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Applying a Highly Precise CAE Technology Component Model Automotive Bolt-Loosening Mechanism

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In this study, the authors apply their highly precise Computer Aided Education (CAE) technology component model to explain the bolt-loosening mechanism in automotive parts that are secured with nuts and bolts—a problem that plagues manufacturers. This was accomplished by first visualizing the situation during prototype testing and then using CAE to accurately describe the problem. Specifically, three types of bolted pieces, each with a different pitch, were subjected to a prototype test in order to visualize their dynamic behavior along with changes in the amount of axial force applied to the bolted parts. And then, in conducting a high quality CAE analysis, the first step is to define the problem that needs to be solved and then model it using some kind of numerical formula. A computer is then used to analyze the model using an algorithm (calculation procedure). The appropriateness, applicable scope, and performance of the algorithm itself are developed based on theory, and the computer technology (calculation technique) is able to actually perform the calculations. The analysis verified that uneven stress on nut-bearing surfaces in particular was a primary cause of loosening on parts secured with nuts and bolts. In conclusion, this study applied the highly precise CAE technology component model to explain the problems associated with the loosening of parts tightened with nuts and bolts as well as to clarify the mechanism involved in similar types of technical problems affecting the auto industry. The desired results were obtained.

Keywords: computer-aided engineering (CAE), technology component model, nut-bearing surface

Introduction

Since today's analysis methods depend heavily on analytical engineers' unspoken experiential knowledge or rules of thumb, analytical accuracy varies. Therefore, there is an urgent need to establish a more precise form of CAE analysis which is capable of producing results that consistently match those obtained through prototype testing (Amasaka, 2007, 2008).

In order to take steps to resolve this issue, the authors in this study formulate a highly precise CAE technology component model and verify its effectiveness. More specifically, manufacturers could cut back significantly on preproduction experiments if the discrepancy (or gap) between prototype testing and CAE analysis results was brought to around 5%. In effect, this would eliminate the need for reworking, which would in turn shorten development design times and allow manufacturers to simultaneously achieve their quality, cost,

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and delivery (QCD) targets (Amasaka, 2007, 2008, 2010).

This paper uses the knowledge gained through the authors' previous efforts to propose a "Highly Precise CAE Technology Component Model" that can be used to reform the business processes involved in development design. The model is then applied to the analysis of nut-bearing surfaces on bolted parts, and its effectiveness is verified.

The authors focus on form, quantifying parameters like roundness and angularity in order to identify the relationship of these qualities to customer preferences. Specifically, in order to fully understand the relationship between forms as a whole (which consists of front, side, and rear elements), the authors use 3D-CAD software and statistics to quantify form, and then an eye-tracking camera to analyze line of sight and establish a cause-and-effect relationship between form and where customers focus their attention. The desired results are obtained in the field of automotive design development.

Automotive Development and Current Status of CAE

Japanese automakers are renowned over the world for their production methods. In recent years, these automakers have been faced with the urgent task of drastically reduced their development design times in order to respond quickly to changing consumer needs. One of the most important challenges for manufacturers is strengthening and enhancing computer-aided engineering (CAE) methods of analysis in order to achieve quality development design processes that are also very brief (Amasaka, 2007, 2010).

Figure 1 shows the current status and future of the automotive development process. Automotive development in the past has involved repetitive post-development experimenting, prototyping, and evaluation based mainly on problem-detection and Kaizen. Nowadays, in some development processes, body prototypes are not produced and CAE and Simultaneous Engineering (SE) are applied in the early stages of development instead, resulting in a greatly shortened vehicle development period (Amasaka, 2007, 2008, 2012; Whaley, Petitet, & Dongarra, 2001).

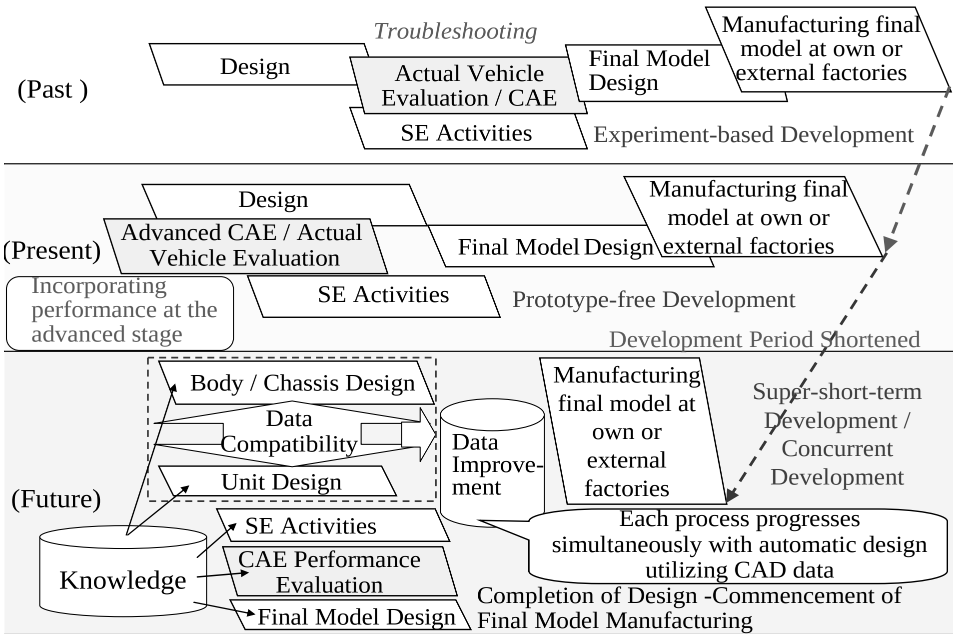

Figure 1. The present and future of development process.

For this reason, it is considered necessary to change over from the conventional confirmation of actual products for improvement to a predictive evaluation-based approach employing digital engineering methods such as CAE in order to achieve extremely short development periods (Amasaka, 2007).

Applying the Highly Precise CAE Technology Component Model to Explain the Loosening Mechanism in Automotive Bolts

In this section, the authors take prior research on bolted parts (Ueno, Yamaji, & Amasaka, 2009; Takahashi, Ueno, Yamaji, & Amasaka, 2010; Yamada & Amasaka, 2011; Fukuoka, Nomura, & Morimoto, 2006; Zhang & Jiang, 2004; Izumi, Yokohama, Iwasaki, & Sasaki, 2005; Onodera & Amasaka, 2011) to a new level by analyzing nut-bearing surfaces and then verifying the effectiveness of the highly precise technology component model that is created as a result of that analysis.

Applying a "Highly Precise CAE Technology Component Model"

In conducting a high quality CAE analysis, the first step is to define the problem that needs to be solved and then model it using some kind of numerical formula. A computer is then used to analyze the model using an algorithm (calculation procedure). The appropriateness, applicable scope, and performance of the algorithm itself are developed based on theory, and the computer technology (calculation technique) is able to actually perform the calculations (Amasaka, 2012; Nozawa, Yamashita, & Amasaka, 2012). The relationship among these factors is indicated in the technological element model shown in Figure 2.

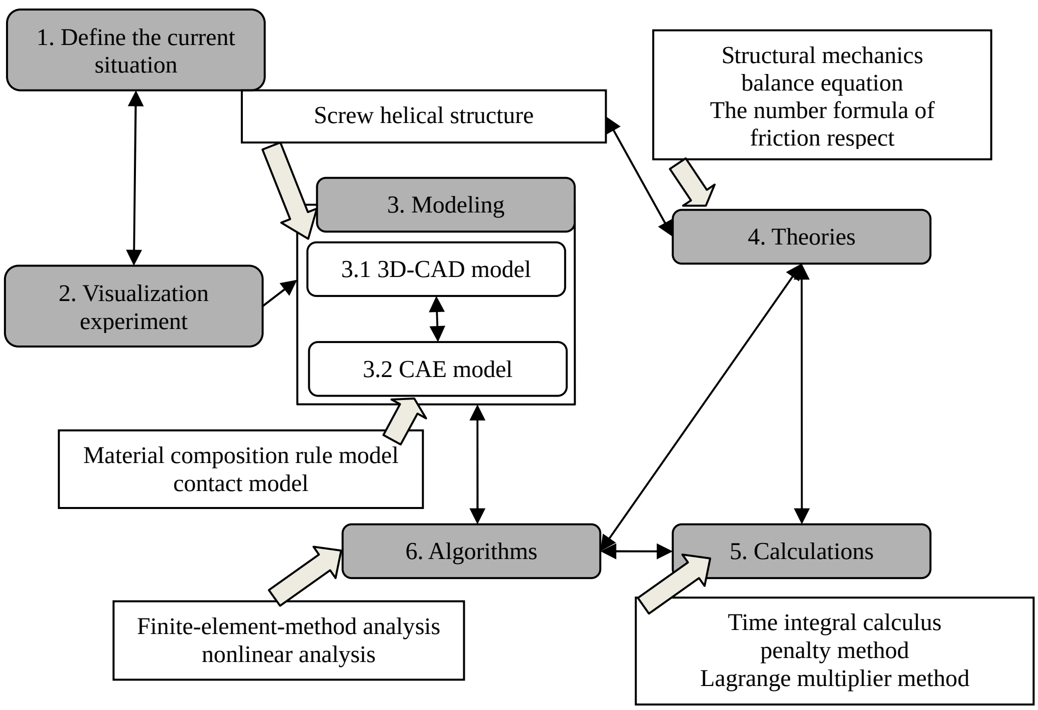

Figure 2. Highly precise CAE technology component model.

Define the Current Situation and Conduct a Visualization Experiment

Defining the current situation, the important task is to clarify why the breakdowns are occurring as well as the mechanism that is generating them. In order to grasp what is kind of causal relationship on the problem concretely, a previous work is investigated, and it focuses on the behavior change of bolt axial tension.

Next, the visualization experiment, prototype testing is conducted in order to visualize the mechanism (dynamic behavior) that is generating the defect. This is how the faulty mechanism is further defined. Therefore, in "a visualization experiment", it supposes that the phenomenon of an axial tension fall is caught, and measures axial tension as a numerical object which should be measured.

Modeling

The preparations for performing a CAE simulation are made by modeling. The computer performs the modeling in which analysis is possible to the phenomenon caught in the visualization experiment. Especially, a three-dimensional CAD model and CAE model serve as an important element. This section describes how the model which can be dealt with analysis software is set as the target to analyze.

3D CAD Model

First, a CAD model of an actual object is created. The existence of CAD models tends to be underplayed during CAE analysis, but the key to expressing an actual phenomenon through a computer is the way in which the structure is simplified. If this is not done accurately and in line with the aims of simplifying the structure, it will be impossible to produce a highly precise CAE analysis. For this reason, the precision of the analysis results can vary greatly depending on how the 3D CAD model is created—particularly the way in which the spiral structure is defined. The authors thus took the following two points into consideration when constructing the bolt:

(1) Reducing the number of assembled parts;

(2) Defining the spiral screw area as "cut threads".

For the first point, reducing the number of parts would likely make it easier to define operator contact and cut back on analysis time in later CAE analyses. For the second point, this definition was adopted because the bolts used in prototype testing had a structure where threads cut through a circular pillar. Many prior studies defined the spiral screw area as being separately attached to the circular pillar, but the authors of this study felt that their definition would reduce calculation times and increase precision.

CAE Model

Next, a CAE model was created to resolve the problem. A CAE model defines the particular characteristics and properties of a structure. Because of this, the numerical values and differences in the definitions established at this point have a significant impact on CAE analysis results (Alba, 2005).

The characteristics and properties of the analysis models were defined using material composition rule models and dynamic element models. Material composition rule models define the material characteristics of a structure, which can be roughly classified into four types: elasticity, plasticity, viscoelasticity, and viscoplasticity. Specifically, the Young's modulus and Poisson's ratio values obtained when the nut and bolt were manufactured were entered into the analysis software. Material composition rules are absolutely essential for numerically understanding the material property values of the items tested and thus being able to reproduce the prototype experiment.

The dynamic element models show the dynamic characteristics of structures, and are essential for focusing on partial differential equations that show time evolution. Because they are used in the calculation process used to control the geometric models that recreate bolt tightening, these models allow for faster calculation speeds.

Theories

Appropriate theories are articulated in line with a phenomenon of identification and algorithms. The theories on the visualization experiment formulated in this step support the precision of the CAE analysis from the ground up by defining the numerical values that require measurement and by serving as a bridge between those values and the CAE model. Selecting the right theoretical formula is critical to guarantee algorithm precision. The key theories used here are a theory of structural mechanics, equation of equilibrium, and coefficient of friction calculation formula optimally suited for resolving the problems defined in this study.

Theories of structural mechanics target a single physical phenomenon, describing the internal forces in the object and the dynamics affecting material strength when that object is created. In order to clearly understand the contact pressure on bolted pieces, load and support must first be defined. For this reason, a proper theory that includes the finite element method used in the algorithm was used.

The equation of equilibrium (an equilibrium equation for stress) is a formula that expresses the relationship of stress to each coordinate axis when the stress on an elastic body is in a balanced state. Using an equilibrium equation takes into account coordinate axes when deriving a finite element method formula makes it possible to calculate stress on nut-bearing surfaces.

Finally, the coefficient of friction calculation formula is used to determine the dynamic friction for bolt piece boundary conditions. Static tests done during the prototype experiment generate sliding on nut-bearing surfaces, and the formula actually uses the numerical values for torque and axial force obtained during this process. This allows analyses to be conducted with little divergence from the prototype experiments.

Calculations

To ensure precision, a methodology that allows calculations to be performed in a reasonable amount of time was determined. Calculation techniques certainly depend on the type of software and hardware used, but the precision and required time selected for those calculations must be optimized from the perspective of the CAE model. The level of precision in computer technology can be equated with the success of the CAE analysis.

First, a time integration technique is used to run separate calculations for each step of the analysis. In this analysis, even the time integration technique uses an implicit method whereby information obtained after the first step is used to determine the next time value. Implicit methods are extremely well-suited to vibrational analysis, one of the benefits being the ability to come to a stable solution even with large time increments. It is therefore the most appropriate time integration technique for the CAE analysis in this study.

Next, a penalty method is used to take the analysis of contact pressure on the nut-bearing surfaces of the bolted pieces (which are nonlinear) and treat it as a linear problem. The penalty method follows Hooke’s law to adjust the drain that objects have one another. Even though taking into account the massive calculations required for this analysis, the time spent does improve solution convergence and precision, making analysis possible in a shorter time.

Finally, the method of Lagrangian multipliers is used in place of the penalty method, particularly in locations where highly precise calculations are needed. However, because these multipliers require even more calculation time than the penalty method, the “quality” and “deliver” aspects had to be considered together. In order to reach a conclusion with the CAE analysis, boundary conditions for the nut-bearing surface and base material use Lagrangian multipliers, while other boundary conditions mainly use the penalty method.

Algorithms

The CAE analysis requires that an algorithm be assigned as an analysis procedure for the software. The suitability, applicable scope, performance, and expected precision of the algorithm are guaranteed by the use of a theory. The analysis is thus performed in line with the problems confirmed in the visualization experiment as a feasible calculation procedure for the software.

A finite element method that can perform calculations to make the differential equations derived from the structural mechanics theory discrete is used. Because this study requires that the contact pressure on the nut-bearing surface be visualized, it is possible to calculate highly precise results on the minute element level. This analysis procedure can achieve an extremely fine division of elements on the nut-bearing surface, which makes the analysis more precise.

In order to resolve the material fatigue and loosening affecting bolted parts as a linear problem, a nonlinear analysis must be performed. Further, the Newton-Raphson method is used in the nonlinear analysis to improve calculation precision and set up a repetitive operation whereby solutions are repeatedly calculated, corrected, and recalculated. This result in longer calculation times, but analysis precision does increase—generating results with almost no deviation from the prototype experiment in terms of axial force lowering behaviors.

If the above elements are not combined properly, CAE and the process as a whole will not function efficiently. In short, the success of the CAE analysis does not affect only the sophistication of individual technological components, but the overall capacity of the entire process as well.

Bolts and Nuts Used

A bolt-tightening experiment was conducted using hexagonal bolts and nuts equipped with a flange. By using nuts and bolts of varying pitches (0.50 mm, 1.25 mm, 1.75 mm), the authors were able to observe the axial force lowering behavior when the angles of external forces of the bolt threads were changed.

The Bolt-Tightening Experiment

Experiment purpose. In looking at the direction of external forces, vibration was applied to the pieces with nuts and bolts in order to measure the lowering of axial force on the pieces with a strain gauge. This allowed the authors to visualize the relationship between axial force and stress when the angle of the threads was changed.

Content of experiment. In order to estimate the vibration load to be used in the vibration experiment, a static experiment was carried out. In the static experiment, a bolted workpiece was subjected to a tightening load of 20 kN and 35 kN, and the load that rapidly increased bearing surface slippage was measured with a testing apparatus.

Specifically, vibration was displaced by applying external force to the upper vibrating jig perpendicular to the axis. The tightening load on the bolt was measured and changes in the tightening load due to displacement were checked. The testing apparatus was then vibrated with a vibration load of ±90% the measured static release load at a right angle to the axis and parallel to the axis.

Surface slippage repeatedly occurred, resulting in loosened bolts. Changes in the placement of the bolts-testing apparatus as well as in bolt-tightening load were measured based on the number of repetitions and the contact pressure (stress) generated on the nut-sliding surface was measured.

Experiment results. The results of the prototype testing are shown in Figures 3 and 4. The ways that differences in the pitch and direction of the external force affected the rate at which axial force dropped were as follows. At a right angle to the axis, the rate at which axial force fell increased sharply as pitch increased. Parallel to the axis, a commensurate drop in axial force was not observed.

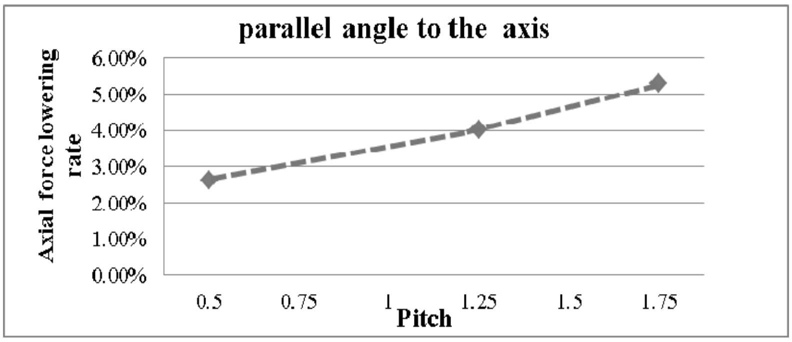

Figure 3. Axial force lowering rate (parallel angle).

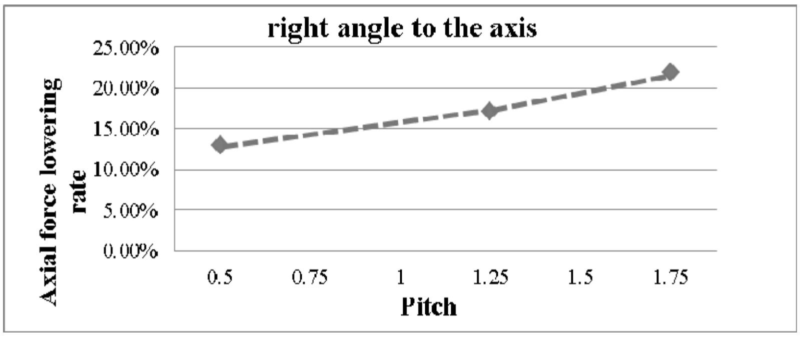

Figure 4. Axial force lowering rate (right angle).

In looking at these two results, it was concluded that differences in pitch and in the direction of external forces had a mutual impact on the lowering of axial force. The insights obtained from this study made it clear that the conclusion from the visualization of experiment, namely, that the established problem of differences in external force direction and pitch affected the loosening of nuts and bolts (when everything outside of the pitch was held constant) is valid. This means that reproducing the prototype experiment CAE analysis to delve deeper into behavioral changes in the lowering of axial force and changes to stress to nut-bearing surfaces was worthwhile.

A surface pressure distribution measurement sheet created by Nitta Corporation was used to measure contact stress. This device shows how the relative strength of contact stress is distributed along nut-bearing surfaces in 13 different colors.

Numerical Simulation

The CAE analysis of nut-bearing surfaces was first conducted using a two-dimensional analysis, allowing the researchers to identify the stress distribution along bolted parts. The insights obtained through this analysis were then used to conduct a finite element method analysis with a 3D model that considered the spiral structure on threaded areas, and stress on the nut-bearing surface was visualized. The three-dimensional finite element model creates a detailed mesh showing the area around the bolt/nut and areas of contact.

The CAE analysis included a simulation of external forces applied to the bolt in a perpendicular and parallel direction. The first analysis procedure was conducted according to the following steps. First, the two bolted workpieces are placed between the bolt and the nut. Axial force is applied to the bolt (securing the edge of the lower piece) and perpendicular to the upper piece. Finally, the analysis looks at the pressure on the contact surface (between the bolt/nut-bearing surface and the workpieces and between the bolt threads and the nut) and at the behavior of the pieces in terms of reduction in axial force when pressure changes.

The second analysis, however, was conducted as follows. First, the two bolted workpieces are placed between the bolt and the nut. Second, axial force was applied to the bolt, the right edge of the base material was fixed in place, and vibration was applied to the left edge in a perpendicular direction. Finally, the analysis looks at the pressure on the contact surface and at the behavior of the pieces in terms of reduction in axial force when pressure changes. The results of this analysis are shown in Figures 5 and 6 with a sample pitch of 1.75 mm.

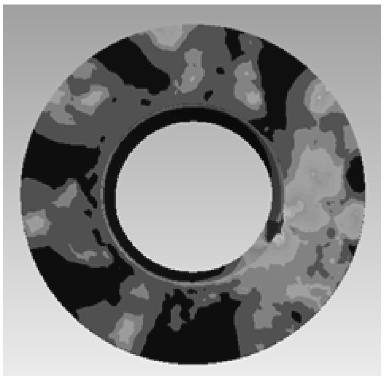

Figure5. Right angle.

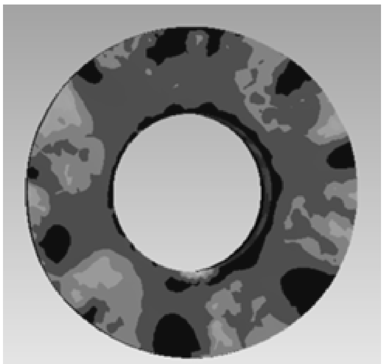

Figure 6. Parallel angle.

Figures 5 and 6 compare the 13-color contour diagrams showing stress on nut-bearing surfaces. The shades change from white to black to indicate greater stress. In the experiment where force was applied parallel to the axis, stress is distributed in a circular pattern. This suggests that external force is being applied to the surface in a perpendicular direction. When force is applied perpendicular to the axis, the stress to the surface is characterized by an uneven distribution.

The fact that repeated vibration causes the nut-bearing surface to wear against the base material suggests that it is easy for sliding to occur on that surface. A numerical comparison of these results indicates that the analysis that included external force applied in a perpendicular direction to the axis resulted in a significant drop in both stress and axial force values.

The numerical values representing stress and axial force also changed in the analyses that used pitches of 0.50 mm and 1.25 mm, but a comparison of the analysis results in the parallel and perpendicular directions obtained a similar outcome. The analysis results confirm that the pitch length in nuts and bolts has a major effect on stress distribution along surface contact areas.

Verification

Comparisons were made between the prototype experiments and the CAE analysis results using two different approaches in order to verify the precision of the CAE analysis. The first approach compared the rate at which axial force dropped in the prototype experiment and CAE analysis. Comparing the axial force reduction behavior measurements obtained through prototype testing and those obtained through CAE analysis verified the precision of the CAE analysis results.

Figure 7 compares the results of prototype testing and CAE analysis for the bolt and nut with 1.75 mm pitch under a fastener load of 35 kN. The dashed line shows a margin of error of 3%, indicating that a high-quality CAE analysis was achieved. Similar results were achieved for the 0.50 mm-pitch bolt and nut as well.

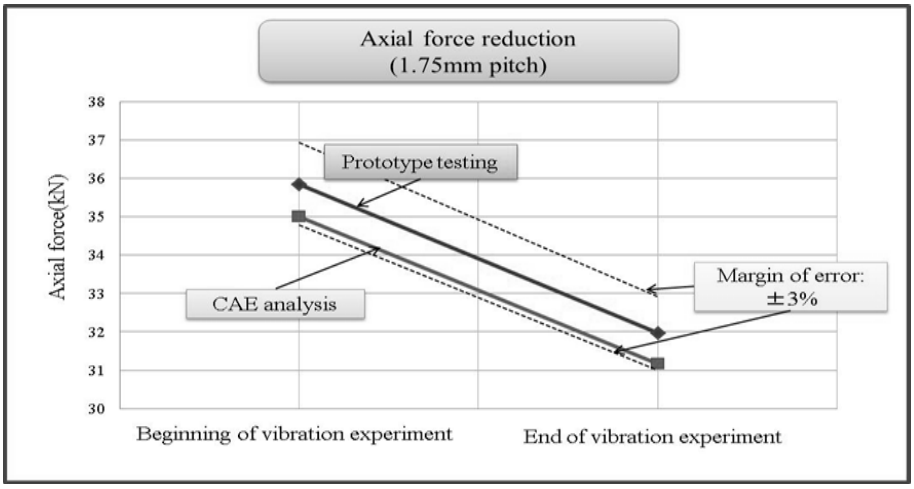

Figure 7. Comparing the results.

The second approach used pressure distribution measurement sheets to measure the pressure applied to contact surfaces of the nut and base material, and then compared these measurements with the CAE analysis results to verify the precision of the analysis. Figure 8 shows the stress measurement results from the surface pressure sheets, while Figure 9 shows the CAE simulation results, both figures reveal powerful stress generated in areas surrounding the initial thread structure on the nut and bolt areas of the nut-bearing surface.

Figure 8. The measurement sheet.

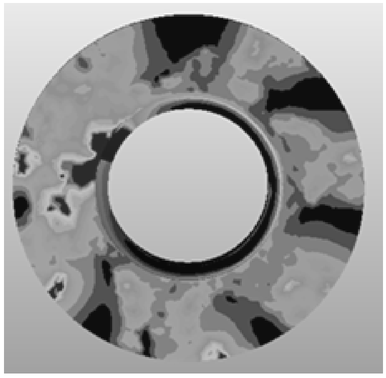

Figure 9. The CAE simulation.

Though there is a difference in the values representing deformation and wear in the base material following the bolt-tightening experiment as well as values representing the roughness of the contact surface, the analysis offered previously unknown facts about the actual distribution of stress along the nut-bearing surface—and these results could be replicated using the simulation. The study also yielded new insights on just how much intensity and distribution of surface stress varies with respect to differences in pitch length.

Conclusions

This study applied the highly precise CAE technology component model to explain the problems associated with the loosening of parts tightened with nuts and bolts as well as to clarify the mechanism involved in similar types of technical problems affecting the auto industry. The desired results were obtained.

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