

# Enhancement of Vibration Analysis Accuracy Using FE Model Applied by Three-dimensional Measurement Technology

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## ABSTRACT

The influence of shape differences between the experimental part and the CAD shape, which is thought to be an error factor in the finite element method, was verified. Three-dimensional shape measurement and modeling technologies were applied to power train structural parts that have a complex shape, and a finite element model was created that reproduces the real shape. The shape error between the real shape and the CAD shape of a prototype transmission case was clarified, and the vibration characteristics of a model created from the CAD and a model created from the real shape were compared and verified. The results confirmed that shape error has a noticeable influence, particularly in the high frequency mode shape. These results clearly showed the importance of shape reproducibility in a finite element model, and proved that real shape measurement technology can be used as an accurate modeling tool for the finite element method.

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## 1. Introduction

Recently demands to reduce individual part weights, to enhance the environmental performance of automobiles, have been increasing. On the other hand, conventional structural measures for enhancing vibration and noise performance often involve weight increases, so there are demands for structures that can simultaneously achieve both lighter weight and low vibration and noise.

Vibration analysis that uses the finite element method (FEM) is performed as an effective means of investigating the power train structure. However, the frequency range to be investigated is expanding into the high frequency range, which is making it more challenging to maintain accuracy.

The high frequency range has a complex vibration mode shape, so highly accurate FE models should be created.

Three-dimensional CAD models are becoming more common, and it has become possible to create FE models from three-dimensional CAD shapes. However, when compared with the vibration characteristics (eigen frequency, vibration mode shape, frequency response

function (FRF)) obtained by experiments, the accuracy is sometimes insufficient. Therefore, analysis error factors should be clarified and methods established to enhance accuracy.

The model update method<sup>(1)</sup> revises the plate thickness, material properties and other factors so that the model matches the experimental results, and has conventionally been used as a method for enhancing vibration analysis accuracy. When using a solid element model the material properties are used as the change parameters. However, this method has various issues, such as that experimental modal analysis is required so analysis takes a long time, and revised material properties are not necessarily physically correct values and may lack general applicability.

The accuracy of vibration analysis for individual power train structural parts is thought to depend on the following three factors.

- (1) Shape
- (2) Material properties (Young's modulus, Poisson's ratio, mass density)
- (3) Element size

Shape error has conventionally been assumed to have

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an influence, but there were no detailed three-dimensional CAD models for power train structural parts with complex shapes, three-dimensional shape measurement technology was insufficient for parts with complex shapes, and calculation environment limitations made it challenging to execute calculations with FE models that accurately reproduce shapes. For these and other reasons, the influence of shape error has not been sufficiently investigated.

Recent advances in three-dimensional CAD modeling, shape measurement technology, application technology, and calculation capabilities have established the necessary environment for verifying the degree of influence of shape. Examples of use for CAE that applies three-dimensional shape measurement technology have also been reported<sup>(2),(3)</sup>, but so far there are no reports of verifying the influence of shape differences in vibration analysis.

This paper reports the application of three-dimensional shape measurement and data processing technologies to power train structural parts with complex shapes, and the creation of FE models that reproduce real shapes. This clarified the influence of shape and proved that accurate analysis is possible.

## 2. Shape Measurement Methods

### 2.1. X-ray CT Scanner

Given recent advances in three-dimensional shape measurement technology, optical scanners and X-ray CT scanners are becoming widely used as means of verifying CAD models.

X-ray CT scanners are particularly advantageous in that they allow non-destructive measurement of parts with hollow or internal structures. This makes them suitable for evaluating the shape of power train structural parts with complex shapes.

Fast and accurate CT scanners that use high energy X-rays with high transmissive performance have also been developed, and there are reports of use even for large parts such as cylinder blocks<sup>(2) - (4)</sup>.

In order to use the CT image information of evaluation subject parts for shape evaluation, equal pixel value surfaces that serve as component boundaries are extracted from layered three-dimensional images to create a polygon model<sup>(5)</sup>. This processing provides the same data structure as that from an optical scanner.

### 2.2. Equipment Used and Scanning Conditions

Table 1 shows the X-ray CT scanner used and the scanning conditions.

### 2.3. Shape Measurement Accuracy

Figure 1 shows the artifact used for verification. Verification was performed using a polygon model created from a three-dimensional CT image obtained under the

Table 1 Equipment and conditions for CT scanning

|                  |                    |
|------------------|--------------------|
| X-ray CT scanner | HITACHI HiXCT-1M   |
| Energy of X-ray  | 0.95 MeV           |
| Permeation       | Aluminum 330 mm    |
| Scanning mode    | Rotate-rotate mode |
| Slice thickness  | 1.0 mm             |
| Slice pitch      | 0.5 mm             |
| Image size       | 1500 x 1500        |
| Pixel size       | 0.4 x 0.4 mm       |

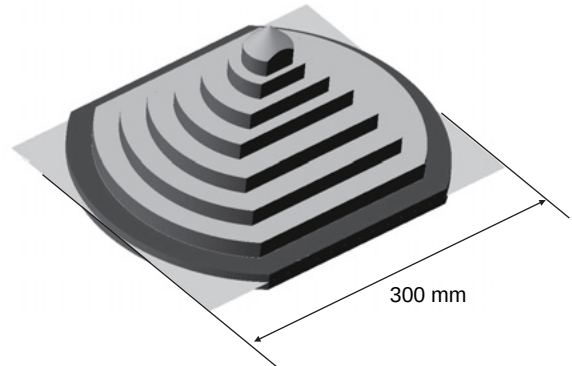


Fig. 1 Artifact used for verification

conditions in Table 1, and the results showed an accuracy of approximately  $\pm 0.15$  mm for general surfaces. This level of accuracy enables use for evaluation of the non-machined area shapes of cast parts.

## 3. FE Modeling Method

Polygon models created from CT images are comprised of millions to tens of millions of minute surfaces. Therefore, directly creating solid elements inside the model results in a number of degrees of freedom, and is unrealistic given current processing environments.

FE modeling methods that allow calculations can be broadly classified into two methods.

### 3.1. FE Modeling Method via CAD Surface

This method creates an approximate free curve surface based on a polygon model, and then uses this as the CAD surface to create a FE model using an ordinary mesh generator.

Various design application software is also available on the market as technology for creating CAD surfaces, but these have the issue that it is difficult and time consuming to generate the feature lines needed for FE modeling. However, recently, there have also been reports of research on technology for creating surface models with feature lines<sup>(6)</sup>.

### 3.2. FE Modeling Method by Mesh Reduction

This method reduces the number of meshes of the polygon model to a mesh number that can be applied to FEM.

This method also has a number of issues. For example, clear edges cannot be created in polygon models generated from X-ray CT scanner images; image noise often causes minute unevenness, which makes it unlikely to sufficiently express shape features when the number of meshes is reduced; the element quality is low, and the like. A mesh generation system (MRR mesh generator) that uses multi resolution representation (MRR) has been reported as one technology for addressing these issues<sup>(7)</sup>.

This method extracts the surfaces, ridgelines, and other feature information in the large-scale polygon model stage where there is little shape error, and provides this information as attribute information in order to maintain a shape accuracy close to the large-scale polygon model. At the same time, the element quality is enhanced to create the FE model.

### 3.3. Selection of FE Modeling Method

CAD surfaces are useful in that they can be used for various applications, but in terms of reproducibility during FE modeling, they are thought to be same as the MRR mesh generator. Therefore, this study tried the MRR mesh generator, which is expected to be better in terms of modeling process time.

## 4. Shape Measurement Results

### 4.1. Subject Part

A sand mold cast transmission case in the prototype stage was selected as a part that experience has shown is often challenging to create an accurate FE model from the CAD shape.

Figure 2 shows the CAD shape, Fig. 3 shows the three-dimensional rendition of 455 CT images obtained under the above-mentioned conditions, and Fig. 4 shows the polygon model created from the CT images.

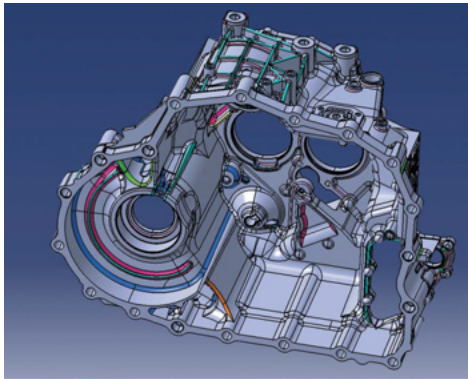


Fig. 2 3D-CAD model of subject part

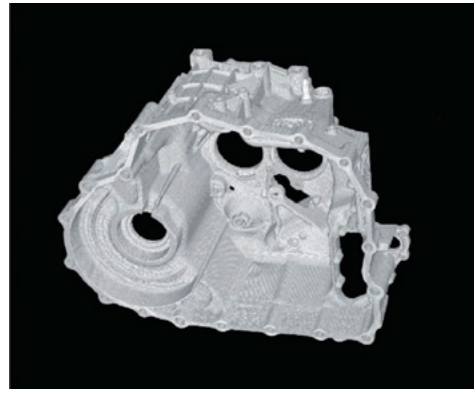


Fig. 3 3D-CT image

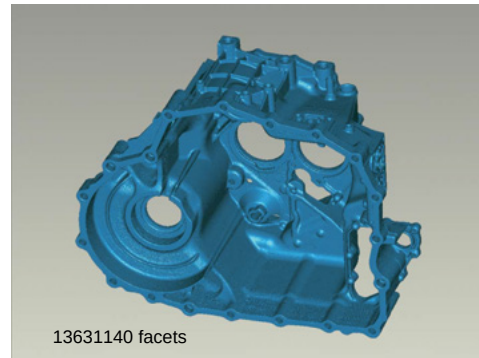
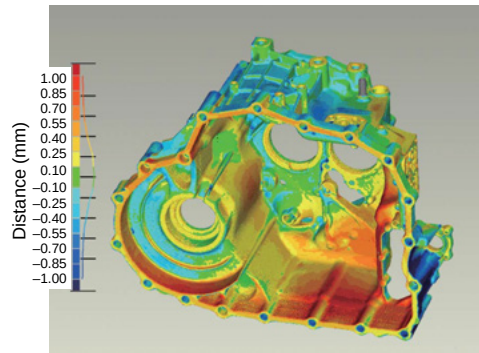
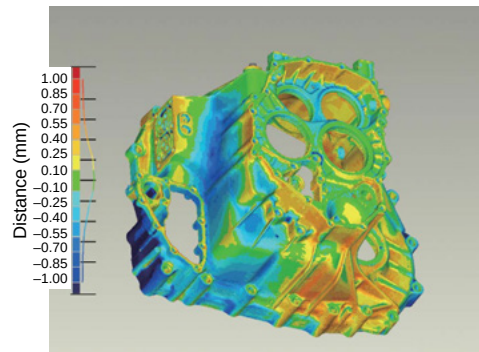


Fig. 4 Polygon model made from CT image

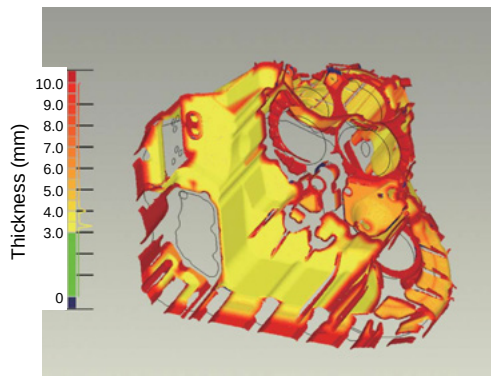


(a) View A

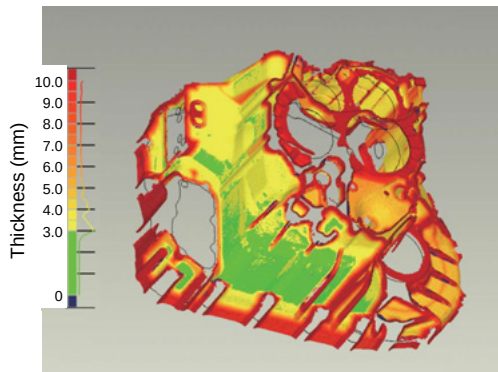


(b) View B

Fig. 5 Difference between CAD and polygon model



(a) CAD model



(b) Polygon model

Fig. 6 Wall thickness

#### 4.2. CAD Shape Verification Results

Figure 5 shows the shape differences between the polygon model and the CAD shape. The difference is defined as positive (+) when the CAD surface is outside, and negative (-) when inside the polygon model surface.

In addition, Fig. 6 shows the results of evaluating the wall thickness as the distance from the inner surface to the outer surface of the transmission case.

These results show that there is strain overall, and that the bottom and side surfaces are approximately 0.5 mm thinner compared to the CAD shape.

### 5. FE Models

#### 5.1. FE Model Based on CT Scanning (CT base model)

The large-scale polygon model (13 631 140 facets) created from the CT images posed an issue for the calculation capacity of the MRR mesh generator, so a polygon model with reduction processing performed (1 466 387 facets) was used.

Figure 7 shows the created FE model. This model is comprised of 2nd order tetrahedral elements.

Figure 8 shows the shape differences between the FE model and the polygon model. The difference is defined as positive (+) when the FE model surface is outside, and negative (-) when inside the polygon model surface. Some difference was seen in the fillet areas due to the influence

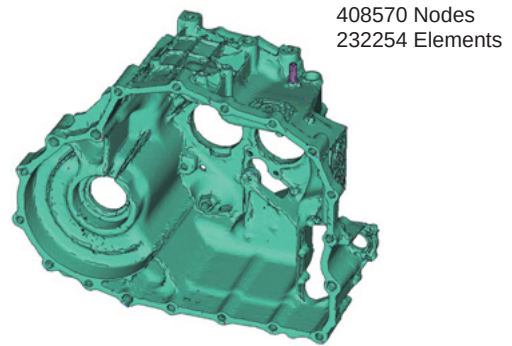


Fig. 7 FE model based on CT scanning

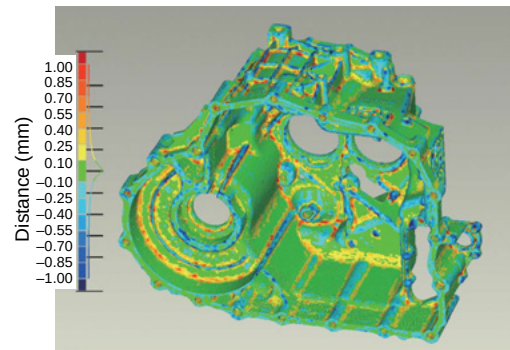


Fig. 8 Difference between FE model and polygon model



Fig. 9 FE model based on CAD

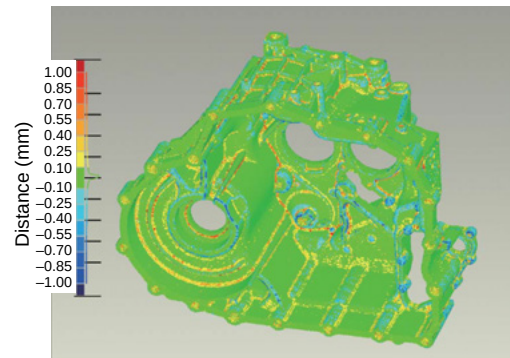


Fig. 10 Difference between FE model and CAD

Table 2 Material properties

|                 |                          |
|-----------------|--------------------------|
| Young's modulus | 7.2e10 Pa                |
| Poisson's ratio | 0.33                     |
| Mass density    | 2.74e3 kg/m <sup>3</sup> |

Table 3 Comparison of mass

|                | Mass (kg) | Error ratio (%) |
|----------------|-----------|-----------------|
| Measurement    | 8.24      | –               |
| CT base model  | 8.32      | +0.96           |
| CAD base model | 8.43      | +2.20           |

of the set element length, but it was confirmed that overall the shape is maintained well. Therefore, it is thought that this FE model can be used to evaluate the influence of differences between the CAD shapes shown in Figs. 5 and 6 and the real object.

The time needed for FE modeling in this case was approximately 3 hours using an ordinary PC (32-bit Windows XP, 2.5 GHz, 2 GB memory, single CPU processing), which confirmed that a practical process time can be achieved. The work time for the series of operations from CT scanning was approximately 3 days.

## 5.2. FE Model Based on CAD (CAD base model)

Figure 9 shows the FE model comprised of 2nd order tetrahedral elements that was created from the CAD shape as a comparison subject. Shape reproducibility was provided by setting a shorter element length, so the model scale is larger.

Figure 10 shows the shape differences between the FE model and the CAD shape. The difference is defined as positive (+) when the FE model surface is outside, and negative (-) when inside the CAD surface. These results show that this model has high CAD shape reproducibility.

## 5.3. Material Properties

To help eliminate error due to the material properties, the material properties were measured using a test piece cut from a part in the same lot as the subject part.

The Young's modulus and Poisson's ratio were obtained using the resonance method<sup>(8)</sup>, and the mass density was obtained using the Archimedes method. Table 2 shows the material properties.

## 5.4. Comparison of FE Model Mass (Comparison with Actual Measured Value)

Table 3 shows the results of comparing shape differences using the real shape model mass.

These results show that shape differences between the FE models and the real object appear as mass differences, and that there is 2.2% error even when the CAD shape is accurately reproduced. In contrast, the error for the CT base model is within 1%.

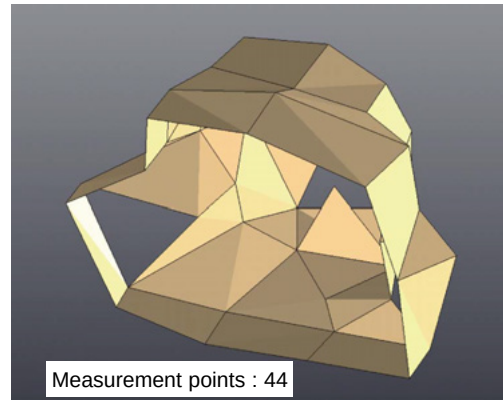


Fig. 11 Measurement points for EMA

## 6. Experimental Verification Method

This study performed verification by comparing experimental modal analysis (EMA) with FEM eigenvalue analysis and frequency response analysis.

Experimental analysis is used to verify the high frequency range, so high accuracy is also demanded.

The hammering excitation method was used as the excitation method, due to the high subject frequencies, and in order to help eliminate the influence of the excitation machine support. In addition, experimental error was minimized by adding weights with the same mass as the sensors to the measurement points, and by switching around the sensors and weights for each measurement in order to reduce the influence of changes in the sensor mass distribution when FRF measurements are divided into multiple times, etc.

The measurement points shown in Fig. 11 were selected to enable expression of high-order, complex vibration mode shapes.

The model was made equivalent to the FE model by reflecting the sensor mass as added mass.

## 7. FEM Accuracy Verification Results

### 7.1. FEM Vibration Analysis

The FEM solver used MSC/NASTRAN 2005 eigenvalue analysis (SOL 103) and frequency response analysis (SOL 111).

### 7.2. Comparison of Eigen Frequencies

The frequencies subject to comparison were up to 2.5 kHz (24th order mode) from the viewpoint of experiment reliability.

Figure 12 compares the eigen frequency for each mode, and Fig. 13 shows the eigen frequency error ratio compared to EMA.

Table 4 shows the average error ratio and maximum error ratio compared to EMA. Here, the average value of

Table 4 Eigen frequency error ratio

|                | Average error ratio (%) | Maximum error ratio (%) |
|----------------|-------------------------|-------------------------|
| CT base model  | 0.36                    | -1.67                   |
| CAD base model | 1.55                    | -5.52                   |

the absolute error ratio values was used as the average error ratio.

Experimental comparison of eigen frequencies showed that the CT base model had an average error ratio of 0.36% and maximum error ratio of -1.67%, indicating that this is an accurate simulation.

On the other hand, the CAD base model had larger error than the CT base model, with an average error ratio of 1.55% and maximum error ratio of -5.52%.

### 7.3. Comparison of Vibration Mode Shape Correlation

The EMA and FEM vibration mode shapes were compared and evaluated using mode assurance criterion (MAC)<sup>(9)</sup>. Figure 14 shows the results.

When using the CT base model shown in Fig. 14(a), a high correlation could be obtained up to the high order vibration mode shapes. In contrast, when using the CAD base model shown in Fig. 14(b), the correlation drops

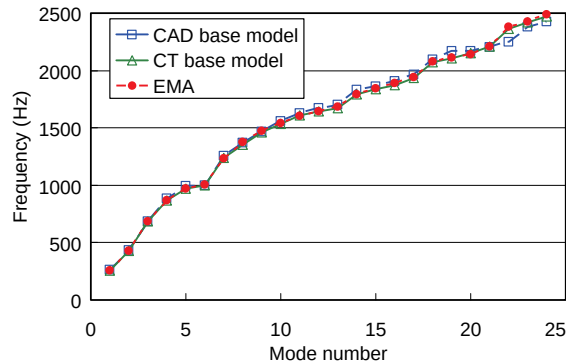


Fig. 12 Eigen frequency to mode number

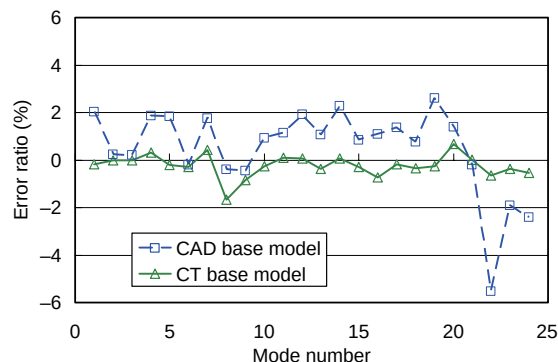


Fig. 13 Error ratio to mode number

even for relatively low order vibration mode shapes such as those of 5th and 6th order, and the correlation is low for 12th order and higher order vibration mode shapes.

### 7.4. Comparison of Element Strain Energy

Figure 15 shows the results obtained by FEM eigenvalue analysis of both the CT base model and the CAD base model for the 6th order vibration mode shape, which shows a difference in the FEM and EMA vibration mode shape correlation. The color scale indicates the element strain energy.

Based on the correlation height obtained by MAC, the element strain energy distribution of the CT base model is thought to accurately express the status in an actual part.

The vibration mode shape for the CT base model exhibits large deformation in the upper part of the openings. In contrast, the vibration mode shape for the CAD base model differs in that it also exhibits large deformation in the lower part of the openings, and has

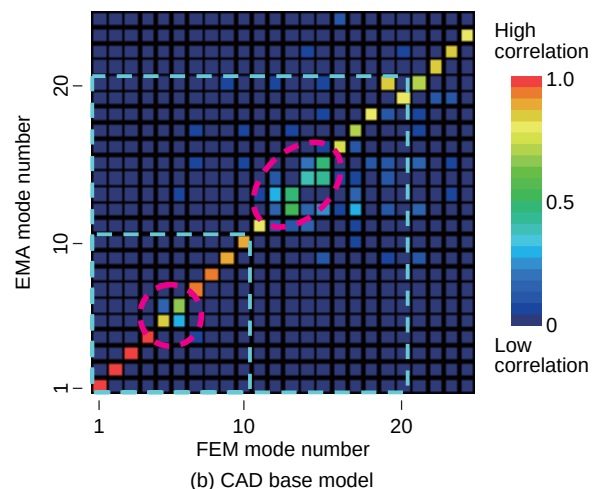
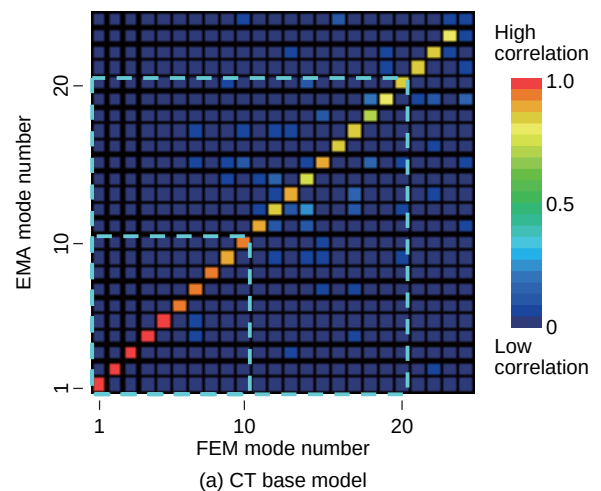


Fig. 14 Comparison of MAC

areas with high element strain energy in both the upper and lower parts of the openings. This is thought to be caused by a difference of approximately 0.5 mm in the bottom and side wall thickness as shown in Fig. 6.

Measures for vibration issues generally consist of investigating countermeasure structures by considering the vibration mode shape for the frequency in question and the element strain energy which represents the rigidity sensitivity. These results indicate the possibility of investigating different measures for different vibration mode shapes.

### 7.5. Comparison of Frequency Response Function (FRF)

The average value of the modal damping ratio obtained from the experimental modal analysis results was applied to FEM, and the FRF was calculated.

Figure 16 compares the FRF of both models with the experimental results. The CT base model obtained accurate results for both peak frequency and response level up to 2.5 kHz. In contrast, the CAD base model exhibited increased FRF error at a frequency of 2 kHz or higher due to the influence of eigen frequency error as described in section 7.2 and vibration mode shape differences as described in section 7.3.

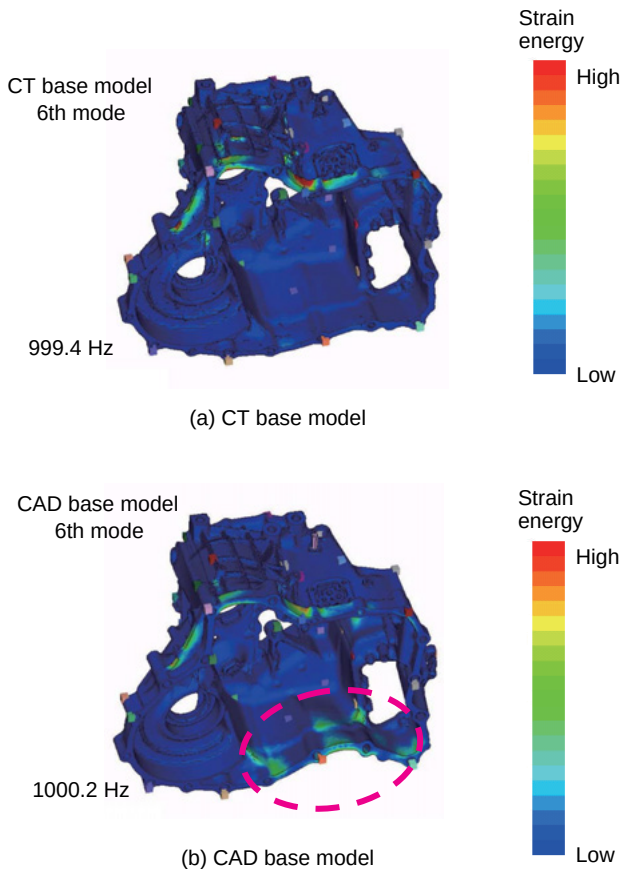
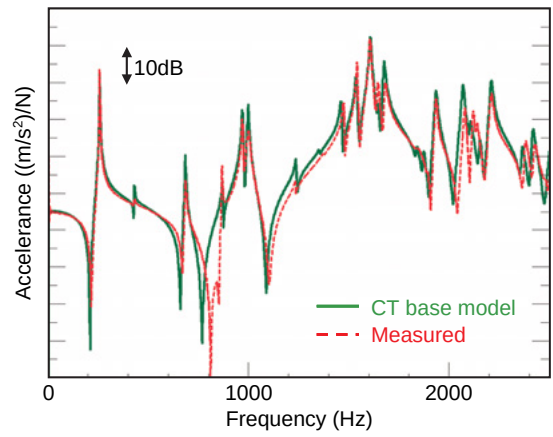
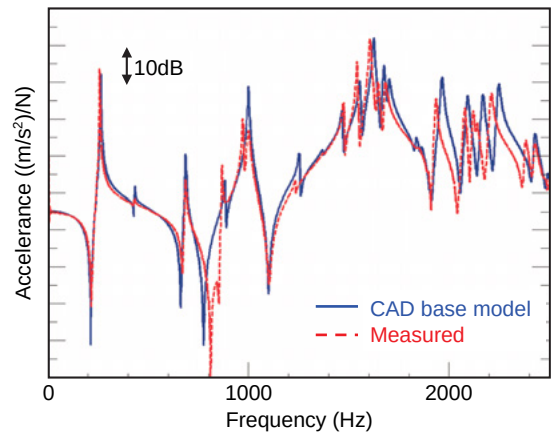


Fig. 15 Strain energy of 6<sup>th</sup> mode



(a) CT base model



(b) CAD base model

Fig. 16 Comparison of FRF

## 8. Conclusion

Three-dimensional shape measurement and modeling technologies were applied to power train structural parts that have a complex shape as a means of enhancing vibration analysis accuracy. The results verified the efficiency of the method for creating a FE model that reproduces the real shape.

- (1) It was clearly shown that using a model that reproduces the real shape allows accurate FEM vibration analysis up to the high frequency range.
- (2) The influence of shape differences, which is an error factor for FE models of complex-shaped parts that could not be clearly evaluated thus far, was clarified.
- (3) FE modeling can be performed using only physical measurement data, which proved that this is a widely applicable method for enhancing accuracy.

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