A NEW DEVELOPMENT DESIGN CAE EMPLOYMENT MODEL
Applying Numerical Simulation to Automobile Bottleneck Technology

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Abstract: With the rapid move towards global production, it has become increasingly critical for manufacturers to drastically cut back on the time it takes to move a product from design to production while ensuring quality. This research addresses the necessity reforming the business processes associated with development design in particular, proposing a "New Development Design CAE Employment Model" using four core models: the "Highly Reliable CAE Analysis Technology Component Model", the "Highly Precise CAE Analysis Model", the "Total QA High Cyclization Business Process Model", and the "Intellectual Customer Data Collection/Analysis Integrated Model" that takes manufacturers away from conventional preproduction and prototype testing methods and towards a better predictive evaluation method. The effectiveness of the model is verified by successfully applying it to the technological problem "automotive transaxle oil seal leakage" of development design bottlenecks at auto manufacturers.

1 INTRODUCTION

This research focuses on reforming the business processes associated with development design, one of the critical components of manufacturing with the rapid move towards global production. In recent years, the author has been looking to move away from the repeated trial-and-error–based preproduction and prototype testing traditionally practiced in the development design process (conventional prototype testing methods) and towards more predictive evaluation methods. To achieve this aim, the author created a "New Development Design CAE Employment Model" that will shorten development times and help manufacturers simultaneously achieve optimum quality, cost, and delivery (QCD).

The author has created four core models that make up the new CAE model: the "Highly Reliable CAE Analysis Technology Component Model", the "Highly Precise CAE Analysis Model", the "Total QA High Cyclization Business Process Model", and the "Intellectual Customer Data Collection/Analysis Integrated Model". Statistical science was used to organically and intelligently put these models to work, and they were successfully employed in resolving the technological problem "automotive transaxle oil seal leakage" of development design bottlenecks at auto manufacturers by utilizing the "Highly Assurance CAE Analysis Model", the "Oil Seal Simulator", the "CAE Qualitative Model", CAE analysis (2D and 3D), and quality improvement. The "New Development Design CAE Employment Model" was then applied to similar technical problems, where its effectiveness was verified.

2 CAE IN DEVELOPMENT DESIGN – APPLICATION AND ISSUES

The time between product design and production has been drastically shortened in recent years with the rapid spread of global production. Quality assurance, or QA, has become increasingly critical, making it essential that the development design process—a critical component of QA—be reformed to ensure quality (Kume, 1999: Amasaka, 2010a). Figure 1 shows the typical product development design process currently used by many companies (Amasaka, Ed., 2007a). The figure shows that companies first create product development design

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instructions based on market research and planning. They then use these instructions to make specific development design specifications (drawings) and to promptly convert them to digital format so that they can be suitably processed and applied. The data is primarily used in numerical simulations known as computer-aided engineering, or CAE.

CAE and other numerical simulations have been applied to a wide variety of business processes in recent years, including research and development, design, preproduction and testing/evaluations, production technology, production preparation, and manufacturing. These and other applications are expected to have effective results (Magoshi, et al., 2003:Leo, et al., 2004: Amasaka, 2010a). In this age of global quality competition, using CAE for predictive evaluation method in design work is expected to contribute a great deal to shortening development design time and improving quality (Amasaka, 2007, 2008, 2010b). However, in the case of automotive production, much of the development design process is guided by unspoken experiential knowledge and rules of thumb, leading to prototype testing guided by repeated trial-and-error efforts; in other words, a series of improvements based on conventional prototype testing methods. This not only draws out the development design process, but also results in enormous testing costs.

Previous forms of CAE analysis were not sufficiently precise, yielding figures that deviated as much as 10–30% from prototype testing evaluations (absolute values). This meant that CAE was hardly

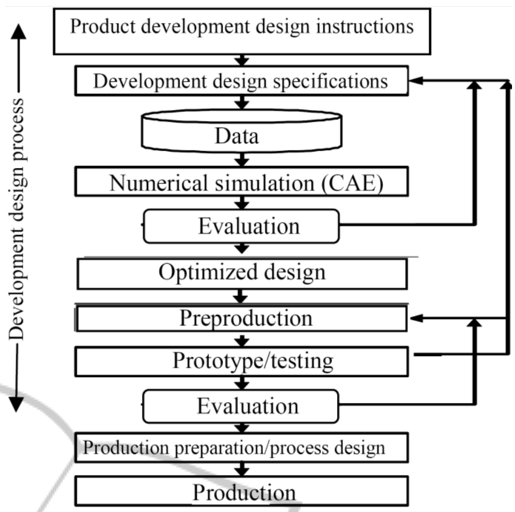

Figure 1: CAE in the development design process.

reliable enough to be an adequate substitute for prototype testing (Amasaka, 2007, 2008). As a result, manufacturers were not able to cut out preproduction and prototype testing (a necessity for shortening development design time) despite the enormous amount of funds they invested in CAE development. This means that many companies are now stuck with applying CAE only to the monitoring task of comparative evaluations of old and new products.

The only way get CAE analysis to function at a sufficient level and firmly establish it as part of (1) preventing recurrence of the pressing technical problem of bottlenecking and (2) the development

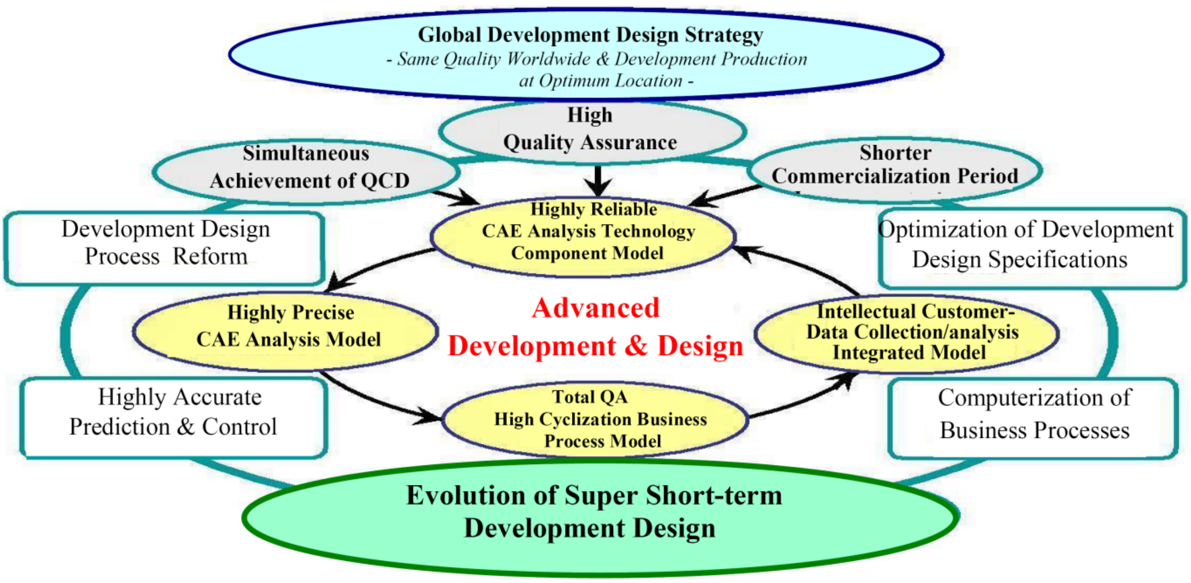

Figure 2: New Development Design CAE Employment Model.

design process for new products, is to make it more precise. Specifically, this means setting up highly reliable CAE analysis that reduce the deviation, or gap, with prototype testing evaluations (absolute values) to 5% or less (Amasaka, 2008, 2010b).

3 CONSTRUCTING A NEW DEVELOPMENT DESIGN CAE EMPLOYING MODEL

The author has created the "New Development Design CAE Employment Model" for the advanced development and design shown in Figure 2 as a way of overcoming these pressing problems in development design. As the figure shows, technical issues that must be resolved by development design departments include development design process reform, design process reform, high accuracy of the prediction and control, computerization of business process, and optimization of development design specifications.

In terms of a methodology for resolving these issues, the author has created four core models: the "High Reliable CAE Analysis Technology Component Model", the "Highly Precise CAE Analysis Model", the "Total QA High Cyclization Business Process Model", and the "Intellectual Customer Data Collection/Analysis Integrated System". The organically integrated and intelligent application of these four models is essential. An overview of each is given below.

3.1 The Highly Reliable CAE Analysis Technology Component Model

The Highly Reliable CAE Analysis Technology Component Model (problem-model-algorithm-theory-computer) shown in Figure 3 was designed to make the shift from conventional prototype testing methods to effectively applying CAE in predictive evaluation methods. The comprehensive issuance of this model is essential to achieving the desired shift. (Amasaka, Ed., 2007b: Amasaka, 2008, 2010b).

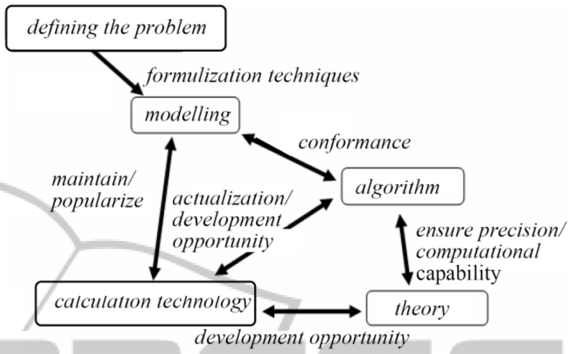

Figure 3: Highly Reliable CAE Analysis Technology Component Model.

More specifically, the critical aspects of this model include (i) Defining the problem (physically checking the actual item) in order to clarify the mechanism of the defect, using visualization technology to identify the dynamic behavior of the technical issue; (ii) full use of formulization techniques to generate logical modeling (statistical calculations, model application); (iii) constructing compatible algorithms (calculation methods); (iv) developing theories (establishing theories required to clarify problems) that ensure the precision of numerical calculations and sufficient computational capability; and (v) comprehensively putting the above processes in action using computer (selection of calculation technology).

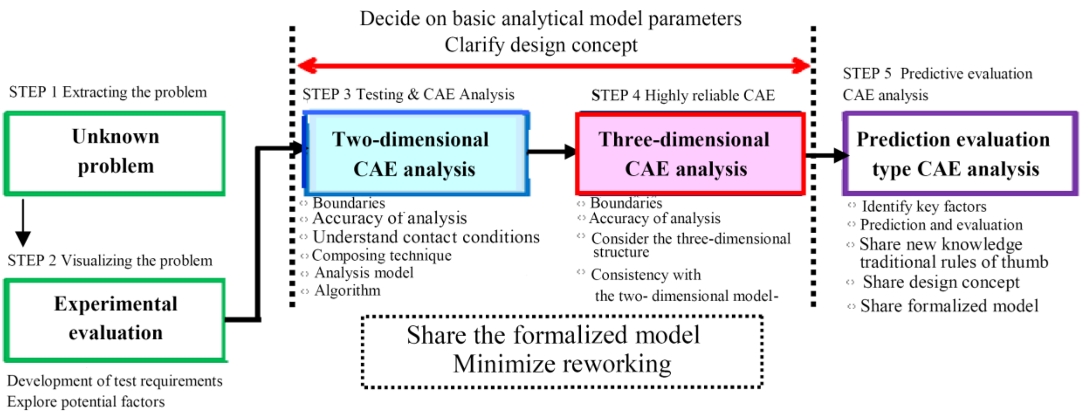

Figure 4: Highly Reliable CAE Analysis Model.

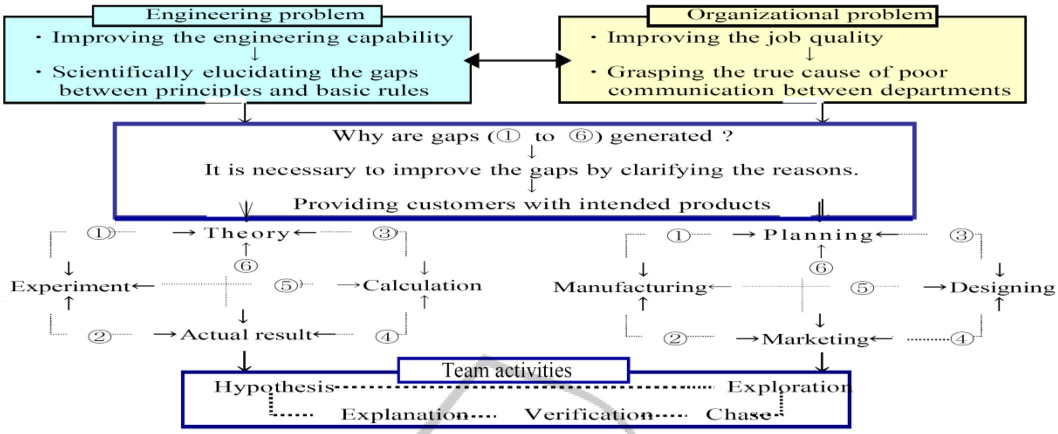

Figure 5: Total QA hight Cyclization Business Process System.

3.2 The Highly Precise CAE Analysis Model

In order to minimize discrepancies in results obtained from testing of actual products and CAE, it is necessary to properly formalize the expertise of the many technical analysts required for CAE analysis.

To achieve this, the author (Amasaka, 2008: Takahashi, et al., 2010) proposes the use of the Highly Precise CAE Analysis Model shown in Figure 4 to enable highly precise absolute analysis.

Functional failures are a recurring cause of market claims in automotive development design, making it necessary to clarify relevant technical issues such as the reasons and mechanisms by which such failures occur. This should be done according to the following steps.

STEP 1 Extracting the problem: Investigate and analyze the causal relationships that become apparent and infer the mechanisms through which failures occur, employing the latest "statistical science methods" backed up by expertise accumulated through the cooperative efforts of internal and external specialists (Amasaka, 2003).

STEP 2 Visualizing the problem: Test actual products demonstrating the failure mechanisms to visualize the dynamic behavior of the problem. In order to accurately analyze the failure and its causes, it is necessary to uncover any underlying factors that were not evident from previous findings and may have been overlooked. A logical reasoning process must be applied to demonstrate the mechanisms of the failure, employing tools and principles such as statistical science methods.

STEP 3 Testing & CAE analysis: Consolidate the findings and apply statistical simulation to create a two-dimensional model integrated on a qualitative level where the visualization produced through actual testing can be reproduced. When creating this two-dimensional model, it is necessary to conduct tests to produce a model (qualitative modeling) of the causal relationships involved in undefined failure mechanisms. Precise calculation methods, analysis models and algorithms must be properly selected in order to clarify boundary conditions and contact situations, as well as to enable highly accurate statistical simulation. It is essential to use such tools to minimize discrepancies between actual testing and CAE absolute evaluation. The findings from such analysis should then be used for more detailed three-dimensional analysis.

STEP 4 Highly reliable CAE: Conduct accurate testing of actual products based on the findings from STEP 3 to gain a more explicit understanding of the failure mechanisms. Consolidate the findings from the processes involved and conduct statistical simulation (quantitative modeling) with a high level of credibility to enable the prediction and control of absolute values.

STEP 5 Predictive evaluation CAE analysis: In this final step, identify the primary factors from the results of the statistical simulation in STEP 4 to be used for prediction and evaluation. The new findings obtained, design concepts, and formulation models should be shared and disseminated. Utilizing models with a higher level of analytic accuracy enables manufacturers to move from relative evaluation to absolute evaluation of analysis results in the actual development process. The authors believe that this will lead to the future establishment of design frameworks involving predictive evaluation.

3.3 Total QA High Cyclization Business Process Model

As the first step, the author proposes the development design business process model. This model is created from the standpoint of Verification/Validation (divergence of CAE from theory and divergence of CAE from testing) in order to make highly reliable CAE analysis that is consistent with the market testing theory profile possible. The author (Amasaka, 2008) therefore recommends the introduction and utilization of the Total QA (Quality Assurance) High Cyclization Business Process System, which systematically and strategically realizes high quality assurance by incorporating analyses made via the core technologies of Science SQC (Amasaka, 2004) as shown in Figure 5. For example, in order to solve the pending issue of a technology problem in the market, it is necessary to create a universal solution (general solution) by clarifying the existing six gaps (1 to 6 in the figure below) in the process consisting of theory (technological design model), experiment (prototype to production), calculation (simulation), and actual result (market) as shown on the lower left of Figure 5 below.

To accomplish this, the clarification of the six gaps (1 to 6) in the business processes across the divisions, shown in the lower right of Figure 5 below, is of primary importance. By taking these steps, the intelligent technical information owned by the related divisions inside and outside the corporation will be fully linked, thus reforming the business processes involved in development design.

3.4 The Intellectual Customer Data Collection/Analysis Integrated Model

Collecting, organizing, and analyzing different types of technical information is a critical part of the development design process. For this reason, it is important that manufacturers set up a comprehensive networking system that makes full use of digital engineering and information technology, allowing them to collect and analyze customer information in real time. Figure 6 shows the Intellectual Customer Data Collection/Analysis Integrated Model developed by the author (Amasaka, 2004, 2005a, 2010a), which uses the Total Technical Intelligence System (TTIS) and the Customer Science Utilizing Customer Information Analysis and Navigation System (CS-CIANS)—two of the core methods of Science SQC.

As indicated in the figure, the system allows companies to collect customer data from (1) domestic and overseas dealers and (2) consulting spaces as well as (3) customer quality information in real time from research firms and the like using (4) customer data input forms and customer data retrieval forms. This information is then stored in a searchable database. The system then uses a company web that allows (5) divisions involved in product design and (6) other related divisions to obtain customer data and analyze it from multiple angles.

This enables the partnering of preproduction, testing/evaluation, and numerical simulations (CAE), and further strengthens mutual collaboration

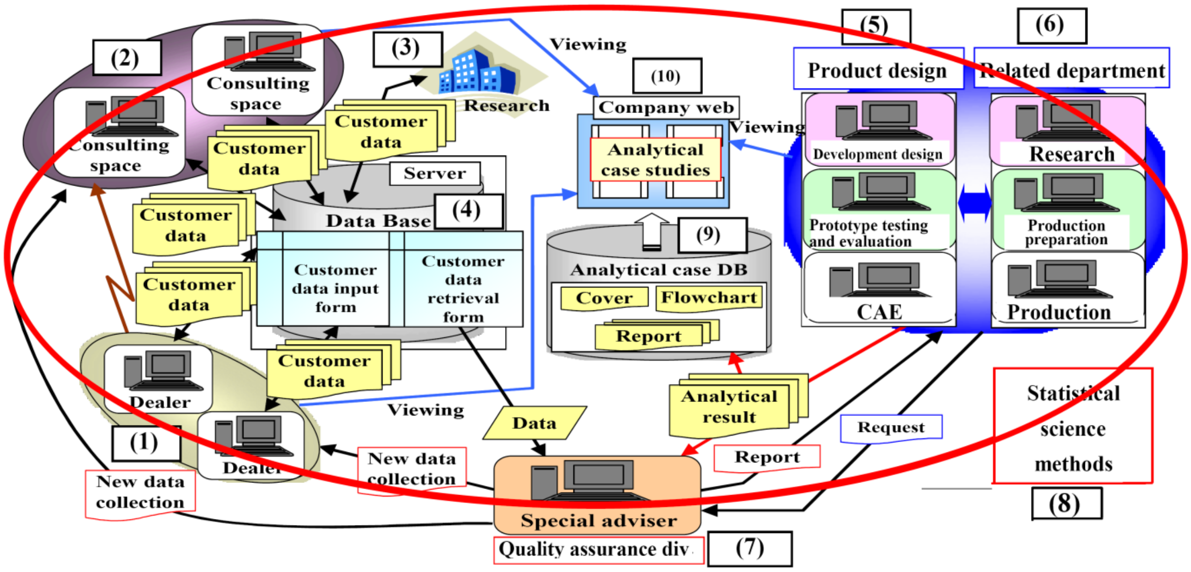

Figure 6: Intellectual Customer Data Collection/Analysis Integrated System.

between related divisions and (7) the special advisor in the quality assurance division. Customer data is analyzed making full use of (8) statistical science methods, which allows optimization of development design specifications in real time, and then (9) recorded in a database of analytical cases. Additional analysis results are recorded as (10) analytical case studies, where they can be viewed using the company web and used by related departments as technical assets. The next chapter presents some application examples where these core models were put to work in a comprehensive way. The case examples verify the effectiveness of the New Development Design CAE Deployment Model created by the author.

4 APPLICATION

This chapter presents the case of automotive transaxle oil seal leakage, a technical reliability problem that generates bottlenecks for auto manufacturers around the world. The author applied his New Development Design CAE Employment Model to resolve this issue. The model was then applied to similar technical problems, where its effectiveness was verified.

4.1 Automotive Transaxle Oil Seal Leakage

The key to resolving problems where the faulty mechanism is unclear is to use an empirical approach and apply technology that allows visualization of the dynamic behavior at the moment the problem occurs. The structure of the problem must then be unraveled so that an accurate model of cause-and-effect relationships can be built. To achieve this, the authors (Amasaka, 2004, 2005b, 2008, 2010b: Amasaka, Ed., 2007b: Ito, et al, 2010a, 2010b) applied the following analytical process: (1) understand the phenomenon, (2) conduct a visualization experiment, (3) conceptualize the problem logically, (4) apply CAE analysis, and (5) optimize the design. The result was a plan to resolve oil leaks caused by age-related wear to the transaxle oil seal lip.Figure 7 uses a relational diagram to organize related causes and knowledge previously collected on the problem. Because the mechanism causing the oil leak was unknown, the pathway by which it was generated is not clearly shown. Areas of dynamic behavior that needed to be visualized were specified and tested using a visualization device.

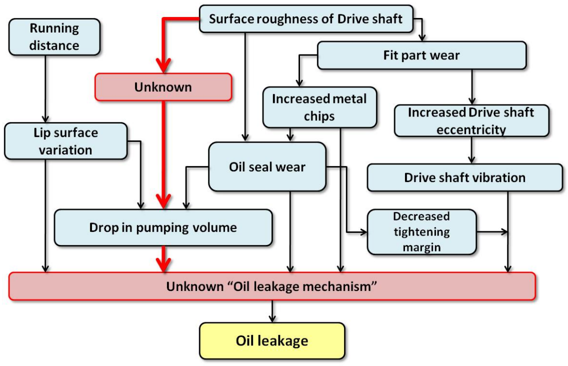

Figure 7: Estimation of the Oil leakage mechanism.

4.1.1 Highly Accurate CAE Analysis Model Using Science SQC Approach

The problem is an unknown mechanism causing an oil seal leakage on the surface of the drive shaft during high-speed rotation (Lopez, et al., 1997). Now, the authors will discuss the application of highly accurate CAE analysis for drive train oil seal leaks through a partnership between company C (automotive assembly company) and company D (parts supply company) as an example of cases where the mechanism of technical problems is unknown. As shown in Figure 8, the authors applied an optimal CAE design approach to prevent automobile oil seal leaks, incorporating Science SQC approach methods.

As the figure shows, the authors contributed to solving the problem of drive train oil seal leaks, which is a bottleneck technological problem for automotive manufacturers worldwide. This was achieved through an analysis process involving problem clarification, visualization experiments, theoretical conceptualization, CAE analysis, and optimal design. First, the authors began by developing a device for visualizing the ascertained phenomena in order to estimate the unknown mechanisms involved in the leaks. This made it possible to estimate the mechanism of the oil seal leaks by visualizing the dynamic behavior involved in the process whereby metal particles (foreign matter) from gear rotation wear, found around the rotating and sliding portions of the oil seal lip, become mechanically fused and accumulate.

Next, the findings obtained were used to formulate the following design countermeasures.

(i) Strengthen gear surfaces to prevent occurrence of foreign matter even after 100,000 km (improve quality of materials and heat treatments)

(ii) Formulate a design plan to scientifically ensure optimum lubrication of the surface layer of

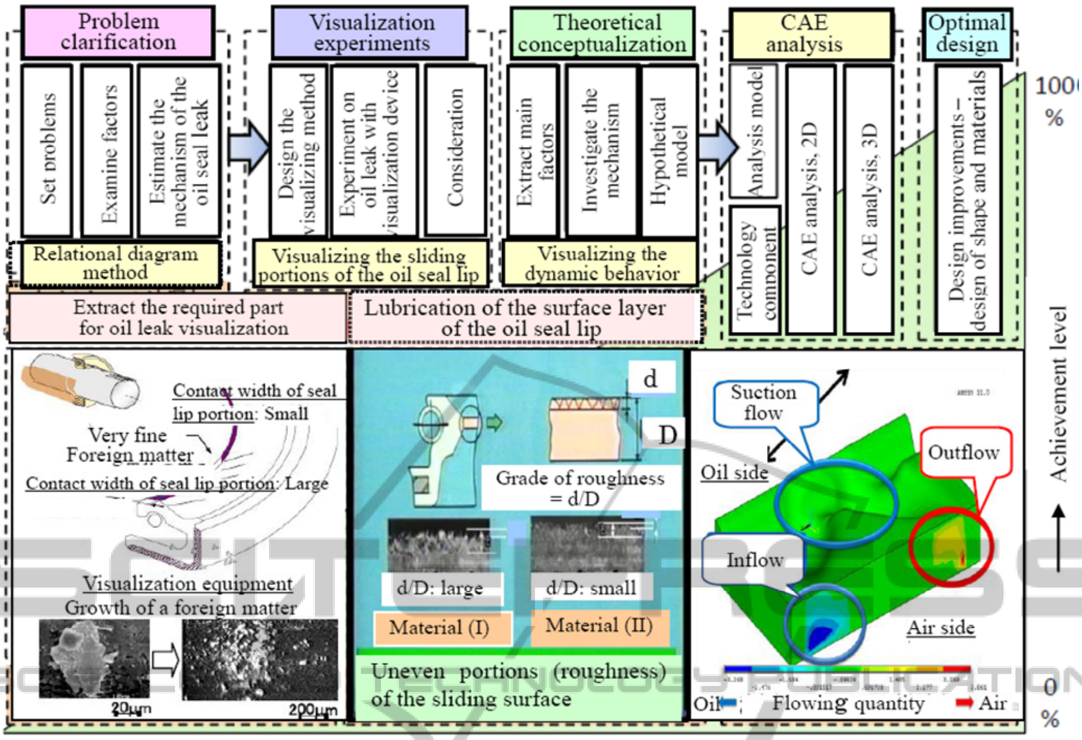

Figure 8: Highly Accurate CAE Analysis Model using Science SQC approach.

the oil seal lip (uneven portions of the sliding surface) where it rotates in contact with the drive shaft.

4.1.2 Sliding Surface Visualization Experiment

The sliding side observation experiment was conducted using three types of seals made of different materials and shapes. Here, two seal characteristic values are defined: (1) XG and (2) AR as shown in Figure 9. XG is the distance that the true contact area center of gravity is biased from the sliding side center to either the oil side (1>XG>0) or the atmospheric side (-1<XG<0); it is the characteristic value that shows the extent true contact area distribution bias axially. XG can be interpreted as the maximum pressure position of the contact pressure distribution. AR is a characteristic value indicating roughness on the seal sliding side level, and shows the proportion of the visible touch area that is the real contact area.

Table 1 shows the characteristic seal values and the outcome of the experiments for the three types. In addition, leakage stopping can be classified according to both characteristic values by looking at the relationship between these two characteristic values and the observed state of the leakage stopping shown in Table 1. Sealing is achieved only in Seal 1 in the table, and sliding surfaces show the characteristic values XG>0 and AR<0.05 (5%). It is evident that the unique sliding side structure to ensure sealing has minute surface roughness (existence of minute projections) and the true contact area is biased towards the oil side (Sato et al., 1999: Kameike et al., 2000).

$$A_R = \frac{\text{The real contact area}}{\text{The visible touch area}} = \frac{(\text{Shaded area})}{(a \times b)} \quad (1)$$

$$X_G = \frac{\sum dAi\left(\frac{Xi}{b/2}\right) - \sum dAj\left(\frac{Xj}{b/2}\right)}{\sum dAi + \sum dAj} \quad (2)$$

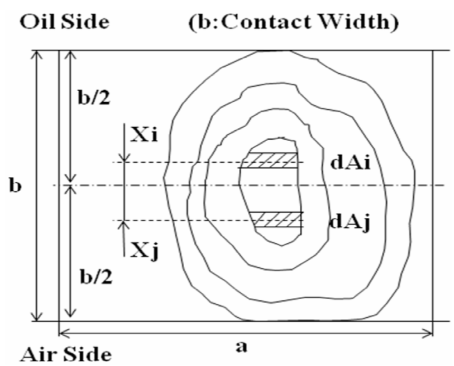

Figure 9: Pattern Diagram of the Sliding Side.

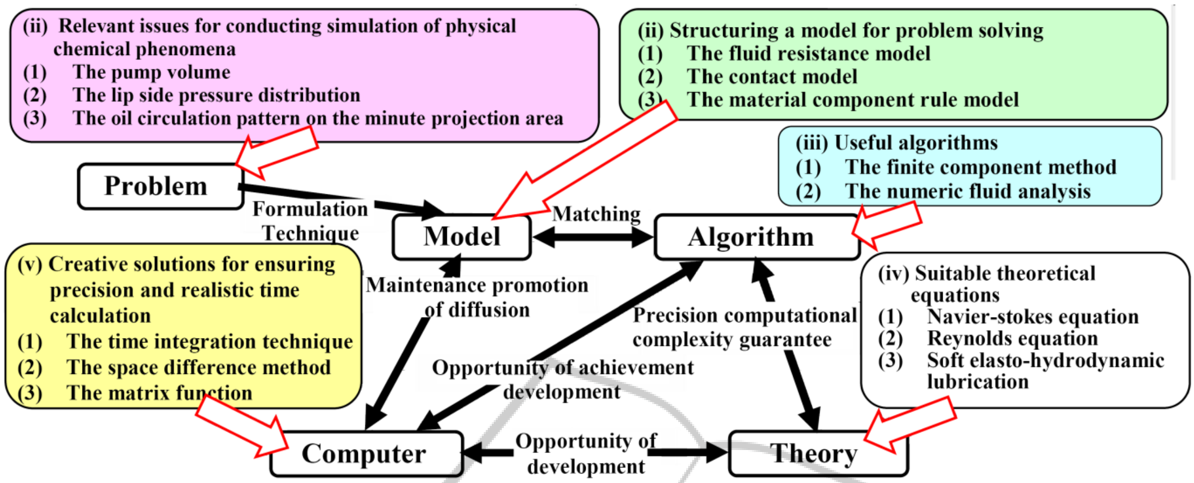

Figure 10. Technology Component Model of the “Oil Seal Simulator”.

Table 1: Outcome of the Experiments.

	Type 1	Type 2	Type 3
X_G	0.02	0.47	0.04
A_R	0.14	0.05	-0.21
result	Sealing	Leakage	Leakage

4.1.3 Technological Component Model of the Oil Seal Simulator

In order to conduct a numerical analysis based on the knowledge gained from the visualization experiment, it is necessary to select the kinds of technological elements involved. Appropriate selection of technological elements (defining the problem, modeling, algorithms, theory, and computer technology) is a critical part of generating highly reliable CAE analysis results.

Organically linking these technological elements is what will make the CAE analysis a success.

The authors thus added the needed technological component to the “Oil Seal Simulator” as shown in Figure 10. In addressing the oil leakage phenomenon, the problem is understanding the pump volume and lip side pressure distribution that directs the behavior and the oil circulation pattern on the minute projection area of sliding surfaces. The fluid resistance model, the contact model, and the material component rule model were used to solve these problems. The finite element method and numeric fluid were analyzed as a convenient algorithm. The Reynolds equation, Soft Elasto-Hydrodynamic Lubrication, and Navier-Stokes equation were appropriate theoretical formulas. Accuracy is ensured, and the time integration method, space difference method, and procession method were the computer technologies used to perform calculations in a realistic timeframe. Each of the above elements was used to construct the oil seal simulator.

4.1.4 CAE Qualitative Model of the Basic Oil Seal Lip Structure

The visualization experiment yielded the conditions on the sliding surface of the oil seal lip as a basic structural element. The authors then used this element to construct the CAE qualitative model of the basic oil seal lip structure shown in Figure 11 in order to demonstrate sealing conditions. The model uses a statistical approximation of the slight roughness on the sliding surface to show the wedge effect created by minute projections.

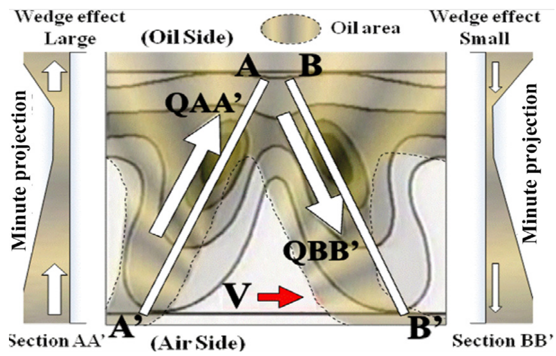

Figure 11: CAE Qualitative Model of the Basic Oil Seal Lip Structure.

In looking at seal conditions on the sliding surfaces as a whole, the authors concluded that the volume of inflow was greater at QAA’ than the outflow at QBB’, based on the fact that minute projections in section AA’ created a larger wedge effect than the minute projections in section BB'. These conditions also generated the oil circulation pattern on the minute projection area of sliding surfaces, which meant that wear could be prevented by separating the two surfaces (Sato, et al., 1999: Kameike, et al., 2000: Dong, et al., 2011).

4.1.5 CAE Analysis (2D and 3D)

Using the technological elements mentioned above, a two-dimensional CAE analysis was used to conduct a numerical simulation that would accurately describe the behavior of the oil on the problematic minute projection areas. Figure 12 shows the results of this analysis. It shows the space between the shaft near minute projection AA' and minute projection BB' and the seal where oil is getting trapped. This two-dimensional analysis shows that shear stress is being generated by the fluid (oil) due to the rotation of the shaft and that the seal side flow direction is being reversed as the minute projections narrow the fluid channel. Next, a three-dimensional analysis was conducted using a structural model of the sliding surfaces as a whole. The model took into account the direction of oil flow in a third dimension (depth) based on the knowledge gained from the visualization experiment and the two-dimensional CAE analysis. The model was used to do a numerical simulation of the oil film present on the sliding surfaces.

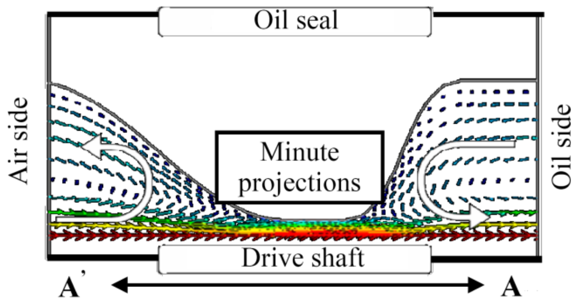

Figure 12: A two-dimensional analysis.

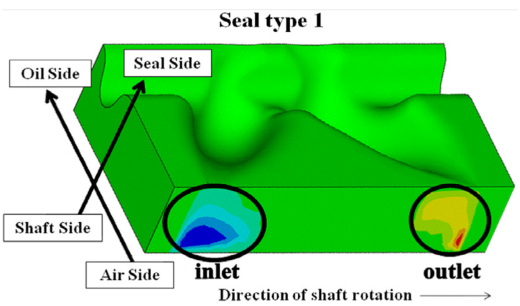

Figure 13: A three-dimensional analysis.

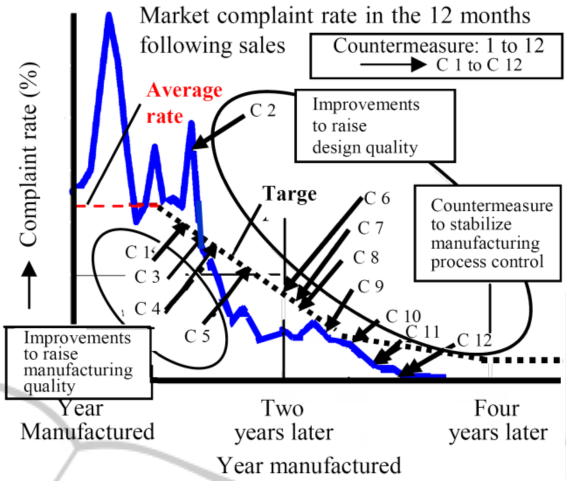

Figure 14: Reduction in market complaint rate.

The analytical model shown in Figure 13 was constructed based the CAE qualitative model of the basic oil seal lip structure shown in Figure 11. By imposing conditions such as shaft rotation speed, the amount of oil flow on the oil side and air side could be calculated. The oil flow to the seal side and to the air side was compared, producing similar results to the visualization experiment.

4.1.6 Quality Improvement

The visualization experiment above allowed the dynamic behavior of the oil leak to be visualized; more specifically, the dynamic behavior involved in the process whereby metal particles (foreign matter) from gear rotation wear, found around the rotating and sliding portions of the oil seal lip, become mechanically fused and accumulate. This phenomenon was then reproduced in a two- and three-dimensional CAE analysis with high precision (with a deviation of around 3% versus prototype testing evaluations). This information made it possible to gain an approximate understanding of the oil seal leak mechanism and optimize design parameters using a numerical simulation.

These results led to two measures to improve design quality (shape and materials): (1) strengthen gear surfaces to prevent occurrence of foreign matter even after the B10 life (L10 Bearing to MTBF (Mean Time Between Failures)) to over 400,000 km (improve quality of materials and heat treatments) and (2) formulate a design plan to scientifically ensure optimum lubrication of the surface layer of the oil seal lip (uneven portions of the sliding surface) where it rotates in contact with the drive shaft. As shown in Figure 14, the result of these countermeasures was a reduction in oil seal leaks (market complaints) to less than 1/20th their original incidence.

4.2 Application to Similar Problems

With its effectiveness verified, the authors were able to apply the New Development Design CAE Employment Model to critical development design technologies for automotive production, including predicting and controlling the special characteristics of automobile lifting power, anti-vibration design of door mirrors (Amasaka, 2010b), urethane seat foam molding (Amasaka, 2007), and loosening bolts (Yamada and Amasaka, 2011:). In each of these cases as well, discrepancy was 3–5% versus prototype testing. Based on the achieved results, the model is now being used as an intelligent support tool for optimizing product design processes.

5 CONCLUSIONS

This research addresses the necessity reforming the business processes associated with development design, a critical component of manufacturing, by proposing a New Development Design CAE Employment Model that takes manufacturers away from conventional preproduction and prototype testing methods and towards a better predictive evaluation method. The effectiveness of the model was verified by successfully applying it to the technological problem of development design bottlenecks at auto manufacturers. The author wants to make it further established as "Optimal CAE Design Approach Mode" by deployment of this model from now on.

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