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Sensitivity analysis method for the design procedure in the precision machine simulator platform

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Abstract
A precision machine simulator which is an internet based simulation platform has been developed. It can simulate the performances of a machine and the machine can have linear and rotary motion axes. Through the simulation platform GUI (Graphic User Interface) a machine designer inputs design data (for example machine configuration, ball-screw model, fluid bearing parameters, rotary axis shaft shape, guide straightness data, etc.) and examine the calculated performance result. The calculated performances include axis stiffness (linear and rotary), axis motion error and finally those performances of the machine. Recently a machine designing tool is being developed to enhance the performances of a machine whose design parameters are given by the designer and a nonlinear programming (constrained minimizing) is used to find out the performance improving parameters. Considering the whole machine there are a lot of design parameters to give much calculation burden to the simulator. Therefore a method to decrease the number of involved parameters and reduce solution feasible range for each parameter is strongly required. A sensitivity analysis method is being developed to analyse the nonlinear programming problem. The problem parameters include, for example, axis parameters, hydrostatic bearing parameters, machine configuring dimensions, etc. and a sensitivity analysis can also generate the calculation burden. Therefore, an efficient way to analyse the parameter sensitivity of the problem is needed. A Taguchi's method is adopted and implemented to the sensitivity analysis. The method is to analyse the sensitivity and locality of each parameter to the nonlinear programming problem and the result can make the designer choose the most influential parameters. And it finds out the solution feasible region which can reduce the parameter range for the problem. For the first application the method is applied to the hydrostatic bearing design problem, which is shown in the presentation.

sensitivity analysis, machine simulator platform, nonlinear programming, Taguchi's method

1. Introduction

In order to design a machine (machine tool or semiconductor /display industry multi-axis stage) a designer need to know the performance of the machine which is designed or drafted. For that purpose, a physical simulation method is required from the unit (linear axis unit, rotary axis unit, spindle unit) level to the total machine level. There are a lot of related research results to simulate the performances and characteristics with component (bearing stiffness, ball-screw stiffness, linear motor cogging forces, spindle shaft dimensions, etc.) model, unit model and total machine model [1]. Applying those previous modelling methods and also new approaches a precision machine simulator which is an internet based simulation platform has been developed.

A designer can simulate a unit and a machine with design parameters given to the simulator. And recently a kind of design tool, which can show and recommend more desirable design directions and parameters, is being developed and the tool includes design optimization and sensitivity analysis. The sensitivity analysis is thought of as a tool to support and help the optimization. The designer can analyze the parameter sensitivity to specific performances and can determine the dominant parameters to be selected for optimization. The sensitivity analysis includes also the determination of the locality. The locality means that those selected dominant parameters are dominant throughout the selected parameter domain region.

In this paper, a method of sensitivity analysis is presented and the optimization strategy with the sensitivity analysis is shown with rotary unit examples.

2. Rotary unit performance simulator

For the first application of the sensitivity analysis the rotary unit simulation part is used because the versatility and clarity of the parameter (such as ball bearing span dimension) contribution to the spindle performances. In figure 1 the GUI (Graphic User Interface) for the rotary unit is shown and the designer can input arbitrary shaft dimensions and bearing parameters.

3. Sensitivity analysis method

The Taguchi's method is applied to the sensitivity analysis with two objectives [2]. The first one is to reduce the parameter domain region for optimization and the second one is to check the parameter sensitivity to specific performances (such as spindle first mode frequency) throughout the domain. The simple method for these two tasks is randomly selected parameter set testing method which will randomly select parameters and calculate performance value (objective value) or sensitivity values. However, this method requires too much

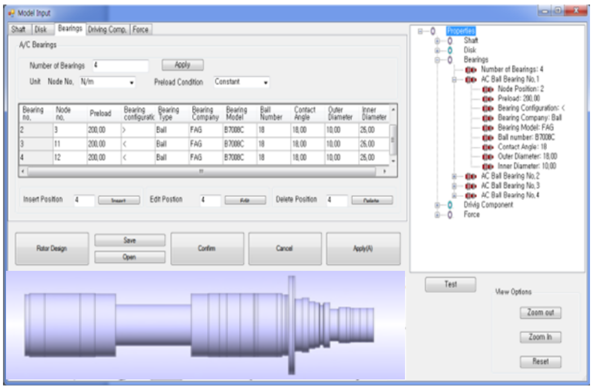

Figure 1. GUI (Graphic User Interface) for the rotary unit simulator is shown.

calculation amount as the design parameter number increases If ten design parameters are considered and three test sets are used 59 049(= 3^{10}) times of calculation should be performed. However, if the proposed method is used (L-54 orthogonal array) only fifty-four calculations are needed.

The proposed method is used for both optimal design objective function and objective function sensitivity calculation. With the objective function itself the parameter domain reduction is achieved and with the sensitivity calculations dominant parameter determination can be achieved. And also by the sensitivity calculations the determination of the locality can be achieved. The locality means that those selected dominant parameters are dominant throughout the selected parameter domain region.

$$\eta = -10\log_{10}\left(V_{norm}\right) \tag{1}$$

$$V_{norm} : \frac{w_1}{\left(f / f_{norm}\right)^2} + \frac{w_2}{\left(g / g_{norm}\right)^2} \tag{2}$$

The equation for the Taguchi's method is shown in equation (1) and (2). The V_{norm} is a kind of normalized function with weighting factors and the function is the same one as for the optimization objective.

$$\eta = -10\log_{10}\left(\frac{\partial V_{norm}}{\partial x_i}\right)^2_{norm} \tag{3}$$

Equation (3) is the objective function for the sensitivity case and its form is a kind of derivative formulation by one-at-a-time differential measure.

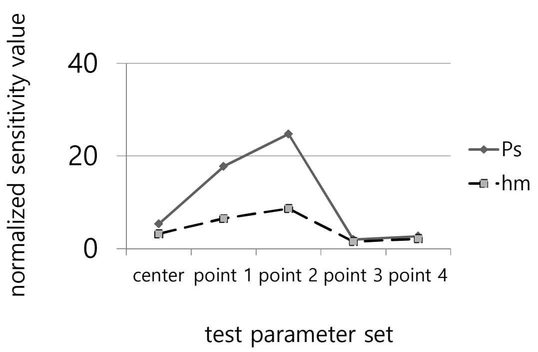

Figure 2. An example of the sensitivity analysis result by the proposed method for hydrostatic bearing design.

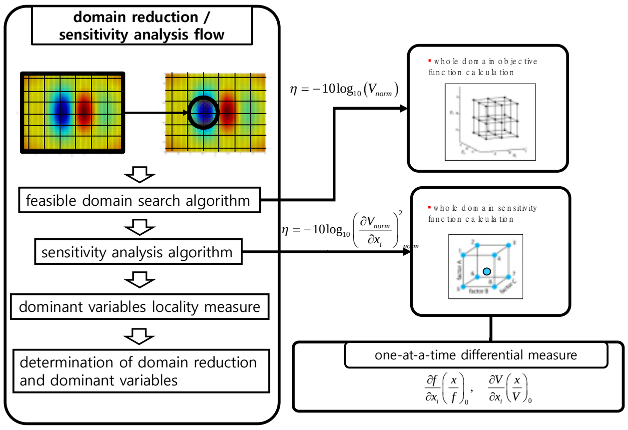

Figure 3. The algorithm flow chart showing domain reduction and sensitivity analysis process.

The proposed method was simply applied to the hydrostatic bearing pad design optimization problem and the sensitivity analysis result is shown in figure 2. The objective function for the optimization is maximizing bearing stiffness and load capacity using equation (1). There are a few constraints for fluid flow rate, temperature rise, etc. The tested design variables (parameters) are the input pressure(P_s) and bearing gap(h_m). Two test points for each variable is used for simple result check and the sensitivity analysis is successfully completed. By the Taguchi's method the ANOVA (analysis of variance) information for the sensitivity data can be achieved and it can be seen visually by the simple example as seen in the figure 2. The sensitivity value with the pressure variable is dominant in some domain but in other domain the pressure and bearing gap equally dominate the problem. By this information, the designer can determine the locality of the domain region considering the ANOVA result. The sensitivity analysis procedure is explained in figure 3. The feasible domain search process and sensitivity analysis process are implementing Taguchi's method with small variation as seen in the equation (1) to (3).

4. Machine design optimization

The machine design optimization ranges from the bearing design, through the unit design to the unit assembled machine design. For example, by the hydrostatic bearing case the designer can design a linear thrust pad bearing or a rotary journal bearing. The many design parameters exist for the problem such as supply pressure, orifice design, pad dimension, etc. The objective function can be the stiffness of the bearing and the constraint can be the flow rate, load capacity, etc. If the nonlinear programming for the optimization is too complex, for example due to many variables, the proposed sensitivity analysis is used for reducing domain region and reducing variable number. In addition, due to the algorithm the calculation time for the analysis is dramatically decreased.

References

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