NOTE

Prototype-less CAE Design of Mechanical Component for Automobile

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1 Introduction

In recent years, automobile development periods have been shortened, and shortening of development periods has also been requested to parts manufacturers. As one of means for responding to the request, prototype-less design is raised.

In the prototype-less design, a prototype is not created before mass production, and a determination for mass production is made on the basis of simulation results by computer aided engineering (CAE). Thus, higher reliability is desired for the CAE. In addition to creation of a CAE model that is capable of simulating behaviors of a real machine, examination of adequate determination criteria from an engineering perspective and quality assurance of a CAE result are important.

We have improved precision of the CAE and promoted utilization of the CAE by designers since 2011. Thus, we achieved prototype-less design of brackets for millimeter-wave radar units for automobiles in 2014. The brackets are each designed exclusively for certain vehicle types. The prototype-less design has produced significant effects, one of which is shortening of a development period per vehicle type to approximately 1/4 of the conventional development period.

This article will introduce an example of the CAE that has contributed to the prototype-less design of the brackets for the millimeter-wave radar units and our company's effort in quality assurance of the CAE that is essential for the prototype-less design.

2 Vibration Proof Design of Bracket for Millimeter-wave Radar Units

2.1 Structure of Bracket for Millimeter-wave Radar Units

Fig. 1(a) illustrates the exterior appearance of our current millimeter-wave radar unit. It largely consists of three components: ① a millimeter-wave radar body including an aluminum die-cast housing; ② a mounting bracket made of a steel plate and exclusively designed for each vehicle type and ③ a beam-axis adjustment bolt.

The structure for holding the millimeter-wave radar unit will be described based on the assembling procedure of the radar unit in **Fig. 1(b)**. First, ① the beam-axis adjustment bolt is attached to the radar housing, and plastic bearings are attached to projections of the surfaces on both side in a lower portion of the radar housing. ② The outer circumference of the bearing is in an elongated circular shape, and the bearing is longitudinally inserted in the oval hole provided in the bracket. ③ By rotating the radar unit rearward in this state, the bearing rotates and is fitted to the oval hole of the bracket. ④ At the end, the bracket and the axis adjustment bolt are fastened by screws from the back surface.

Regarding a process of beam-axis adjustment, as shown in **Fig. 1(c)**, a gear (crown gear) that is joined to the axis adjustment bolt is rotated from above the radar unit by a Phillips screwdriver, the radar body oscillates about the plastic bearing by a feed mechanism of a screw, and an installation posture of the radar unit can thereby be adjusted.

As described above, the radar body and the bracket are coupled via the plastic bearings and the axis adjustment bolt.

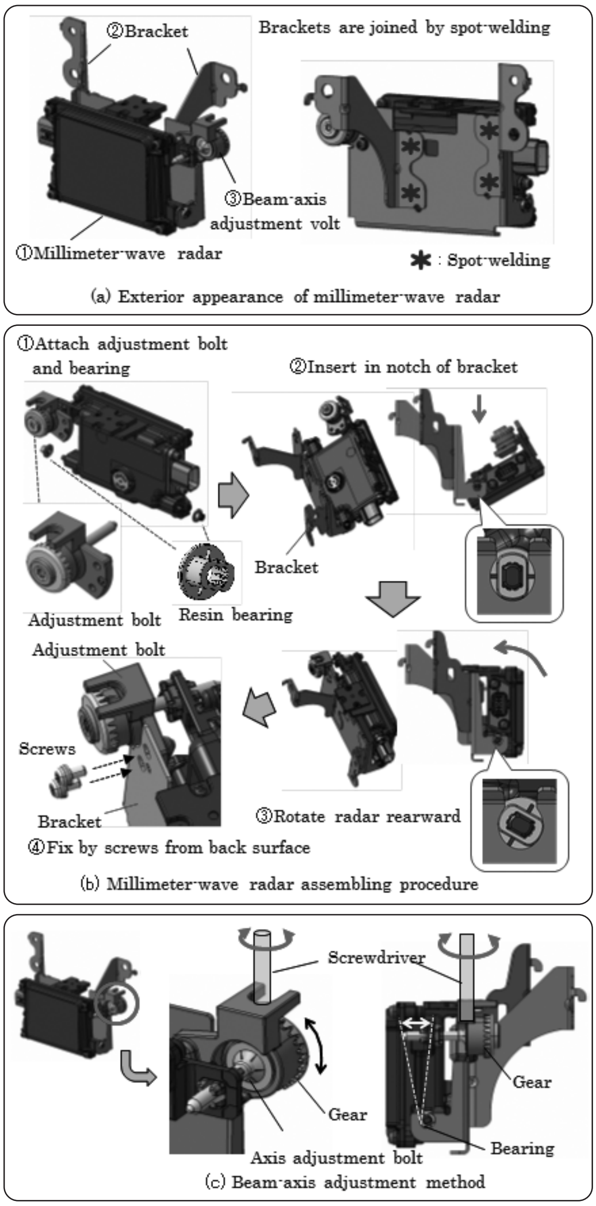
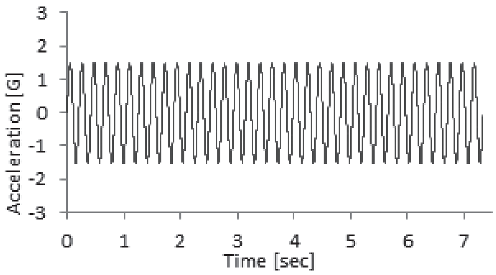


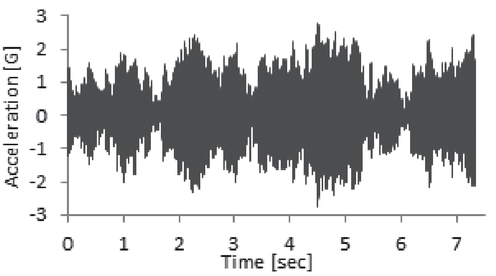
Fig.1 Structural of Bracket for Millimeter-wave Radar

2.2 Issues of Prototype-less Design

Brackets have to satisfy various strength requirements. One among them is vibration durability, a requirement difficult to determine based on design and this section will describe it. The vibration durability is evaluated by a vibration test, and vibrations are divided into periodic sine vibration and aperiodic random vibration, based on the mode of the vibration to be generated in the test. **Fig. 2** illustrates an example of each vibration waveform.



(a) Sine vibration waveform



(b) Random vibration waveform

Fig.2 Sine Vibration and Random Vibration

One of typical test methods of the sine vibration in **Fig. 2(a)** is the vibration test conducted by a test frequency fixed to a principal resonance frequency of equipment. Because a vibration load is repeatedly applied at the resonance frequency, at which the equipment is amplified the most, in this method, the vibration durability can be evaluated in a relatively short time.

Meanwhile, the random vibration shown in **Fig. 2(b)** has become the mainstream as a vibration test standard in recent years. As a reason for this, because the test is conducted by utilizing irregular vibrations containing various frequency components, vibrations during traveling of an actual automobile can be simulated during the vibration test. In addition, since vibration components in a wider frequency band can be simultaneously applied, plural types of natural vibrations the equipment has can be simultaneously generated. Thus, a failure mode of the equipment resulted from the vibrations can be efficiently evaluated without omission. Due to such characteristics, breakage and deterioration, which cannot be detected by the sine vibration, possibly becomes apparent.

A damage mode of the bracket for the millimeter-wave radar unit becomes apparent in the random vibration test, and vibration wear of the plastic bearing is raised as the damage mode. **Fig. 3** illustrates an example of the vibration wear of the plastic bearing.

A functional problem does not occur with slight abrasive wear. However, when the abrasive wear is significant, the bearing rattles against the oval hole of the bracket. Consequently, the radar posture may no longer be maintained, or another failure mode is possibly induced. Adequate design determination criteria related to the abrasive wear that causes a complex behavior have not been conventionally established. Thus, it is necessary to establish a method for determining acceptance/rejection of abrasive wear damage of the bearing under this random vibration, in order to realize the prototype-less design of the bracket for the millimeter-wave radar unit.

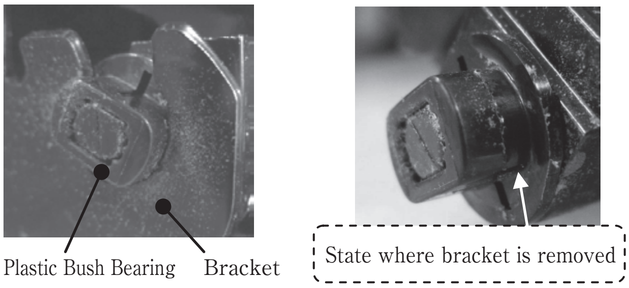


Fig.3 Abrasive Wear of Resin Bearing

2.3 Strength Design Method[1] Utilizing Random Response Analysis

The random vibration is not steady like the sine vibration, and it is thus difficult to predict an instantaneous acceleration value. For this reason, an idea of introducing a statistical method is efficient.

An outline of the random vibration is shown in **Fig. 4**.

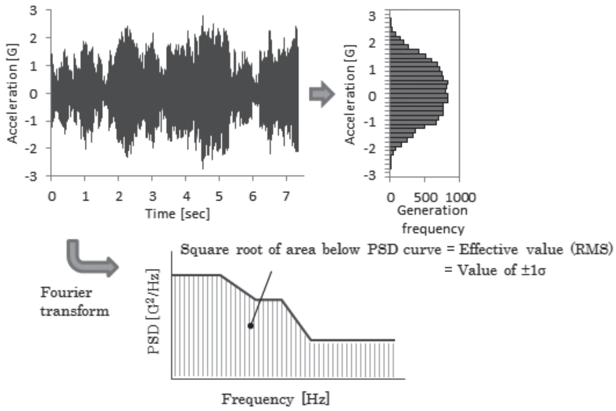


Fig.4 Outline of Random Vibration

The distribution of magnitudes of the acceleration generated in the random vibration test generally follows normal distribution with an average of 0, and the maximum acceleration becomes three times (3σ) as high as a standard deviation σ. The high acceleration, such as 4σ or 5σ, is generated in the actual vibrations; however, since generation probability of the acceleration of $\pm 3\sigma$ accounts for 99.74%, it is considered to be approximately 100%, and the acceleration is cut at an effective value of 3σ by electric control of a vibration tester. Meanwhile, the distribution of the frequency components is defined by a power spectral density (PSD) curve that is obtained by subjecting a time-series wave to the Fourier transform. The PSD curve indicates vibration strength at each frequency included in the random vibration, and a square root of an area below the PSD curve represents a root mean square (RMS) of the generated acceleration of the random vibration, that is, the effective value. Because the distribution of the magnitudes of the generated acceleration follows the normal distribution with the average of 0 as described above, the effective value is coincided with standard deviation of amplitude $\pm 1\sigma$. Due to these statistical properties, the input by the complicated random vibrations can be efficiently characterized.

Meanwhile, response of a structure exposed to the random vibrations can also be evaluated statistically. In general, a degree of fatigue damage by vibrations is estimated through calculation utilizing generated stress, the number of repeated cycles, and an S-N line. However, since the generated stress and the number of repeated cycles cannot be accurately calculated under the random vibrations, the degree of fatigue damage is generally calculated by utilizing a statistical method and Miner's rule.

Fig. 5 illustrates an outline of a calculation method of the fatigue damage under the random vibrations, and a procedure therefore will be described below.

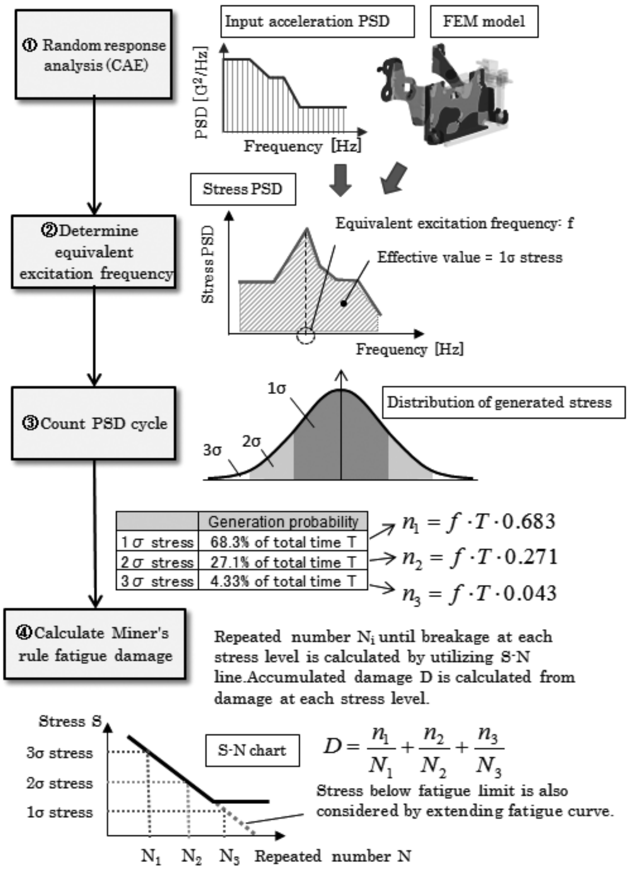


Fig.5 Calculation Procedure for Random Vibration Strength

①The PSD curve of the random vibrations is defined for an FEM model, a simulation of a real machine structure, and a random response analysis (CAE) is conducted. In this way, stress PSD generated in each portion of the structure is calculated.

②Next, an equivalent excitation frequency f that is required to calculate the number of fatigue cycles is determined. As a simple method, a frequency at which the stress PSD has the maximum value is set as the equivalent excitation frequency f.

③Although an instantaneous value of the generated stress cannot be predicted, similar to the input acceleration, the generation distribution follows normal distribution with an average of 0. Based on an assumption that the generated stress is limited to the generation probability of up to $\pm 3\sigma$, generated stress levels are divided into three probability bands of 1σ, 2σ, and 3σ. Since 1σ stress is calculated from the square root of the area below the PSD curve, each of the stress levels is calculated. For example, a double of the 1σ stress is 2σ stress, and a triple of the 1σ stress is 3σ stress. The repeated cycle number ni is calculated by multiplying the generation probability of each of the stress levels by a test time.

④The lifetime Ni at each of the stress levels calculated in ③ is calculated from the S-N line of the material. Then, the fatigue damage D is calculated by utilizing Miner's rule.

2.4. Quantification of Abrasive Wear Damage of Bearing

When a state of abrasive wear of the bearing after the vibration test was checked, significant abrasive wear was found in an outer circumferential portion of the bearing. In addition, it was understood from results of the real machine test that there was positive correlative relationship between magnitude of oscillation of the housing oscillated about the bearing and degree of the abrasive wear caused by the oscillation. Thus, a mechanism for the abrasive wear was assumed as follows: When the housing slightly oscillated about the bearing by θ by the vibrations, as shown in **Fig. 6**, the bearing repeatedly slid on the oval hole of the bracket, and the abrasive wear was thereby progressed.

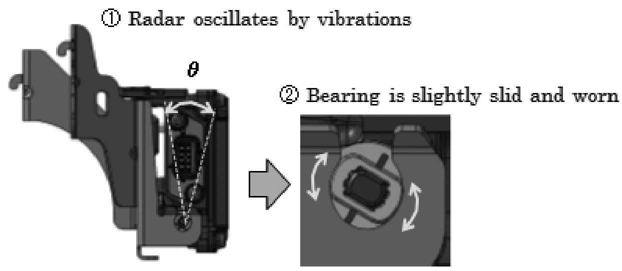


Fig.6 Mechanism of Abrasive Wear

Meanwhile, it has been known from the abrasive wear theory[2] that a total abrasive wear amount is proportional to an abrasive wear distance in a case of abrasive wear between two materials with a large difference in hardness, such as plastic and metal.

Here, it was assumed that the housing oscillation angle θ by the vibrations corresponded to the abrasive wear distance of the abrasive wear theory. Then, it was considered that, if a regression expression of a correlative relationship between the angle θ and the number of oscillation N until occurrence of rattling, i.e., a θ-N line as a lifetime curve could be created, the abrasive wear life under the random vibrations could be quantitatively predicted and determined by utilizing the same method as in **Fig. 5**.

In order to derive the θ-N line, the vibration test was conducted under various vibration conditions by utilizing a developed prototype of the bracket for the millimeter-wave radar unit. A magnitude of the radar oscillation angle θ produced by the vibrations and a generation probability thereof were calculated in advance by the CAE. When rattling occurred in the real machine test, the time elapsed from the start of the test was recorded, and multiple test results were sorted out to derive the θ-N line.

In order to validate the derived θ-N line and the determination method utilizing the method in **Fig. 5**, a comparison was made with results of the real machine vibration tests. We obtained the results from the real machine vibration tests, based on the 11 conditions, with six types of bracket shapes ① to ⑥ and six input PSDs A to G and differences in the elapsed time from the initiation of the test. **Fig. 7** illustrates the plotted correlations between presence/absence of rattling of the bearing and the abrasive wear damage D calculated from the CAE at defined time points from the initiation of those tests.

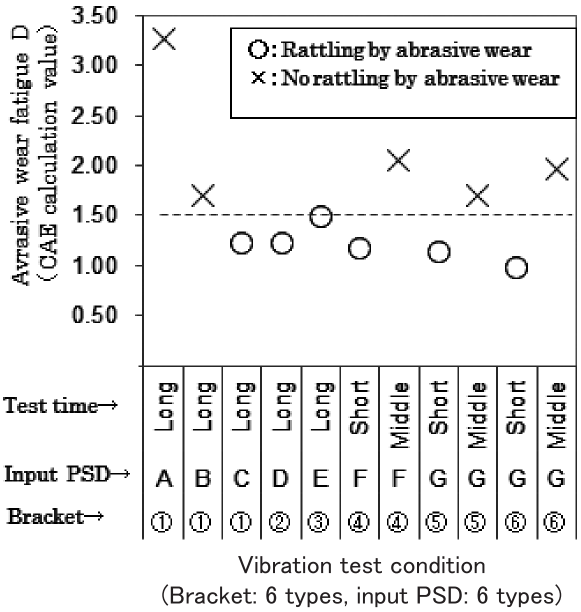


Fig.7 Comparison of Estimated Abrasive Wear Damage with Result of Real Machine Test

Despite a fact that the tests were conducted under different conditions of the shapes of the bracket and the input PSD, rattling occurred when the abrasive wear damage D exceeded a certain value. Thus, it was determined that the design method was adequate for the bearing that is damaged due to abrasive wear under the random vibrations. It became possible to prevent failure caused by the abrasive wear of the bearing because the abrasive wear damage of the bearing can be quantitatively determined by the CAE from a design stage of the bracket shape by utilizing this method. The degree of abrasive wear damage of the brackets for millimeter-wave radar units was added to the determination criteria of strength of those brackets and their prototype-less design has been conducted since 2014.

For prototype-less design, it is essential to set the CAE determination criteria that are quantitative and adequate from the engineering perspective. However, examination by the CAE only is insufficient. It is considered essential to comprehend failure modes and failure mechanisms of the equipment. It is important to create the CAE model and to examine the determination criteria, with an understanding of those modes and mechanisms, based on the result of the real machine test.

3 Approach to CAE Quality Assurance by Designers

3.1 Effects and Issues of Expanded Utilization of CAE by Designers

Currently, the designers themselves conduct the CAE of almost all designs of mechanical parts for in-vehicle equipment including the brackets for the millimeter-wave radar units partly because the CAE can be easily conducted by those who are not full-time operators due to improvement in GUIs*(1) and usability of CAE software and also because the designs can be verified in a timely manner.

Meanwhile, CAE conducted by the designers may be problematic from a perspective of quality assurance. An analysis result can be easily obtained due to the improved usability of the CAE software. However, because the CAE result greatly varies depending on setting of a boundary condition, element breakdown, a calculation method, etc., there is possible danger of obtaining completely irrelevant results. These factors have to be set appropriately for each event, but it is difficult to thoroughly cover all possible events for standardization. Thus, it is recommended that a person who has sufficient knowledge and experience in CAE should conduct CAE.

Conventionally, a certain quality level was assured because CAE was conducted by a full-time operator who had a thorough knowledge in CAE. On the other hand, in the case where CAE is conducted by designers, there is a concern that the CAE quality depends on knowledge and skill levels of the designers who conduct the CAE because not all of the designers are familiar with the CAE. In addition, while "validity of the design" based on the results of the CAE are discussed at the DR by each actually-designing team, it is often the case that emphasis is not placed on "validity of the result of the CAE." In prototype-less design, a slight error in the CAE may directly lead to a serious quality problem. Thus, the quality assurance of the results of the CAE was an important issue.

3.2 Process of CAE Quality Assurance

For the purpose of assuring the quality of the CAE by the designers, we defined a CAE process including verification & validation (V&V), important concepts for the CAE, with reference to a Model Procedure for Engineering Simulation HQC002[3] set by the Japan Society for Computational Engineering and Science.

＊(1) An operation method that enables an intuitive operation by utilizing a pointing device such as a mouse.

The point emphasized in this process is sufficient technical examination conducted among a designer who conducts the CAE, a CAE authority and a design authority who have vast knowledge and experiences, before and after the CAE. An outline of the CAE process is illustrated in **Fig. 8**.

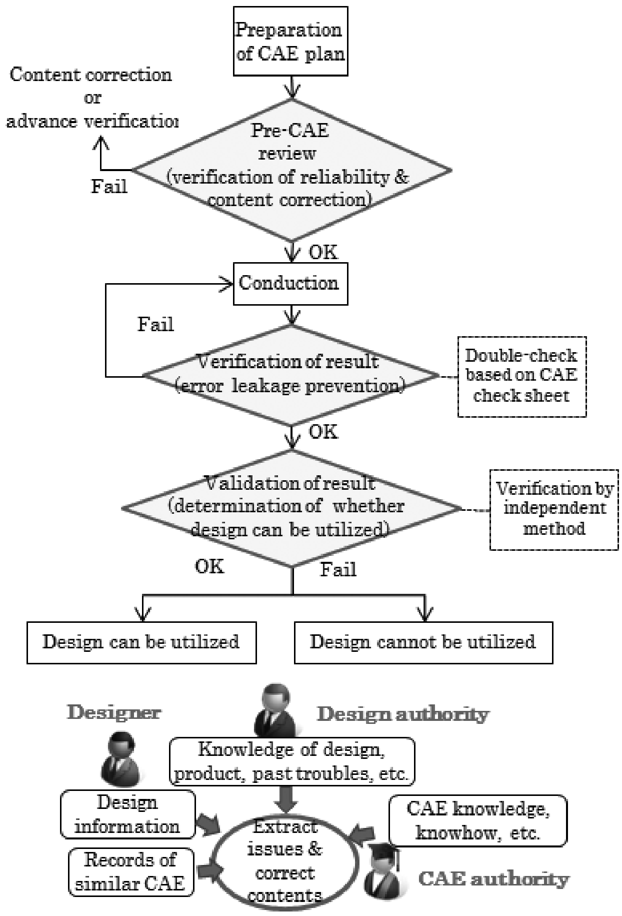


Fig.8 Process of CAE Quality Assurance

First, before CAE is begun, whether intended design can be examined by the CAE is discussed in "pre-CAE review." If similar CAEs were conducted in the past, correlativity and an error rate compared to the real machine test are checked, and points to be improved and the appropriate safety rate are examined for the CAE model. In a case of new CAE, it is checked whether the CAE model can simulate behaviors of the real machine. If accuracy of the simulation is unclear, whether the CAE model is undervalued is carefully checked. For example, the examination is conducted from a perspective of whether an input load is underestimated, whether rigidity of the equipment is overestimated, etc.

After the CAE, whether the analysis of the CAE is correct is examined by the "verification of the result." More specifically, absence of an input error, a determination error, omission of check, etc. is double-checked by the designer who conducted the CAE and the CAE authority, in accordance with a CAE check sheet that covers recommended setting, essential points to be checked, etc. for each analysis method.

After it is confirmed that the CAE was conducted in the intended manner with no error, the "validation of the result" is conducted. A point of attention in this step is that validity has to be confirmed in a method different from the CAE. For example, some among commonly used methods are: comparison of the CAE results with hand calculation results of an engineering expression, theoretical solution, etc.; comparison of the CAE results with similar CAE results; comparison of the CAE results to response of the real machine. In general, the CAE handles a complex problem that cannot be handled by the hand calculation so that its validation is not easy. However, it is an important work to confirm no serious error in the analysis results, and thus the validation must be conducted. In the validation confirmation, it is recommended to check*(2) whether the results match to estimates of a significant figure in one or two digits.[4]

In addition, review by each authority is a key to quality assurance in this process. If the authority's competence (expertise, skills, experiences, etc.) is insufficient, it is difficult for the authority to detect technical errors and mistakes in the review. Thus, reasonable competence is requested to the authority. It is recommended that there should be objective and quantitative determination criteria to determine whether the authority has the reasonable competence. For this reason, designers who are qualified as Grade 2 or higher computational mechanics engineers*(3) should be selected as the CAE authorities. Some skillful persons from the top based on the in-company skill evaluation are selected as the design authorities for each special field. Those authorities have participated in the reviews in each of the steps.

Use of this process enables organizational verification and correction of the CAE. In comparison with the conventional process, the quality assurance level of the CAE results has been improved and also awareness of the CAE by the designers has been enhanced by recognizing the importance of the verification and the validation of the CAE result again.

4 Conclusion

While the prototype-less design by the CAE is effective means for enhancing competitiveness of products, there is such a risk that the prototype-less design is directly linked to a serious quality problem caused by the CAE. However, the prototype-less design is possible when characteristics of the CAE are understood and the CAE is appropriately conducted. Moreover, in order to effectively utilize the CAE in design, it is considered that a designer who is involved the most in design should proactively utilize the CAE. In the future, we are planning to reinforce our education system for further enhancement of CAE skills and knowledge of the designers.

*(2) Referred to as order estimation.
*(3) Certifications for evaluating the skill level of the CAE analysis which are issued by the Japan Society of Mechanical Engineers that are available in three specialized fields and four grades.

Cited Literature
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