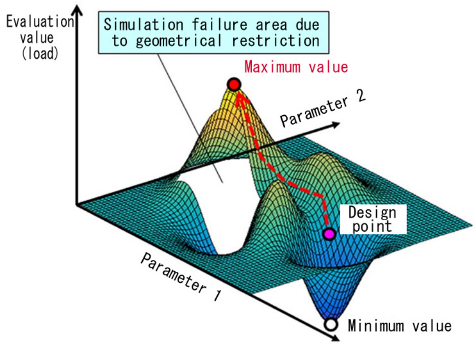
Design Technique for Mechanism Analysis Using Nonlinear Response Surface by Applying High-speed, High-precision Optimisation Method



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Mechanism analysis is an effective tool for evaluating the feasibility of complex mechanisms, but in order to find the worst conditions (singular solution) which cause problems such as wearing, there is a need for parameter combination analysis of huge volumes, causing the cost for calculation and time required for analysis to increase exponentially.

This paper explores the usage of Efficient Global Optimisation (EGO) which uses Kriging (Gaussian) response surface technique and couples it with mechanism analysis software allowing to reduce the total runs needed while handling intractable design space which leads to simulation failure. This technique is used for improving the design of steam turbine valve which regularly suffers from surface wear.

1. Introduction

Mechanism analysis software can be applied to simulate machinery/products with strong nonlinearity, but due to problems such as high calculation cost per case and large number of parameters in complex models, Worst Case Finding using brute force approach such as Monte Carlo is unrealistic. On the other hand, in valves for steam turbines, etc., wear of drive system is occurring at domestic and overseas plants, and there is a need to simulate the extreme conditions behind such occurrences.

Therefore, instead of the conventionally used brute force approach , an automated singular solution finding tool has been developed, which uses an approximate solution technique (Kriging/Gaussian Response Surface) that can support nonlinear responses and a response surface updating technique for accurate response surface generation , making it possible to implement Worst Case Finding with minimal calculation cost. Below are details of the construction tool and examples of product application.

2. Development of WoCaFit (Worst Case Finding Tool)

2.1 Comparison between the conventional technique and adaptive response surface technique

Generally, with an optimization technique using response surface, solution are found with a surface prepared from the initial sampling points, but with EGO, solution is found on final response surface which has been prepared by successive updating by adding one point in each update. . For this reason, there is no dependence on the initial sampling number and sampling location. At this time, an index known as the EIF (Expected Improvement Function) is used in order to determine the next calculation point used in the update. This index shows the expected improvement that will happen to present response surface if an addition sample point is added, and there is a balancing formularization so that the expected improvement index become great not only around the present optimum value , but also in areas where estimations are thought to be uncertain. For this reason, global optimisation become possible without falling into localized solutions.

Calculation of EIF requires uncertainty information; hence Kriging (Gaussian) surface is

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used for response surface generation which can provide this information to optimisation routine.

Furthermore, an additional routine was added in above optimisation method to prevent optimisation stalling, if the additional added point leads to simulation failure.

Until now, calculation was manually repeated whenever mechanism analysis had terminated due to an error for reasons such as geometrical restrictions, but the introduction of this routine has made it possible to implement perfect automation of Worst Case Finding (details regarding error domain avoidance routine are described in section 2.2). Comparisons with conventional techniques are shown in **Figure 1**, **Figure 2** and **Table 1**.

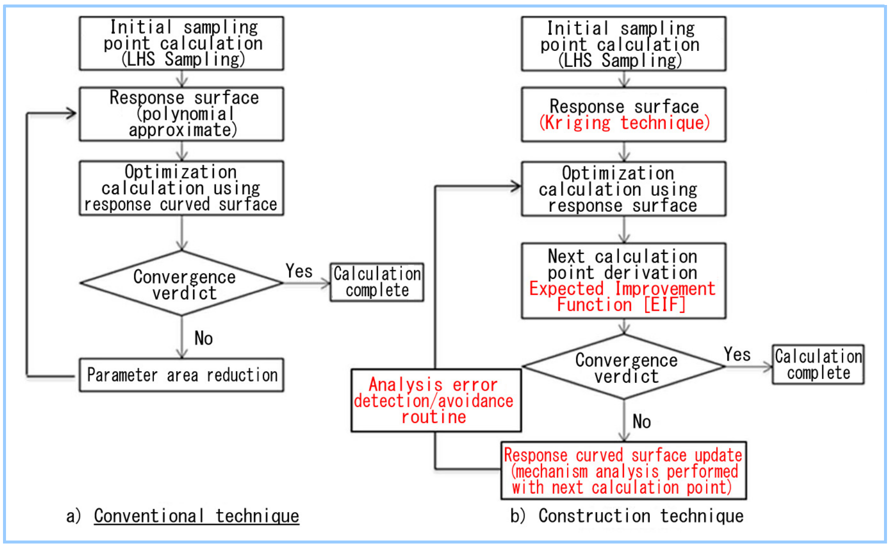

Figure 1 Comparison with conventional technique (calculation flow)

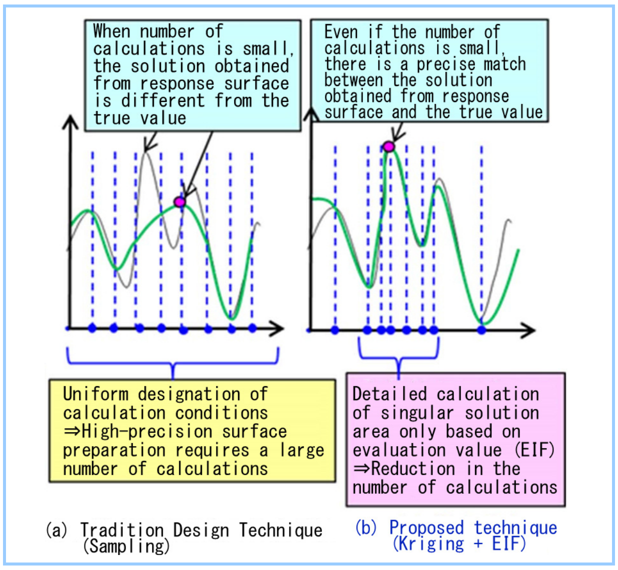

Figure 2 Comparison with conventional technique (required number of calculations)

Table 1 Characteristics of construction techniqueconventional optimization vs EGO

Item	Conventional technique optimization	EGO
Actual Simulation Run (N) required for one iteration	N＝10 to 50(Children) Will fall into localized solution if there is a low frequency are less children Total calculation required increases exponentially with added iteration	N＝1 (Add only 1 point for each iteration)
Convergence criteria	distance < 1.0E-3 to 1.0E-5 Risk of falling into localized solution if performed roughly coarse criteria Many repeated calculations will be necessary on the analytical side if performed roughly near optimum point	**Convergence verdict is not made based on calculation results criterion is not distance based but depends on EIF value** - Repeated calculations near optimum point not needed
Required number of initial sampling points	Large sampling number = N	Final sampling number is small due to successive updates of response surface
Selection technique for sampling points	Selected at random during initialization	Efficiently select the next sampling number using an evaluation index (Expected Improvement Function: EIF)

2.2 Calculation error area avoidance routine (Introduction of Penalized EIF)

When a new simulation is started by optimizer at parameters suggested by EIF, it is possible that simulation failure might happen. Global optimisation for complex mechanisms are generally run on hyper-rectangular design domain, constrained only by lower and upper bound of the parameters as it is difficult to predict failure domain prior to optimisation. The actual feasible design space is quite complex, discontinuous and intractable (explicit constraints on design parameters like amplitude of motion, segment lengths, etc. are not possible), leading to simulation failure (due to numerical instability, Jacobian ill-conditioning, physical assembly violation, etc).

Furthermore, EGO technique used in present study depends upon successive updating of response surface. And simulation failure leads to stalling of optimisation process. Hence there is a need for an algorithm which can dynamically and efficiently avoid failure regions by altering the value of EIF.

Accordingly, the above- mentioned problem of optimisation stalling at failure points is solved by a penalty function multiplied with EIF. Penalized EIF formulation allows for exploration near the failure point while leaving exploitation possibility if optimum lies near failure region. Penalty function is set to 0 at failure points and rises exponentially as we move away from failure. Difference between conventional optimisation routine which stalls at failure and the newly developed method which can effectively avoid failure domain is shown in **Figure3**.

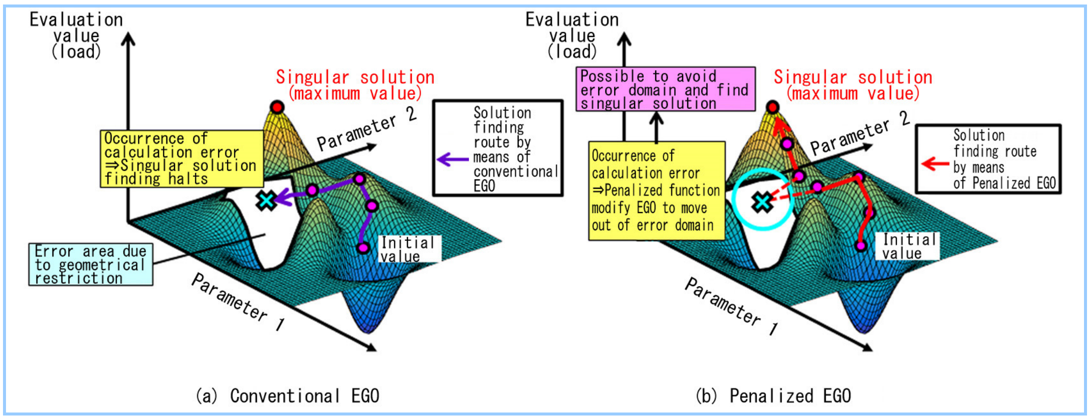

Figure 3 Error domain avoidance routine

3. Verification of WoCaFit

WoCaFit was verified using the Schwefel formula (function of 2 variables), which have strong nonlinearity and is routinely used to test optimisation scheme efficiency. Moreover, the point at which the theoretical formula value is smallest (=0) was searched, and calculation error of WoCaFit solution with respect to theoretical solution was noted. Calculation conditions and WoCaFit results are shown in **Figure 4**.

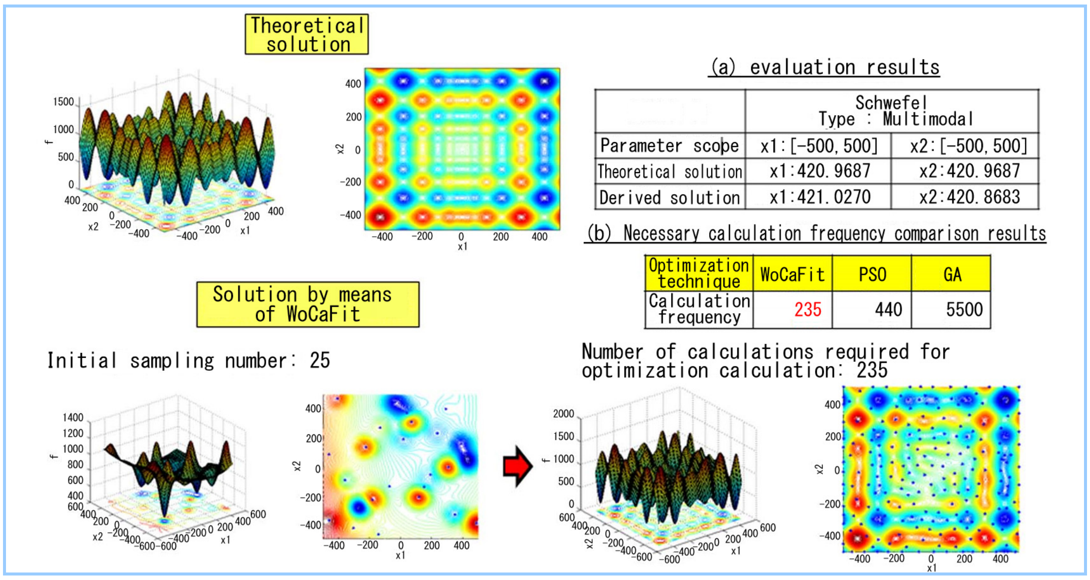

Figure 4 Verification of WoCaFit Efficiency (vs conventional optimization technique)

Response surface obtained by initial sampling do not represent the actual surface, but by successive updating of response surface by adding sample point as suggested by EIF, it was ultimately possible to obtain a response surface which is roughly same as theoretical solution, especially near the solution area. Optimisation performed on final surface match theoretical solution within 1% error as shown in Figure 4.

Different optimization techniques (PSO: Particle Swarm Optimization, GA: Genetic Algorithm) were also tested for the same theoretical formula, and a comparison was made of iterations needed for obtaining solution. Results are shown in (b) within Figure 4.

From these results, it was possible to confirm that the technique developed here could obtain solutions of the same precision at calculation frequencies of about ½ that of PSO and 1/26 that of GA for this example. Also, it should be noted that the total simulations required for convergence in PSO or GA changes drastically even if single additional iteration is required due to "children" configuration parameters being equal to 10～20. But with WoCaFit additional iteration adds only one simulation call. Hence developed technique reaches optimum point in minimum number of simulation calls.

4. Application of WoCaFit for actual machine model (steam turbine valve)

WoCaFit which was earlier verifies in Section 3 has been applied to complex mechanism in present section and countermeasures were considered based on the results

Target product:

This study targets valve structure of steam turbine (**Figure 5**). The target valve performs opening and shutting by driving the lever in an up-down direction by means of a link mechanism, but there is a risk that the PV(note) value in the guide part supporting the rod will become large and wearing will occur.

This time, the maximum PV value was used as objective for different permutation of design variable(clearance and position slippage) in multiple guides supporting the rod.

(note) PV value = P (load pressure acting on a guide) x V (slipping velocity)
PV value shows the load capability limit of a guide.

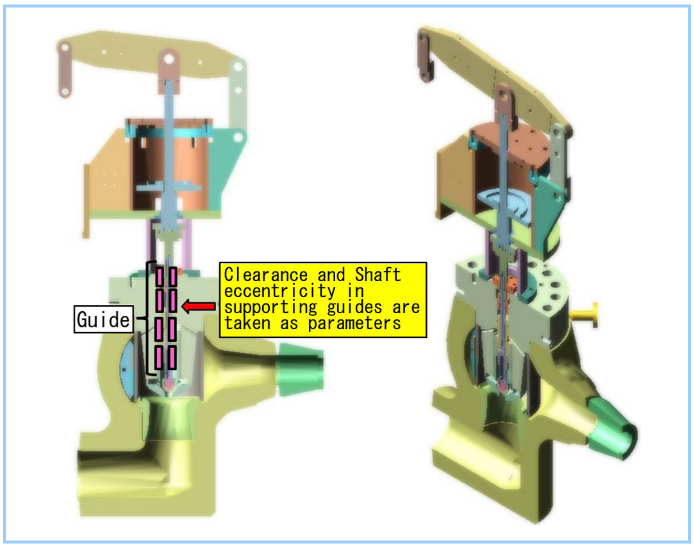

Figure 5 Valve model of steam turbine

Worst Case Finding results, evaluation of target configuration:

Worst Case Finding result in comparison with the initial design (Figure 5) is shown on the left side of **Figure 6**. Moreover, a total of 8 parameters were used in the present study , but since it is difficult to visualize response surfaces with 2 or more parameters, Figure 6 shows a curved surface wrt to 2 parameters (other parameters are kept fixed). Initial design parameters lead to high PV value which was improved in this study.

In order to minimize PV value, an additional guide was added, and the effects of countermeasure were verified by reevaluating improved design using WoCaFit.

As a result, it was confirmed that new design could be maintain a relatively stable PV value

(Figure 6, right). This made it possible to design a valve having little risk of wearing (and therefore excellent reliability) compared with conventional structures.

Moreover, the calculation time required for Worst Case Finding in the conventional structure was about 15H, and a solution could be found within a practical length of time.

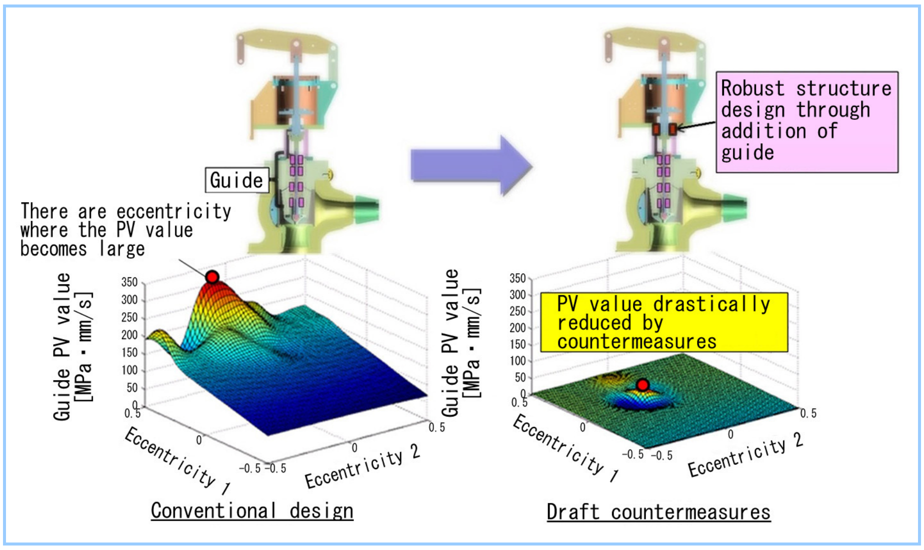

Figure 6 Worst Case Finding results in actual machine model of valve for steam turbine

5. Conclusion

We developed a tool WoCaFit which combines nonlinear response surface generation technique, automatic response surface updating technique (EIF) and mechanism analysis software while avoiding un-realistic design space.

Using theoretical formula, we were able to confirm that the found solution matched the theoretical solution within a calculation error of 1% or less. Also, when comparing the calculation frequency required for obtaining a solution with conventional optimization techniques (PSO and GA), we were able to make reductions of ½ that of PSO and 1/20 or less of GA.

By applying this tool to evaluate wear of steam turbine valve for different parameter combination (8 in present study), it was possible to improve the design while improving the reliability.

Going forward, the developed technique will not only be applied to mechanical problems in our company's products, but we will also develop solutions for optimization problems for structural analysis and flow simulations which will contribute to improved product reliability at reduced cost.