Constructing Optimal CAE Design Approach Model: Application of the *Advanced TDS*

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Abstract: - This paper focus on a strategic development of "*Advanced TDS*, *Total Integrated Development Design Model*" to be used in development design, then proposes an "Optimal CAE Design Approach Model" that can be used to shorted development design times. The model is then used to analyze "cavitation caused by metal particles in the automotive transaxle" and to clarify the technological mechanism generating oil leaks as a result of foreign metallic substances entering oil seals in the drive train.

Key-Words: - *Advanced TDS*, Optimal CAE Design Approach Model, oil seal, oil leaks, metal particles, cavitation, automotive transaxle

1 Introduction

In recent years, the advanced manufacturing industry has 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) of analysis in order to achieve quality development design processes that are also very brief [1-4].

To address these issues, the author conducted research on an "Optimal CAE Design Approach Model" utilizing "*Advanced TDS, Total Integrated Development Design Model*". In this study, the author addresses the technological problem of oil seal leakage in automotive drive trains as a way to construct an Optimal CAE Design Approach Model for quality assurance. The model is used to explain "cavitation caused by the metal particles (foreign matter)" generated through transaxle wear, a pressing issue in the automobile industry.

2 CAE in Product Design - Application and Issues

2.1 CAE in the Development Design Process

The time between product design and production has been drastically shortened in recent years with the rapid spread of global production. Quality assurance (QA) has become increasingly critical, making it essential that the product design process—a critical component of QA—be reformed to ensure quality [3,5].

Fig. 1 shows the typical product design process currently used by many companies [3]. The figure shows that companies first create product design instructions based on market research and planning. They then use these instructions to make specific product 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 analysis enables engineers to determine

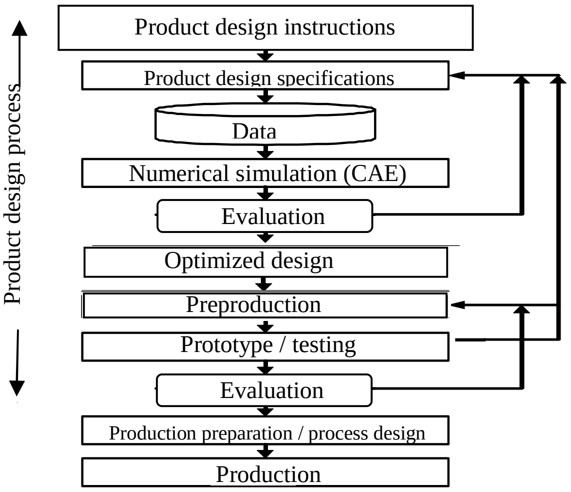


Fig. 1 CAE in the Product Design Process

whether the product design specifications result in sufficient product quality—and if not, the specifications are promptly optimized. Manufacturers then carry out effective preproduction, testing and evaluating prototypes (prototype testing). A final evaluation of the development design is conducted, and if there are no problems, companies move to production preparation and process design in order to get ready for full-scale production.

2.2 CAE Analysis: Current Status and Issues

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 [3,6]. The product design process, for example, is typically one guided by unspoken experiential knowledge and rules of thumb, leading to prototype testing guided by repeated trial-and-error efforts. 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 [1,2,4].

Despite these high expectations, conventional forms of CAE analysis resulted in figures that deviated as much as 10–20% from those obtained through prototype testing evaluations. This means that many companies are now stuck with applying CAE only to the monitoring task of comparative evaluations of old and new products—despite the enormous amount of funds they have invested in CAE development. There are two absolute requirements for precise (highly reliable) CAE analysis methods that can both prevent the critical technical problems plaguing manufacturers from recurring and contribute to new product designs. The first is reducing the deviation from prototype testing evaluation figures to 5% or less, and the second is evaluating the absolute values needed for tolerance designs.

3 Application of the *Advanced TDS, Total Integrated Development Design Model*

Currently, to continuously offer attractive, customer-oriented products, it is important to establish a "*new development design model*" that predicts customer needs. In order to do so, it is crucial to reform the business process for development design [2,3]. Manufacturing is a battle against irregularities, and it is imperative to renovate the business process in the development design system and to create a technology so that serious market quality problems can be prevented in advance by means of accurate prediction/control.

For example, as a solution to technical problems, approaches taken by design engineers, who tend to unreasonably rely on their own past experience, must be clearly corrected. In the business process from development design to production, the development cost is high and time period is prolonged due to the "scale-up effect" between the stages of experiments (tests and prototypes) and mass production. In order to tackle this problem, it is urgently necessary to reform the conventional development design process.

Focusing on the successful case mentioned above, the author [2,7] deems it a requisite for leading manufacturing corporations to balance high quality development design with lower cost and shorter development time by incorporating the latest simulation CAE and *Science SQC (Statistical Quality Control)*. Against this background, it is vital not to stick to the conventional product development method, but to expedite the next generation development design business process in response to a movement toward digitizing design methods.

Having said the above, the author [1,8] established the "*Advanced TDS, Total Integrated Development Design Model*" as the key to the high cyclization of development and design Processes so called "*New Japan Development Design Model*" as described in Fig. 2. This model is aimed at the simultaneous achievement of QCD (Quality, Cost and Delivery) by high quality manufacturing which is essential to realize CS (Customer Satisfaction), ES (Employee Satisfaction), and SS (Social Satisfaction).

For realization, (1) customers' orientation (subjective implicit information) must be scientifically interpreted by means of "*Customer Science*" [9], namely, converting the implicit information to explicit information by objectifying the subjective information using *Science SQC* so as to (2) create "*High Reliable Development Design System*", thereby (3) eliminating prototypes with accurate prediction and control by means of *"Intelligence Simulation"*. To this end, it is important to (4) introduce the "*Intellectual Technology Integrated System*" which enables a sharing of knowledge and the latest technical information possessed by all related divisions.

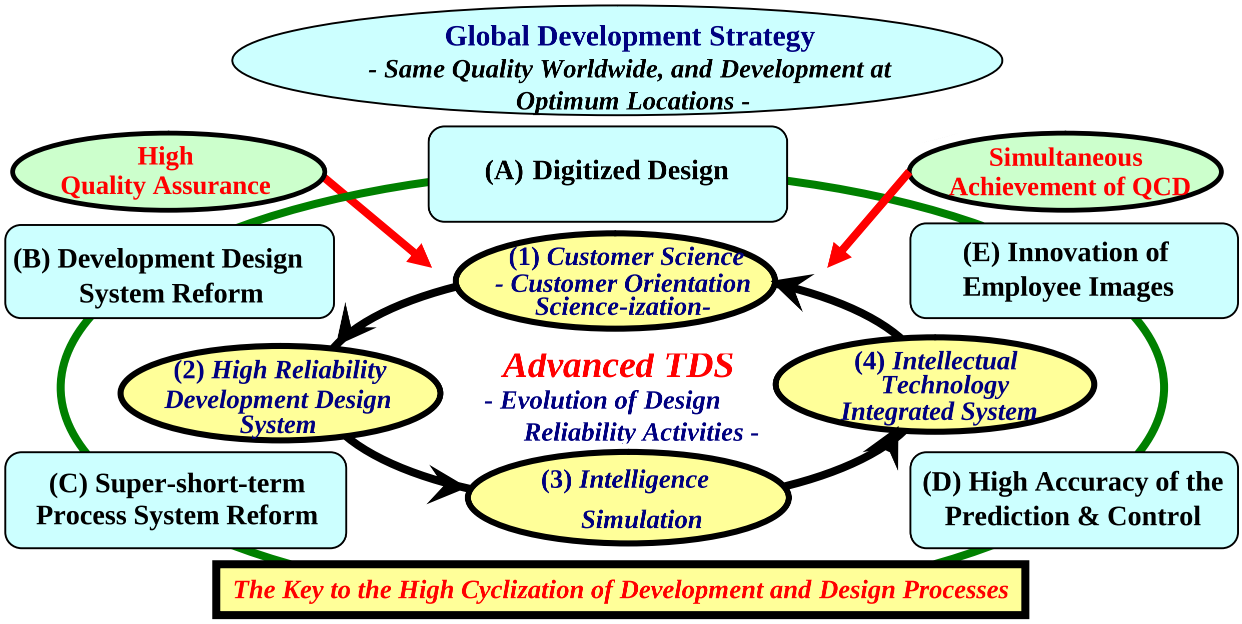


Fig. 2 *Advanced TDS*, Total Integrated Development Design Model

4 Proposal of Optimal CAE Design Approach Model

This chapter presents an Optimal CAE Design Approach Model in Fig. 3, which shows the procedural elements in steps one through five of the business process used in automotive product design [4,10,11].

4.1 STEP 1: Define the Problem

Step 1, defining the current situation, means explaining problematic technological issues where the number of functional breakdowns is to clarify why the breakdowns are occurring as well as the mechanism that is generating them. Experts inside and outside the company use their collective wisdom in collaborative activities, applying the latest statistical methods and investigating and analyzing complex cause-and-effect relationships to define the problem in minute detail and reason out the faulty mechanism.

4.2 STEP 2: Conduct a Visualization Experiment

In step 2, 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

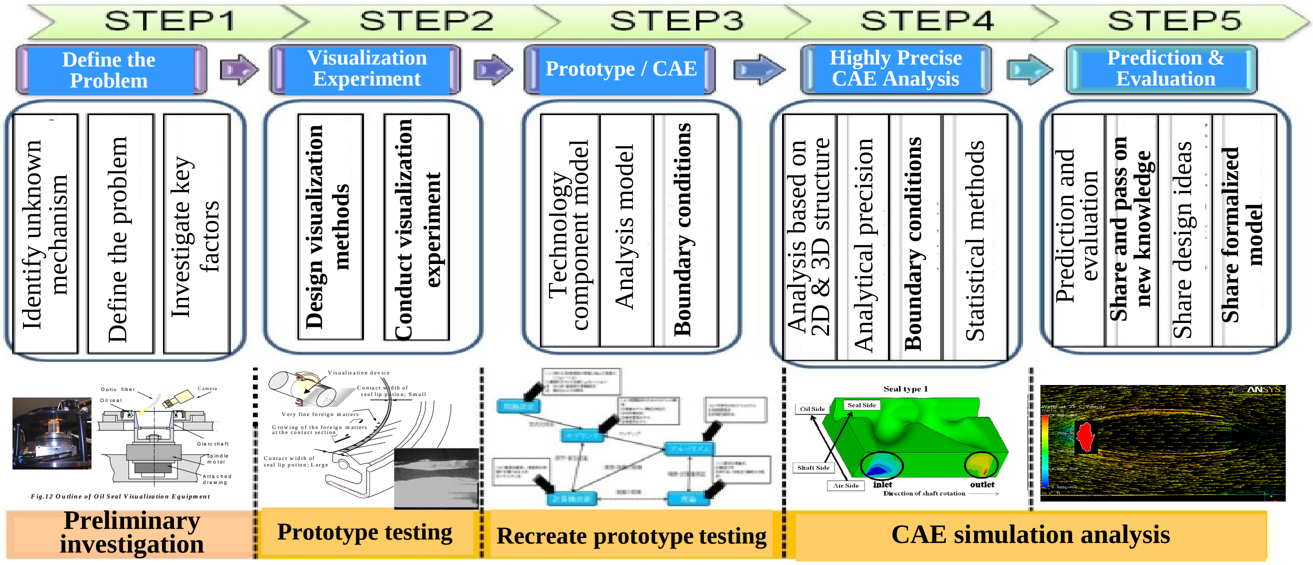


Fig. 3 Optimal CAE Design Approach Model

further defined. Specifically, the *Science SQC* approach—SQC Technical Methods are applied to accurately explain the fault and conduct a factor analysis. These methods use N7 (seven new QC tools), SQC (general statistical methods), RE (reliability analysis), MA (multivariate analysis), and DE (design of experiment) [4,7]. The use of these methods allows the discovery of previously overlooked and unidentified latent factors and the faulty mechanism to be demonstrated via a logical thought process.

4.3 STEP 3: Aligning Prototype Testing and CAE

In step 3, the key factors (technology components) identified in steps 1 and 2 that are generating the fault are subjected to a numerical simulation (CAE). The numerical simulation makes it possible to match results obtained through prototype testing and CAE analysis (Two and Three dimensional model) using absolute values, values for which there is no discrepancy between the prototype testing and CAE analysis. At this point, all business processes are scientifically and comprehensively optimized using the following steps, which must be part of a highly precise CAE analysis: define the “phenomenon (defining the problem) – theory – algorithm (calculation methods) – modelling – calculation technology” by using “Highly Reliable CAE Analysis Technology Component Model as shown in Fig. 4 [1, 3].

In doing this, it is absolutely essential to clearly model the cause-and-effect relationships in unexplained mechanisms identified during prototype testing (visualization). When implementing this step for automotive problems like “urethane foam of seat pads, oil seal leaks and bolt tightening” [2,12,13], for example, it is important to clarify boundary and contact conditions. In order to conduct a precise numerical simulation, there must be both an accurate theory and an experimental model that can logically define the impact of the latent factors identified during the experiment. Selecting a model with logical calculation procedures, analytical modeling, and algorithms is a must, with the goal of qualitatively modeling the fault (mechanism).

4.4 STEP 4: STEP 4: Conduct a Highly Precise CAE Analysis

In step 4, conducting a highly precise CAE analysis, a highly reliable numerical simulation (quantitative modelling/highly precise CAE analysis) is conducted. This makes it possible to predict and control the absolute values needed for the CAE analysis based on the knowledge gained in step 3 [12,13]. In the above case, a mesh was created using optimization and contact conditions were defined.

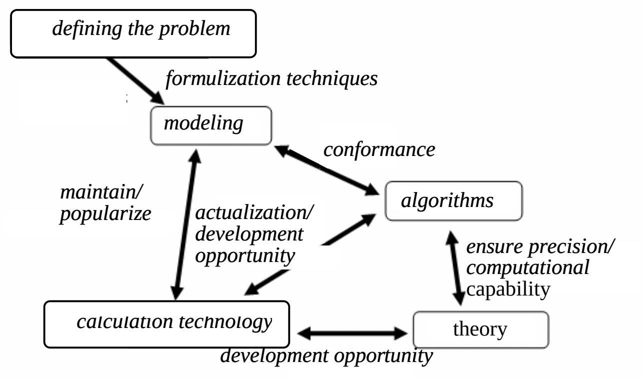


Fig. 4 Highly Reliable CAE Analysis Technology Component Model

4.5 STEP 5: Predict and Evaluate

Highly reliable CAE analysis makes CAE analysis for predictive evaluation possible when carrying out the business processes in steps 1 through 4 in minute detail. In the past, CAE modeling was often conducted in an illogical way, with conventional CAE analysis and an undefined faulty mechanism. The result was a significant discrepancy (10–30%) between prototype testing and CAE analysis values, often confining the use of CAE analysis to the auxiliary monitoring task of comparative evaluations of old and new products [1,2,4].

CAE analysis for predictive evaluation (steps 1 through 4) makes precise prediction and evaluation possible by pinpointing key factors, accurately identifying the development design factors that must be optimally controlled, and making them explicit by incorporating them into drawings and manufacturing techniques. This contributes to swift design development that includes the generation of new knowledge, new design ideas, sharing of explicit models, and creating assets out of new technology that gets passed on and developed.

5 Application: Drive Train Oil Seal Leaks — Analyzing Cavitation Caused by Metal Particles in the Transaxle

In this chapter, the author [2,4,11,12] uses both prototype testing and CAE, applying the Optimal CAE Design Approach Model to explain undiscovered technological mechanisms and then develop a model based on their investigative process.

5.1 Oil Seal Function

An oil seal on an automobile's transaxle prevents the oil lubricant within the drive system from leaking from the drive shaft. It is comprised of a rubber lip molded onto a round metal casing. The rubber lip grips the surface of the shaft around its entire circumference, thus creating a physical oil barrier. In this case the sealing ability of microscopic roughness on the rubber surface is of primary importance [14].

The parameters for the sealing condition of the oil film involve not only the design of the seal itself, but also external factors such as shaft surface conditions, shaft eccentricity, and so on. Contamination of the oil by minute particles was found to be of particular importance to this problem since these are technical issues which involve not only the seal, but also the entire drive train of the vehicle.

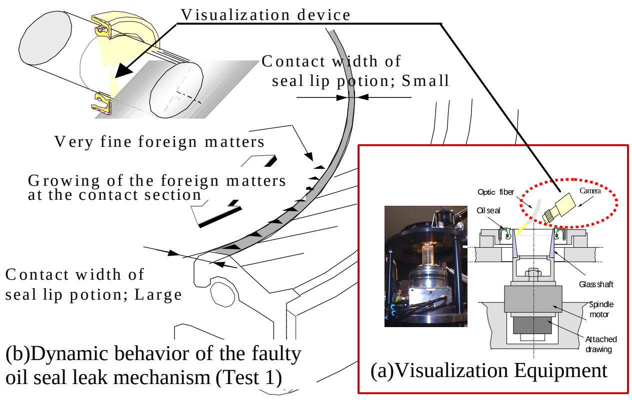
5.2 Understanding of the Oil Sal leak Mechanism through Visualization

The oil leaks and similar problems can result in immediate and critical vehicle defects. One of the primary causes of oil seal leaks is wear to convex areas of the oil seal (O/C) where it comes into contact with the surface of the drive shaft, which is rotating at high speeds. The author is applying their Optimal CAE Design Approach Model to this issue in order to resolve it [2,12].

5.2.1 Defining the Problem and Conducting a Visualization Device (Step1)

This section addresses a second unexplained problem: metal particles (foreign matter) generated from rotation wear in drive train gears. The dynamic behavior of the faulty oil seal leak mechanism causing these metal particles to form was outlined using the developed visualization device in Fig. 5(a), in order to turn this "unknown oil leak mechanism" into explicit knowledge.

As shown in the figure, the oil seal was immersed in the lubrication oil in the same manner as the transaxle, and the drive shaft was changed to a glass shaft that rotated eccentrically via a spindle motor so as to reproduce the operation that would occur in an actual vehicle. The sealing effect of the oil seal lip was then visualized using an optical fiber. It was conjectured that in an eccentric seal with one-sided wear, the foreign matter becomes entangled at the place where the contact width changes from small to large. Three trial tests were carried out to ascertain if this was true or not. Based on the examination of faulty parts returned from the market and the results of the visualization experiment, it was observed that very fine foreign matter (which was previously thought to not impact the oil leakage problem) grew at the contact section, as shown in Fig. 5(b) (Test-1). It was also confirmed from the results of the component analysis that the fine foreign matter was a powder produced during gear engagement inside the transaxle gear box.



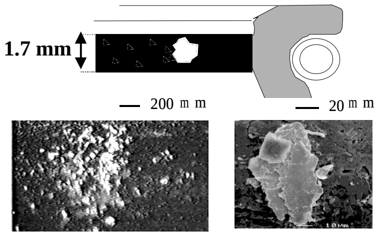
(b)Dynamic behavior of the faulty oil seal leak mechanism (Test 1)

(a)Visualization Equipment

Fig. 5 Oil Seal Visualization Device and Oil Seal Leak Mechanism Causing Metal Particles

5.2.2 Identifying the Oil Leak Mechanism (Step2)

This fine foreign matter on top of microscopic irregularities on the lip sliding surface resulted in microscopic pressure distribution which eventually led to the degrading of the sealing performance (Fig. 6, Test-2). Also, the presence of this mechanism was confirmed from a separate observation that foreign matter had cut into the lip sliding surface, thereby causing aeration (cavitations) to be generated in the oil flow on the lip sliding surface.



Foreign matter on Sliding surface after reproduction test (Video, 10 rpm)

Foreign matter on sliding surface of recovered part (SEM)

Fig. 6 Oil Leakage Mechanism (Test-2)

This caused deterioration of the sealing performance, as shown in Fig. 7 (Test-3). The figure indicates that cavitations occur in the vicinity of the foreign matter as the speed of the spindle increases, even when the amount of foreign matter that has accumulated on the oil seal lip is relatively small. As the size of the foreign matter gets bigger, the oil sealing balance position of the oil seal lip moves more toward the atmospheric side and causes oil leaks at low speeds or even when the vehicle is at rest. This fact was unknown prior to this study, and therefore was not incorporated into the original product design of the oil seals.

As a result of these efforts, the author was able to investigate the mechanism generating the oil seal leaks and use factor analysis to pinpoint the design elements in the oil seal and drive train gears that should have controlled the problem. The mechanism involved cavitation occurring in rotating parts when foreign matter got wedged between sliding surfaces (on the lip surface). This happened in areas where there was variation in the size of the contact surface (from small to large) on the oil seal lip, caused by irregular wear and assembly variations.

The author used the knowledge obtained from the visualization experiment to logically outline the faulty mechanism as shown in Fig. 8. This was done in order to capture the problem using the Highly Reliable CAE Analysis Technology Component Model. Using this process, the authors were able to arrive at a hypothesis for why the cavitation was occurring; namely, factors like low pump volume and seal damage had compromised the tightness of the seal and lead to oil leaks.

5.3 Application of Optimal CAE Design Approach Model

5.3.1 Highly Reliable CAE Analysis Technology Component Model (Step 3)

The Highly Reliable CAE Analysis Technology Component Model shown in Fig.9 was created as

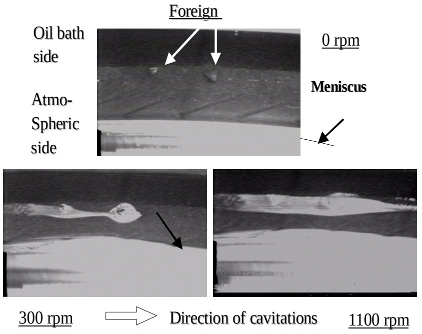


Fig. 7 Oil Leakage Mechanism (Test-3)

an essential requirement for precise CAE analysis. As the figure indicates, the designs are optimized by integrating several aspects of the calculation process, including problem (root cause) identification, conceptualizing the problem logically, using algorithms (calculation procedures), scientific modeling, and calculation methods (precision of calculators). Once the root causes of the problem are identified, it is critical that there is no discrepancy between the mechanism described and the results of prototype evaluations.

The visualization experiment revealed that cavitation was occurring due to a weakening of the oil seal in areas (surfaces) that were in contact with the rotating drive shaft. This weakening was causing oil seal leaks. The Rayleigh Plesset Model for controlling steam and condensation was used as a CAE analysis model that could explain the problem. The finite element method and non-stationary analyses were used as convenient algorithms. The Reynolds-averaged Navier-Stokes equation,

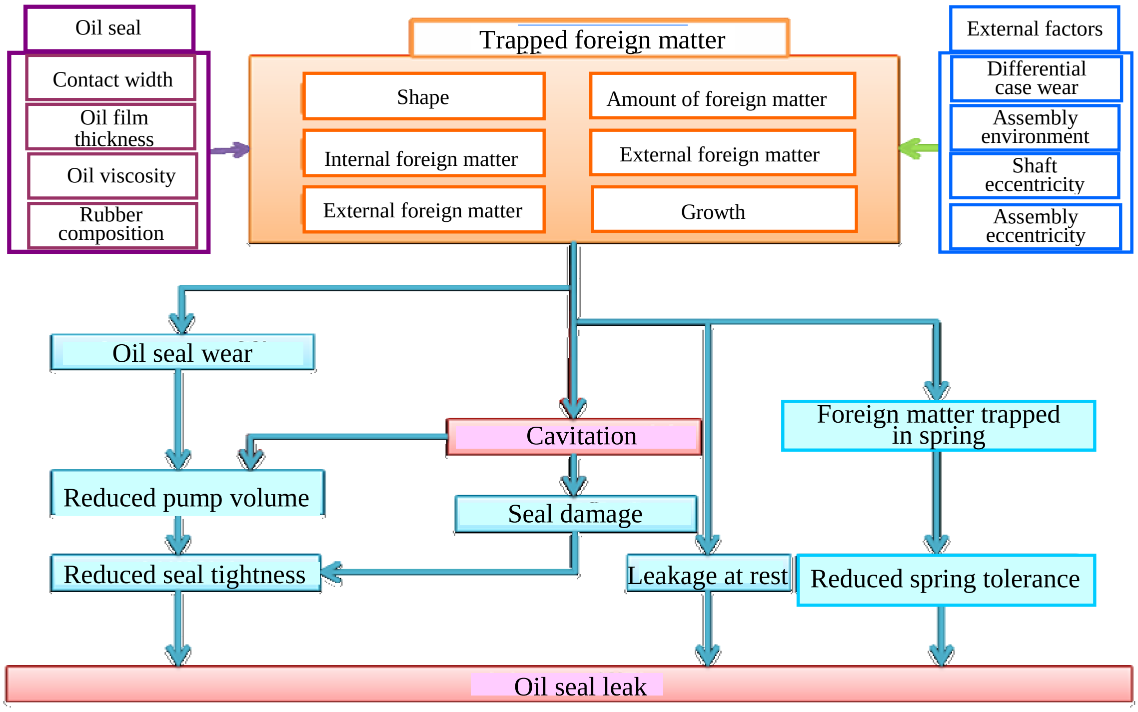


Fig. 8 Faulty Mechanism (oil leaks due to foreign matter)

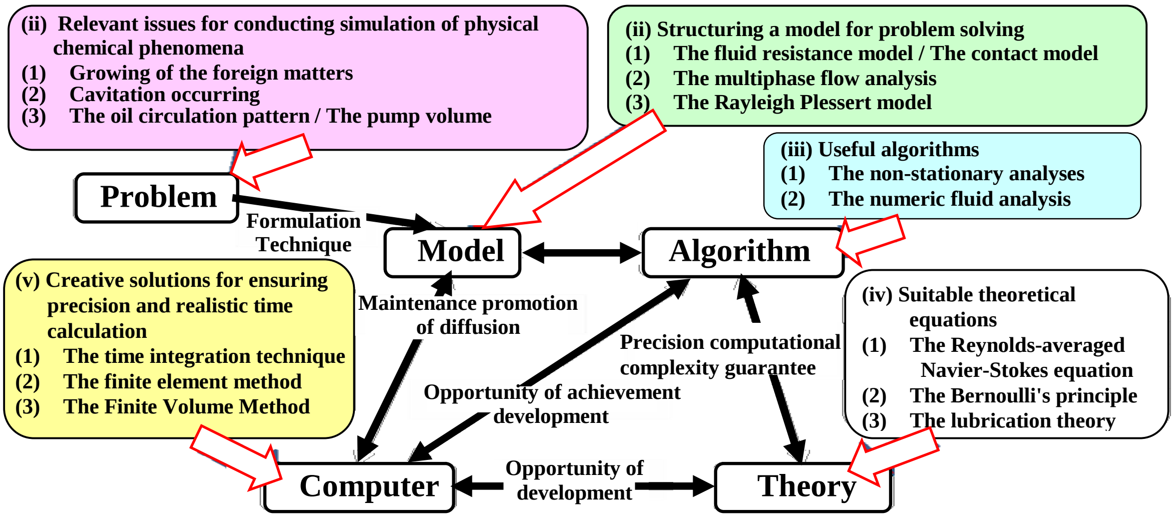


Fig. 9 Technology Component Model of the “Oil Seal Simulator”

Bernoulli's principle, and lubrication theory were appropriate theoretical formulas. Accuracy was ensured, and the time integration method was used to perform calculations in a realistic timeframe.

5.3.2 CAE Qualitative Model of the Basic Oil Seal Lip Structure (Step 4)

(1) CAE Qualitative Model

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 Fig. 10 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.

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 [15,16].

(2) Two-dimensional CAE Analysis

Using the technological elements mentioned above, a two-dimensional CAE analysis (2D analysis) was used to conduct a numerical simulation that would accurately describe the behavior of the oil on the problematic minute projection areas. Fig. 11 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.

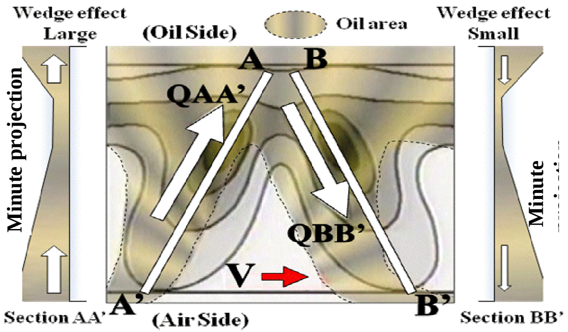


Fig. 10 CAE Qualitative Model of the Basic Oil Seal Lip Structure

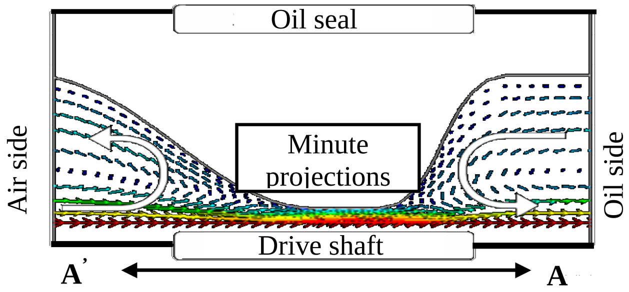


Fig. 11 A two-dimensional analysis

(3) Three-dimensional CAE Analysis

Next, a three-dimensional analysis (3D 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. The analytical model shown in Fig. 12 was constructed based the CAE qualitative model of the basic oil seal lip structure shown in Figure 10. 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.

5.3.3 CAE Analysis (Step 5)

A cavitation is generated at the following steps; Oil collides with a foreign substance - The flow velocity rise near a foreign substance – The fall of pressure - Decreased pressure is carried out to below saturated vapor pressure - Emasculation of oil - Generating of a cavitation.

(1) Cavitation Analysis Example

Fig. 13 shows the CAE analysis results at a rotation speed of 1100 rpm. This analysis confirmed the cavitation occurring around foreign matter, thus replicating the results of the visualization experiment. At the same time, the finding that cavitation becomes more significant as the rotation speed of the drive shaft increases was similarly replicated.

(2) Fluid Speed Analysis Example

The fluid speed analysis like the one in Fig.14 was then conducted in order to look more closely at the mechanism causing cavitation. The analysis revealed that rapid changes in fluid speed were occuring in the vicinity of foreign particles, and that fluid speed drops immediately before the oil collides with foreign matter. This led to the conclusion that the presence of foreign particles was having an effect on oil flow.

(3)Pressure Analysis Example

Comparing cavitation and the fluid speed analysis results against the results of the pressure analysis shown in Fig.15 reveals that in areas of reduced pressure, oil was disappearing inside the cavities being formed—meaning that drops in pressure were likely being caused by these concave areas.

(4) Verification and Consideration

The above CAE analysis allowed the authors to clarify the faulty mechanism causing cavitation; namely, the presence of metal foreign particles was affecting the strength of the oil flow, causing drops in pressure in areas with faster oil flow and creating cavities. In addition, a similar analysis of changes in the shape and size of the foreign particles revealed that these changes were also causing changes in cavitation. These CAE analysis results indicate a close link between particle size/shape and cavitation.

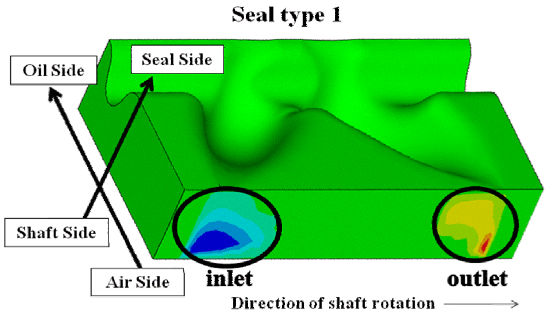


Fig. 12 A three-dimensional analysis

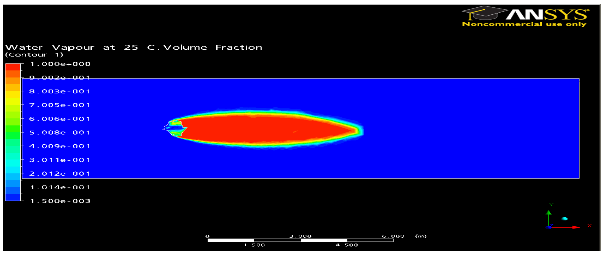


Fig. 13 Cavitation Analysis around Foreign Matter

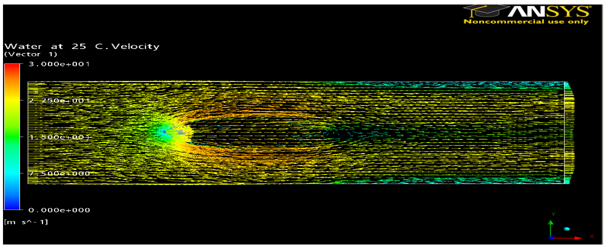


Fig. 14 Fluid Speed Analysis around Foreign Matter

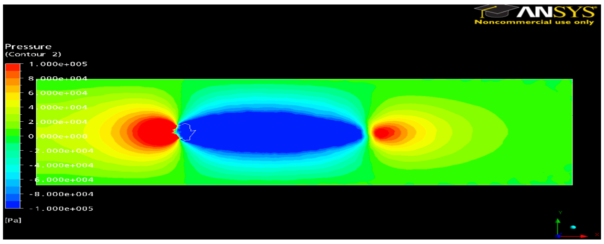


Fig. 15 Pressure Analysis around Foreign Matter

Preproduction and testing/evaluation of prototypes adds a significant amount of time and cost to the development process. However, precise CAE allowed manufacturers to eliminate preproduction (as well as prototype testing/evaluation) and still predict the mechanism causing cavitation and oil leaks. Though gaps such as minute surface variations caused by foreign particles and the shape of the oil film model exist, the CAE analysis allowed the authors to recreate the changes in flow speed and pressure around the foreign metal particles that were causing cavitation—changes which typically cannot be identified. The deviation between the CAE analysis results and the results of the prototype testing were less than 5%, attesting to the usefulness of precise CAE analysis in certain cases.

(5) *Quality Improvement*

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) 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 where it rotates in contact with the drive shaft. The result of these countermeasures was a reduction in oil seal leaks (market complaints) to less than 1/20th their original incidence.

(6) Application to Similar Problems

With its effectiveness verified, the author was able to apply the Optimal CAE Design Approach 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 [4], urethane seat foam molding [1], and loosening bolts [13]. 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 model for optimizing product design processes.

6 Conclusion

In this paper, the author constructed an Optimal CAE Design Approach Model by utilizing *Advanced TDS* for predictive evaluation method in design work is expected to contribute a great deal to shortening development design time and improving quality. The model primarily used numerical simulation to clarify the technological mechanism generating oil leaks as a result of foreign metallic substances entering oil seals in the transaxle.

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