirm accuracy of own products (inspection). Design purpose is further divided into (1) create a 3D mockup to shorten the development period and (2) when own products include some purchased parts, for which 3D data are not available, use as CAD data to implement analysis. Inspection purpose is further broken down into (1) inspect plate thickness in the pressing process, (2) check the amount of springback and (3) check the level of shrinkage and warp in the plastic forming process.

3.2 Data acquisition

3.2.1 Measurement method Noncontact 3D shape measuring systems include a pattern projection system using CCD cameras, a CT scanner system and an FM laser system. The CT scanner type features a short measurement time but introduction cost is high and many restrictions apply to the installation location. The laser type is more popular but the introduction cost is still higher than the CCD camera type. The laser type has the highest freedom for the size of the target subject.

Means of measurement must be carefully selected to match the purpose and the subjects to be measured because the accuracy of point group data varies with the system. Measurement by CCD cameras is generally accurate. The CCD camera system features an accuracy of approxi-

mately 0.1 mm or above. Furthermore, it is less expensive than other systems. The CCD camera measuring method is described in the rest of this paper.

3.2.2 Cleaning and degreasing The cleaning and degreasing process is indispensable in measurement with CCD cameras. Dust, dirt, chips, grease and other oils and fats must be fully removed to achieve high-precision measurement. These impurities, if present, will also be measured and reflected in the point group data. Halation occurs easily to decrease accuracy.

3.2.3 Marking Reference points of an identical shape are pasted to the target subjects after cleaning. The shooting range with one shot of the measuring instrument is fixed according to the conditions so that the subject to be measured is adjusted in position and direction and shots are synthesized to generate the shape. The measured point group data are synthesized relative to the reference points. When the target subject is relatively small and complex, some contrivance is necessary such as fixing the subject on an auxiliary subject that serves as the reference and pasting the reference points to the auxiliary subject.

3.2.4 Prevention of halation Halation is a blurred bright patch around a highly illuminated area. Spraying of fine powder medicines, if possible, is recommended for the prevention of halation caused by a projector's light at the time of measurement. Prevention of halation enhances measurement accuracy and enables the user to acquire effective data from the widest possible single-shot measurement range. Prevention of halation is particularly important when measuring subjects with glossy surfaces or materials through which the projector light will penetrate. Spraying of fine powder medicines is also effective for other materials because they keep the irradiating light uniform at all times and enhance the work efficiency.

3.2.5 Calibration Calibration is used to set numerical standards for measuring instruments and the subject to be measured. Detailed procedures of calibration differ with the measuring instrument. Generally, the subject that serves as the reference is measured and a numerical standard is set. Calibration is indispensable for establishing the standard for measurement data and stabilizing accuracy.

3.2.6 Measurement The shooting range with a single shot of the measuring instrument is fixed so that to measure the target subject in its entirety the subject is moved and/or gradually rotated to continue measurement until the entire shape is represented. Each shot includes at least three reference points that are included in the preceding shot. The method of synthesis varies with the measuring instrument. Generally, the shots are successively synthesized with the help of the minimum three reference points that are shared among the shots. When the target subject is large or long, some suitable contrivance should be used to assure accuracy such as by simultane-

ously measuring a standard piece. When using a measurement method having directivity such as a CCD camera, undercuts, deep holes or bag-like shapes are difficult or impossible to measure. In these cases, the part is disassembled, or the shape of the deep hole is copied using resins or other suitable auxiliary materials to measure the inverted shape. Then the entire shape may be restored by joining the shape data thus derived with the original data. Importantly, the auxiliary materials to be used should be carefully selected by checking the material properties.

3.2.7 Output of point group data The derived data are preferably output after being converted into a data format suitable for the succeeding stage using an appropriate processor. Currently, however, the majority of available tools are satisfactory for data format containing only point group data (x , y and z coordinate values) and STL (triangular data) so that these data formats must be converted or processed as required. Measurement data captured by CCD cameras contain fewer variations from the actual shape than other systems and no high-level filtering is required. Naturally, apparently improper data must be removed.

3.3 Efficient surfacing

3.3.1 Compression of point group data Data obtained by CCD cameras are point groups consisting of synthesized shots. The data size can be enormous. A small dataset contains several tens of megabytes and a large dataset easily exceeds 1 GB. Large datasets by far exceed the memory area of a working machine. Pretreatment is necessary such as compression or thinning using software programs or various general-purpose tools. Several types of compression procedures should be available for selection according to the purpose of use (emphasis on accuracy, uniform array of point groups, etc.).

3.3.2 Definition of surfacing standard Definition of preparation standards for surfacing is important to enhance work efficiency and accuracy. Preparation accuracy is a function of what the prepared surface data are used for. When the data are used, for example, in the design department to check design, surfacing should be carefully performed especially for feature lines and surface continuity. At least C1 continuity is required. When analysis is the main purpose, finish with a high accuracy of about, say, 0.1 mm is required depending on the type of analysis, the part to be evaluated and the size of the target subject. In other cases, non-evaluated areas may be finished in a simplified form. Generally, an exact model is required in analyses where plastic stress and strain are to be studied in particular. In contrast, accuracy is not so important in an overall rigidity analysis. In any case, work efficiency can be improved if surfacing standards suitable for the purpose of work are set before starting operation.

3.4 Preparation of analysis model according to purpose

For an analysis model assuming reverse engineering, a full investigation including surfacing is necessary considering the purpose and computing technique. The shape of a target subject, whether it be a single mold or a welded assembly, can be perfectly reproduced but material properties and mechanical structure are not reflected. It is important to check to which extent the mechanical structure and weld zones are reflected in the analysis model. It is also important to set adequate boundary and loading conditions taking material properties into consideration.

4. Clay Galaxy — Surfacing Tool for Reverse Engineering

Many manufacturers focus on digital mockups that produce virtual products in an attempt to improve quality, shorten the production period, and cut costs. CAD systems are sequentially switched to solid-base systems. The current high-end CAD system requires representation of a very accurate 3D space and does not assume use of the derived data in reverse engineering. Furthermore, the shape is generated by complex mathematical procedures, resulting in a tremendous amount of data being consumed. A new surfacing tool is therefore required that uses CCD cameras, CT scanners, FM lasers or other noncontact 3D measuring instruments to measure point group data and convert them into STL data with triangular patches. In the new tool, noise caused by overlapping measuring ranges is removed, and missing data caused by measuring errors are adequately complemented. We have independently developed the surfacing tool for reverse engineering called Clay Galaxy. The features of the new tool are described below.

4.1 Lightweight point group data

Not all of the several thousand to several million point group data that are measured are necessary for surfacing. Omission is necessary to enhance work efficiency. The new tool provides several kinds of data compression procedures including designation of the rate of reduction, designation of the curvature maintenance rate and retention of edge length.

4.2 Editing point group data and STL data

The point group data measured by a noncontact 3D measuring instrument do not necessarily cover the required parts completely (e.g. start and stop points and the center point of a curve or a surface). The new tool is provided with a function to correct omissions using point group data around the omission while maintaining the original data quality.

4.3 Generation and edition of line and surface data

Lines and surfaces are generated using the point group data. Some functions provided are the same as those of the high-end CAD. Projection onto point group data is

Generated CAD surface and STL are checked on the contour diagram

Fig. 7 Display of tolerance between STL and CAD, and contour

Fig. 8 Automatic surfacing

also possible.

4.4 Visible clearance level

When CAD exists, a contour of difference of data between CADs and between CAD and STL can be displayed to facilitate the verification of errors between design and prototype/product (Fig. 7).

4.5 Automatic surfacing

The most important feature of the new tool is that CAD surfaces are automatically generated from the derived STL data by batch processing. Automatic surfacing is available at the present moment but feature lines are not yet completely generated. An algorithm for reproducing feature lines is already developed and the program mounting procedure is in the final stage of development with its

practical use expected in the near future. The generated surface data can be directly converted into any high-end CAD.

As discussed in detail above, the new tool features those functions that are most earnestly required in reverse engineering. It is provided with many other functions to enhance work efficiency. A single tool is used to process point groups and then generate meshes in succession. This is a great advantage of the tool, and we may add that this is the most suitable tool in this field.

5. Conclusions

Measuring methods and surfacing tools have been described as they relate to reverse engineering. The methods and tools introduced above are effective for manufacturing rather than engineering. Any engineer engaged in development and production can use the tool, not to mention designers. Products with enhanced quality can be developed and produced in a shorter time period if the application range of reverse engineering is enlarged. Our company is committed to the promotion of technology and tool development to assist in the continued enhancement of product quality in the future.

References

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