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The optimal design of hydraulic pump performance and reliability through lubrication, mechanism, and structural coupling analysis

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Abstract.

This study proposes a design method for interacting sliding parts in hydraulic pumps that optimizes both performance and reliability within practical computation time. Conventional design analyzes each part individually using EHL (Elasto-Hydrodynamic Lubrication), overlooking interactions and causing redesign delays. The new approach integrates lubrication-mechanism-structure coupled analysis, Taguchi-based sensitivity analysis, and response surface optimization to determine optimal shapes. Validation using an elastic body model showed only a 7% error compared to the rigid model. Compared to the current design, total loss decreased by about 30%, improving overall efficiency by 4%. This technology enables faster development without compromising reliability.

Keywords. Hydraulic pump efficiency, Sliding part design, Coupled analysis, Response surface Optimization.

1. INTRODUCTION

Figure 1.1. shows the before-after design of the sliding part. In the conventional sliding part design, EHL (Elasto-Hydrodynamic Lubrication) analysis of each sliding part is performed, and the shape is determined individually. Therefore, the interaction between multiple sliding parts is overlooked, and redesign and verification are required to achieve both performance and reliability, resulting in an increase in development time.

In this study, a complex sliding part design method that can determine the optimum shape that achieves both reliability and performance in practical calculation time was constructed by simultaneously designing multiple complex sliding parts by the strong coupled analysis of mechanism and lubrication, extracting design parameters of sliding parts by the sensitivity analysis using the Taguchi method, and performing the optimum solution calculation using the response surface.

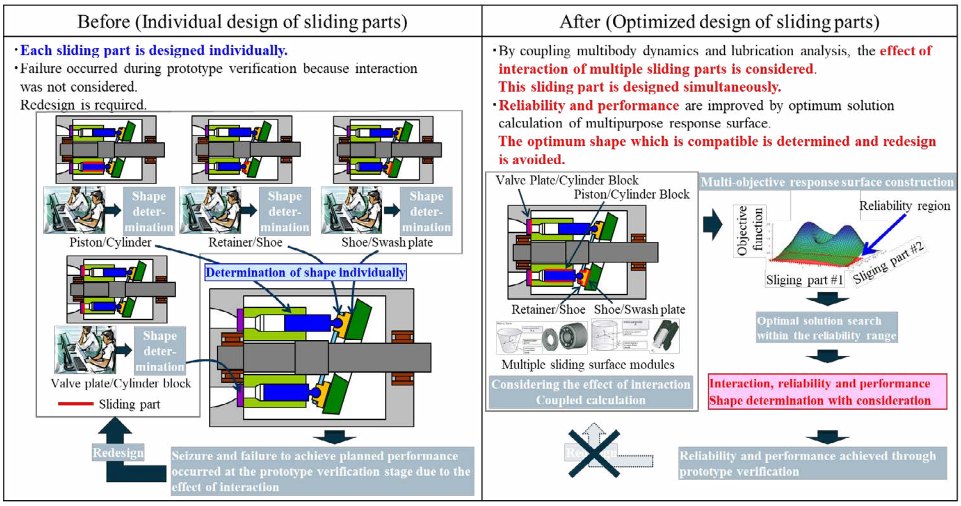


Figure 1.1. Before and After of Designing of Interacting Sliding Parts

2. Optimization Design Method for the Interaction of Multiple Sliding Parts

2.1. Analysis Object

Figure 2.1.1. shows the analysis object. In this study, a simultaneous optimization design method of multiple sliding parts for a swash plate hydraulic pump was verified. In order to achieve both reliability and performance, it is necessary to ensure the integrity of the sliding surface and reduce the power loss. The sliding parts of a swash plate type hydraulic pump are (1) valve plate and cylinder block, (2) piston and cylinder, and (3) shoe and swash plate. In order to improve the output of a hydraulic pump, it is necessary to design the clearance of each sliding part in consideration of the increase of friction loss and seizure of the sliding surface due to insufficient clearance.

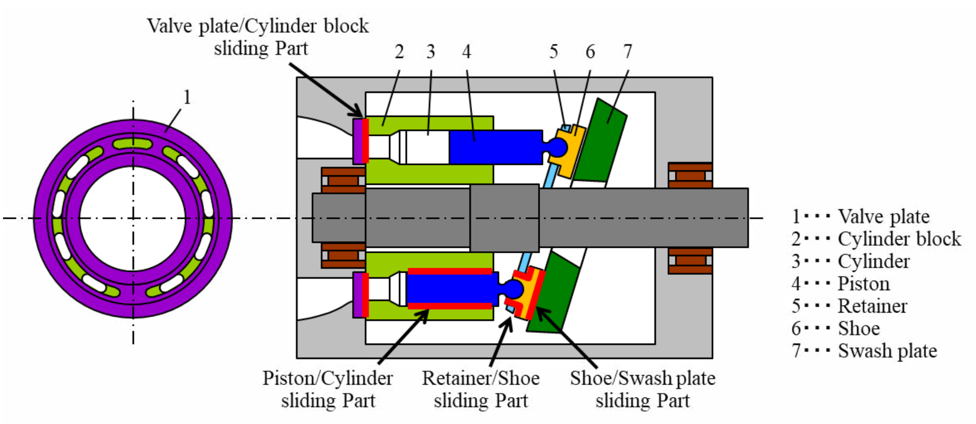
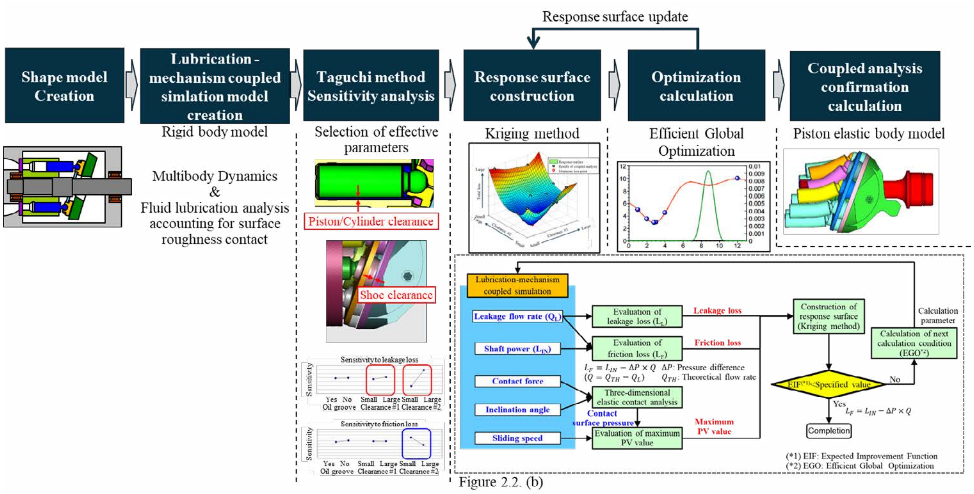


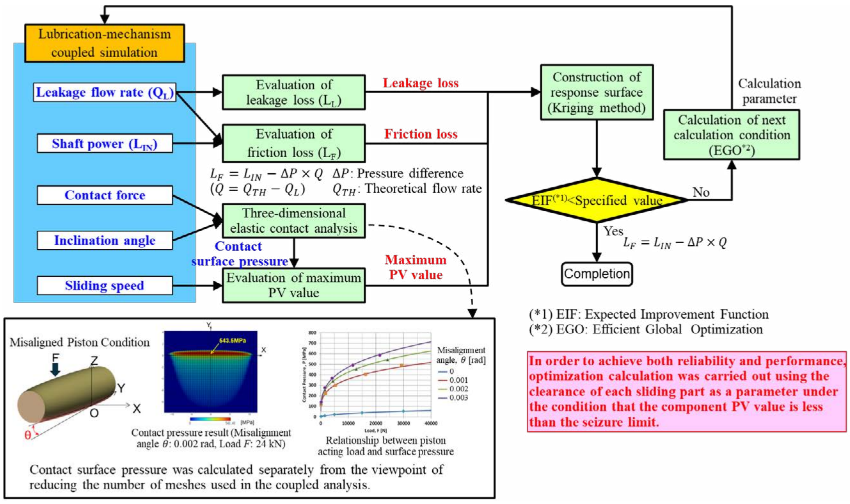
Figure 1.1.1. Analysis Object

2.2. *Design flow for optimization of sliding part*

Figure 2.2.1. shows the design flow for simultaneous optimization of sliding part. The calculation load of the elastic body model is more than 5 times as high as that of the rigid body model (calculation time 20hr per 90deg of axial rotation angle), and it takes time to obtain the optimum design dimensions. Therefore, the rigid body model was used for the coupled analysis in the sensitivity analysis and optimization calculation, which require calculation of multiple cases, and the calculation time was shortened by separately considering the elastic effect in contact with the map data of the 3D elastic contact analysis. For the final verification, the coupled analysis of the elastic body model was confirmed with the optimum solution obtained by the rigid body model.



(a) Overall design flow



(b) Details of Optimization Calculation

Figure 2.2.1. Flow Chart of Simultaneous Optimization Design of Sliding Parts

2.3. Lubrication-Mechanism-Structure Coupled Analysis simulation

The lubrication-mechanism-structure coupled analysis code FIRST developed by IST in Germany was used to construct an analysis model for multiple sliding surfaces. FIRST can couple the mechanism analysis by multibody dynamics with the modified Reynolds equation and the mixed lubrication analysis considering the roughness by the Greenwood-Tripp model, and the analysis considering the interaction of each sliding surface is possible. In addition, the analysis considering the elastic deformation of the parts is also possible by using the structural model of the degenerate parts by the Structural Analysis Tool (ANSYS).

In this study, the main sliding surfaces, (1) valve plate and cylinder block, (2) piston and cylinder, (3) shoe and swash plate, were modeled as sliding surfaces, and the other parts were modeled by connecting spring-damper elements.

As an input condition, the cylinder pressure fluctuation curve obtained by one-dimensional simulation was used as a pressure load on the piston and a pressure boundary condition on the sliding surface.

Using this model, the power loss and efficiency were evaluated based on the driving torque when the pump shaft was forced to rotate and the amount of leakage from each sliding surface.

2.4. Selection of High-Sensitivity Design Factors

In order to select design factors to be used in the optimization calculation, sensitivity evaluation of leakage loss and friction loss for each sliding part was carried out by the Taguchi method. The control factor for the sensitivity analysis is shown in Figure 2.4.1. Three factors (Presence or absence of cylinder oil groove, piston/cylinder clearance, shoe/swash plate clearance) were selected to carry out the sensitivity analysis. Among these three factors, the shoe has a pressure pocket at the bottom where the oil pressure from the cylinder is introduced, and the oil pressure balance is set to float freely. Therefore, the shoe floats from the swash plate during the compression stroke, and leakage occurs through the gap between the shoe and the swash plate, which is considered to have a large effect on the leakage loss. In addition to the leakage loss, the piston/cylinder gap has an effect on the contact pressure at the contact point, which greatly affects the contact PV value of the sliding surface. The cylinder oil groove is provided to improve the loading capacity of the oil film by introducing the high-pressure oil to the side surface of the piston.

Figure 2.4.2. shows the results of the sensitivity evaluation. The shoe/swash plate clearance showed the highest sensitivity for both leakage loss and friction loss, suggesting that it is an important parameter to minimize the total loss. The piston/cylinder clearance showed the highest sensitivity for leakage loss.

Based on the results of the sensitivity analysis, the shoe/ swash plate clearance and the piston/cylinder clearance were set as two design variables for optimization.

Sensitivity parameter	Set value
Cylinder oil groove	Yes, No
Piston/cylinder clearance	Small, Large
Shoe/Swash Plate clearance	Small, Large

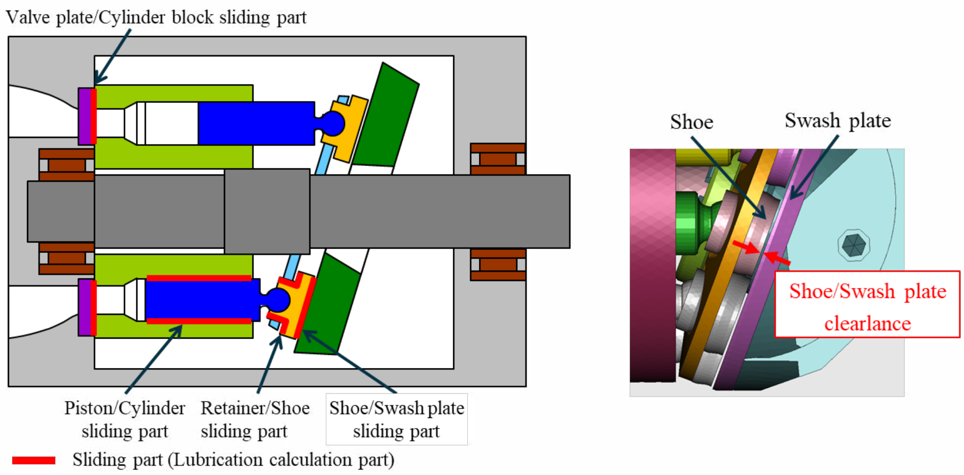
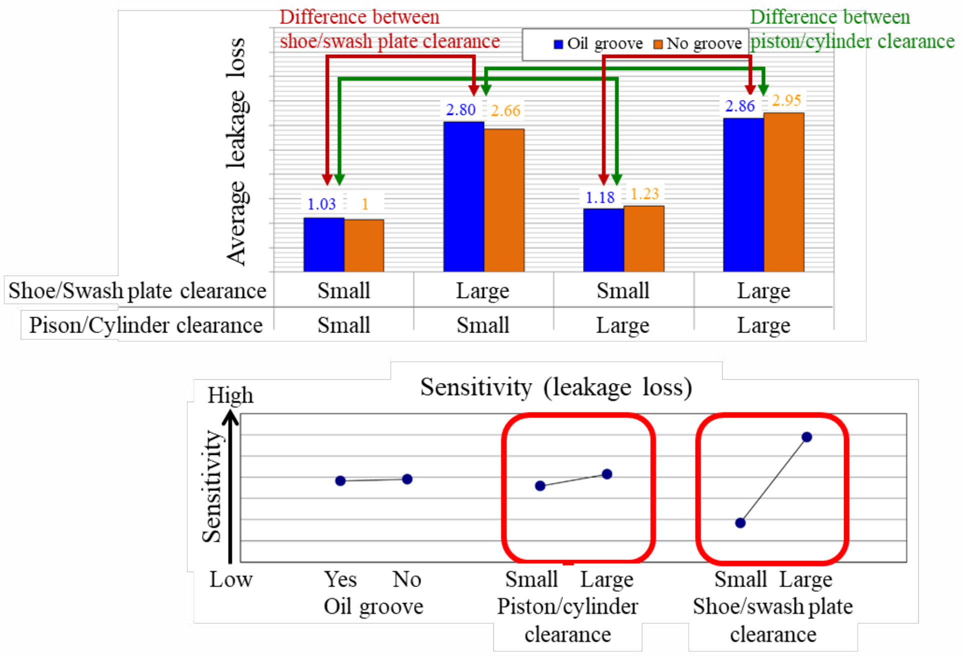
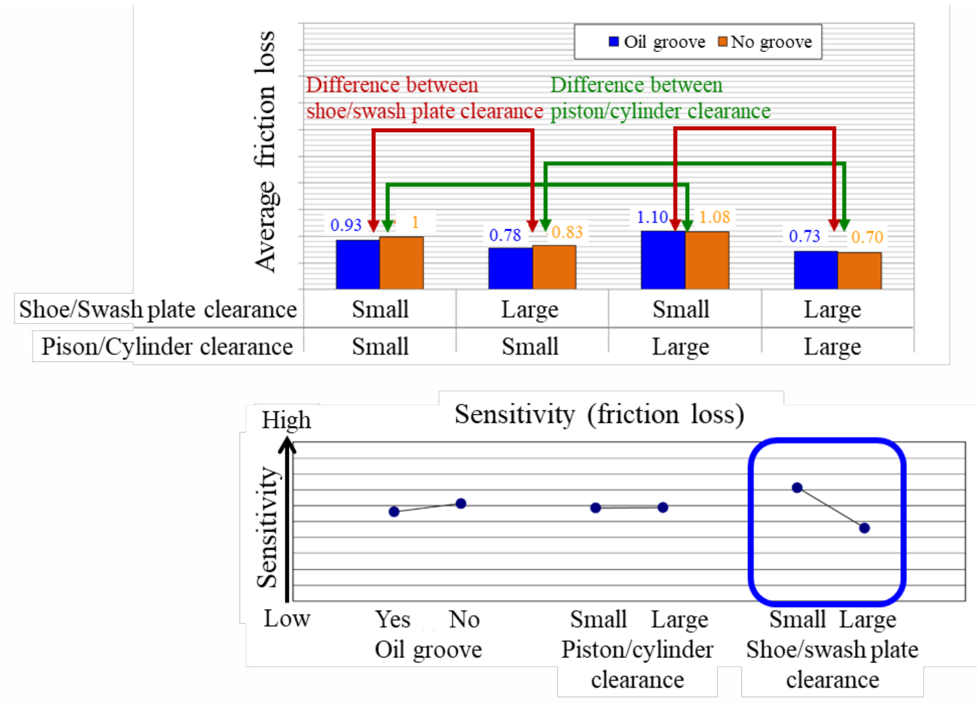


Figure 2.4.1. Control factors for sensitivity analysis



(a) Leakage loss



(b) Friction loss

Figure 2.4.2. Sensitivity evaluation result of the interaction of sliding surfaces

2.5. *Optimal Solution Calculation Using Nonlinear Approximation Surface*

2.5.1. *Calculation method*

The lubrication- mechanism-structure coupled analysis is a large-scale numerical analysis, and the calculation time is several hours to several days per case. By adopting the optimization method using the response surface, the number of analysis cases to obtain appropriate design dimensions can be reduced. In this study, the Kriging method, which is suitable for approximating nonlinear functions, was used as a response surface construction method. The response surface by the Kriging method includes not only the distribution of the function value itself but also the uncertainty (approximation error) information that can be included in the estimated function value. Efficient Global Optimization (EGO), which is an optimization algorithm to improve the accuracy of the response surface, was adopted with this information. In EGO, the expected improvement (EI), which is an index expressing how much the estimation accuracy can be improved when a new sample is added to a certain point and the response surface is reconstructed, is evaluated. Then, the location where the EI value is maximum is searched, and a new sample point is added to reconstruct the response surface. By repeating these operations, the improvement of the approximation accuracy of the response surface and the search for the global optimum solution can be achieved simultaneously. Compared with the conventional optimization method (genetic algorithm), it is reported that the number of calculations required to obtain a solution with the same accuracy is less than 1/20 [1]. Therefore, it is expected that the solution can be obtained in a practical time. In this study, the response surface was generated using Dakota, an open source optimization tool developed by Sandia National Laboratories, USA, and the optimum solution was searched by EGO.

In the optimum solution search, a constrained nonlinear optimization was performed to minimize the total loss by keeping the PV value below the criterion value within the range of design variables (Piston/cylinder clearance, shoe/swash plate clearance) specified in the optimization problem.

In the coupled analysis model used for the optimization calculation, all parts were treated as rigid bodies and the analysis mesh of the sliding surface was made relatively coarse to reduce the calculation time. Considering the periodicity of the pump behavior, the analysis range was limited to 1/4 rotation of the main shaft. As a result, the calculation time per 1 case was about 16 hr, and the optimum solution could be obtained within a practical period. However, the analysis accuracy of the contact pressure could not be guaranteed because the sliding surface analysis mesh is coarse and the number of contact nodes per piston piece may be 1 to several points. Therefore, the contact pressure of the piston was separately calculated based on the three-dimensional elastic contact model from the contact load of each contact region (the upper end of the piston and the small mouth of the cylinder) and the inclination angle of the piston with respect to the cylinder obtained from the analysis result of the coupled analysis.

2.5.2. Optimization calculation result

Figure 2.5.1. shows the response surface at steps 0, 3, and 10 of optimization, and Figure 2.5.2. shows the final response surface and analysis points.

An initial response surface was created based on the analysis result of 4 points used in the sensitivity analysis, and the optimization calculation was executed. As a result, the amount of movement of the search point fell below the criteria at step 10, and it was judged to be convergence. The initial response surface showed a monotonic decreasing trend for each design variable with low estimation accuracy. However, the optimum point appeared at the tip of the bowl-shaped region at step 10.

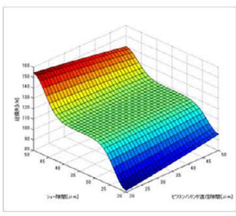
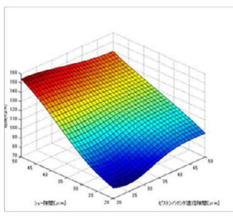
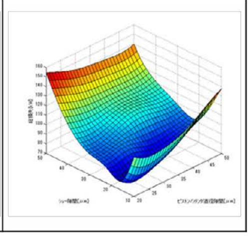
Number of optimization steps	#0 (Initial)	#3	#10 (Convergence)
Response surface			

Figure 2.5.1. Optimization steps

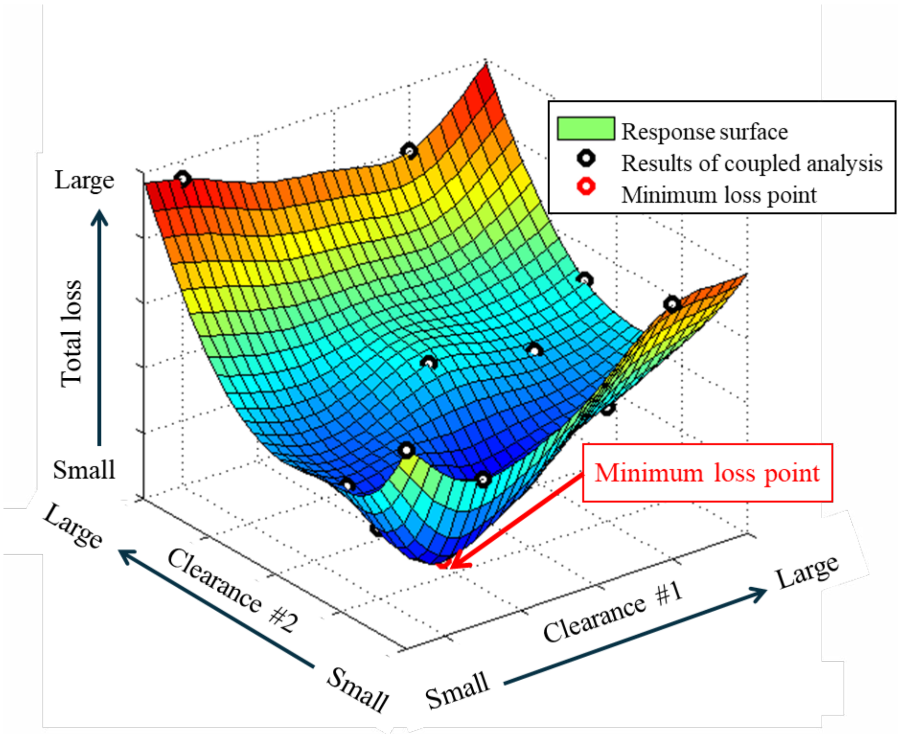


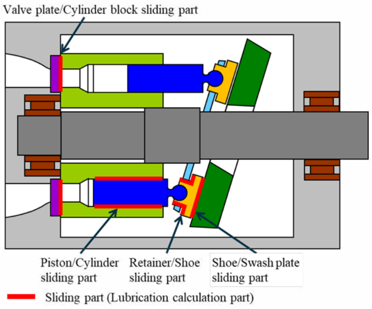
Figure 2.5.2. Optimal solution and kriging surface after convergence

2.5.3. Confirmation of Optimum Solution by Elastic Body Model

Figure 2.5.3. shows the comparison result between the rigid body model and elastic body model. In the optimization calculation, the rigid body model was used to reduce the calculation time. In order to confirm the validity of the optimization result using the rigid body model, an analysis was performed considering the elastic behavior of the piston at the optimum point. Comparing the rigid body model with the elastic body model, the error of the calculation result of the total loss was about 7%, and there was no significant difference in the distribution of the oil film thickness, oil film pressure, and contact pressure (the calculation time of the elastic body model was 4-10 times longer than that of the rigid body model).

Comparison of Loss Calculation Results

	Total loss (-)	Error (%)
Elastic body model	1.07	-
Rigid body model	1	7



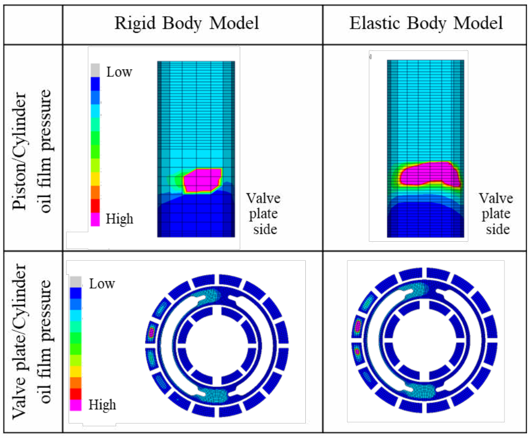


Figure 2.5.3. Comparison of Elastic and Rigid Analysis Result

2.5.4. Comparison of the Optimization Result and the Current Design Result

Figure 2.5.4. and Figure2.5.5. show the comparison between the analysis result and the optimization result and the current design result. Comparing the current design point with the optimization result, it was confirmed that the total loss was reduced by about 30%, and the corresponding improvement in total efficiency was 4%.

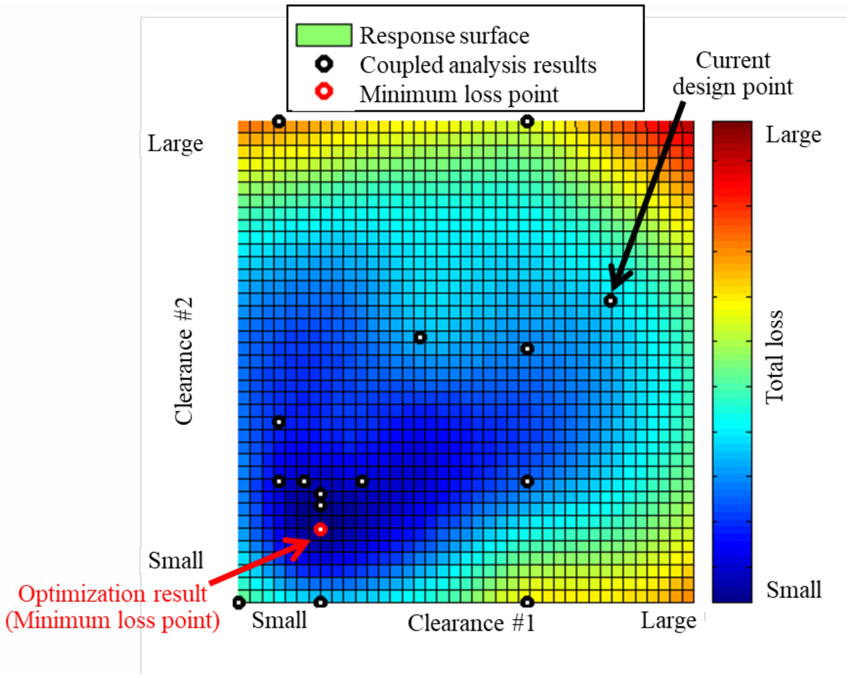


Figure 2.5.4. Response Surface Contour of total loss and tolerance zone of clearance

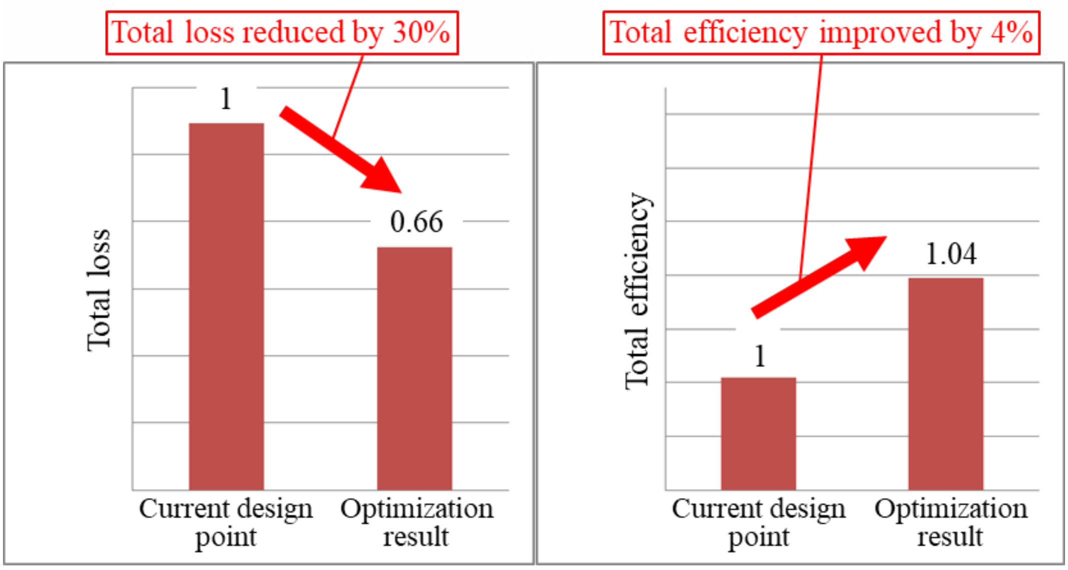


Figure 2.5.5. Comparison between the optimization result and the current design result

3. SUMMARY

By constructing a sliding part design technology that combines lubrication-mechanism-structure coupled analysis and nonlinear optimization technology, it is possible to design a sliding part shape that achieves both performance and reliability of a hydraulic pump in a short period of time, and it is expected to avoid an increase in the development period.

4. REFERENCES

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[2] Y. Chuman, et. al., 'Innovation of Design and Development Process using Structure Optimization Technology', Mitsubishi Heavy Industries Technical Review Vol. 52 No. 4, Dec., 2015.