The role of design of experiments in predictive design analysis

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THE ROLE OF DESIGN OF EXPERIMENTS IN PREDICTIVE DESIGN ANALYSIS

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1 Introduction

During recent years the increasing power of computers has led to the use of more sophisticated analysis tools within the mechanical engineering design process, or design process for short. Projects whose objective has been to introduce the Finite Element (FE) analysis into the early phases of the design process have been carried out at the Department of Machine Design, see e.g. [1]. These works clearly highlight the usefulness of introducing design analysis early in the design process. It is argued that the full power of design analysis can be achieved when it is used not only to verify a design but also to predict the final performance of a product to be. Predictive Design Analysis (PDA) is one important approach in this research, where the objective is to predict the final behavior of a product by utilizing valuable information from different analysis techniques. Design Of Experiments (DOE) technique has successfully been used, in specific problems, to extract valuable results from design analyses, see e.g. [2], with fewer analyses performed.

2 Objective

The objective set out for the work presented in this paper has been to combine design analysis methods with statistical methods in order to give the designer an efficient tool to be used at all levels of abstraction in the design process. The applicability of DOE within PDA is discussed. Further, the use and implementation of DOE together with PDA in the design process is utilized. Throughout the work the DOE is based on a 2-level factorial approach, and FE analysis is used to exemplify design analysis.

3 Integration of PDA into the design process

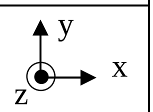
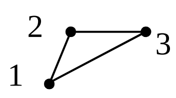
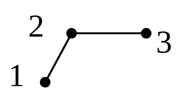
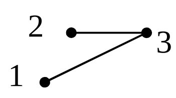
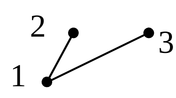
DOE is based on factorial experiments, which are arrays that alter the studied design variables at different levels in a systematic way. Depending on the choice of design variables, different kinds of responses (studied results) can be produced. Statistical evaluation methods are then used to extract vital information from DOE and also to organize and visualize it. The combination of DOE and PDA gives the design engineer a powerful analysis tool to evaluate the product, along with other engineering tools, at all phases of the design process. The vast variety of design procedure models has an overall similarity in that they all focus on the fulfillment of a need for the product that initiated the development activity, see e.g. [3]. The starting point of the majority of these models is the conceptual design phase. Traditionally the synthesis in the conceptual design phase is based on qualitatively oriented criteria. By using the proposed approach, the designer will be able to evaluate some of these criteria using a quantitative approach, thus improving the probability of the subsequent decision making procedure. Based on the problem specification, different physical quantities are evaluated with PDA. The result of PDA can then be evaluated further along with the remainder of the qualitative criteria by some known evaluation technique, see e.g. [4], where the purpose is to sort out those concepts that are most promising and worth looking into in more detail. Note that analysis tools also can be transformed into synthesis tools, thus providing Predictive Design Synthesis (PDS). Predictive Engineering (PE), the combination of PDA and PDS is discussed in [5].

After the conceptual phase, the resulting concepts have to be finalized in the subsequent design phases. The process of developing the final design involves several iterations of synthesis, analysis, evaluation and decision making, where the total cost of the project increases as the number of iterations increases. It is in the later stage of this phase that design analysis is commonly used today. To broaden the use of design analysis also at the earlier stage of this phase, the PDA approach is very powerful in the way that it extracts the few vital variables from the many trivial ones. These vital variables can, if necessary, be studied further, e.g. in an optimization analysis, where the optimum variable setting found in PDA works as a good starting variable configuration. The sensitivity of a product design to environmental factors can also be analyzed by the described approach. Interactions between design variables and environmental variables might also be included in the study. In design for manufacture, the uncertainty in design dimension can be evaluated with PDA, see e.g. [6].

4 An Example

Four different conceptual designs of a lever, shown in Table 1, are considered with the same mass and thickness. The designs are analyzed with a simple FE beam analysis. The first design variable is the applied displacement, at point 1, which acts either in the positive x-direction or in the negative y-direction. The second design variable is a torque, acting around the negative z-axis at point 2, which is either active or not. Point 2 is constrained in all displacement. A spring is acting in the y-direction on point 3. The studied response is the reaction forces at point 1, which represent the stiffness that the design concepts provide.

Table 1. Layout of the four studied design concepts.

Orientation		Design concepts			
		1	2	3	4
					

Making use of the result provided by Bisgaard [7], the four design concepts along with the two two-level design variables are evaluated. To determine the active variables, the charts in figure 1 are developed. The moment at point 2, denoted D in figure 1, has little influence on the response and is not studied further. Figure 1 also shows that the displacement variable, denoted C in figure 1, and the choice of design concepts, denoted AB in figure 1, are active. It further indicates that concept number four has fairly high stiffness and that its sensitivity to direction of the displacements is acceptable in comparison with the other design concepts.

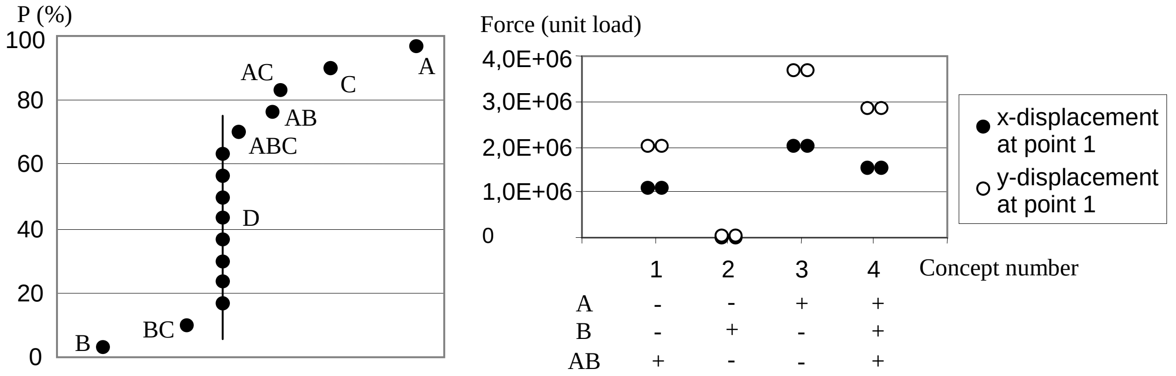


Figure 1. Evaluation of the different design concepts, normal probability plot and force versus concept number.

Concept number four was chosen for further evaluation. The FE model is refined and a 2D plane stress model is considered. At this stage the embodiment of the detail is evaluated with five variables of different nature. The influence of the section height, as shown in figure 2, and the section thickness is studied along with the displacements in point 1 as in the conceptual design phase. Further, the Young's modulus and the spring constant of the applied spring at point 3 are considered. Point 2 is constrained in all directions. The response studied is the displacement of point 3 and also the equivalent von Mises stresses in the lever.

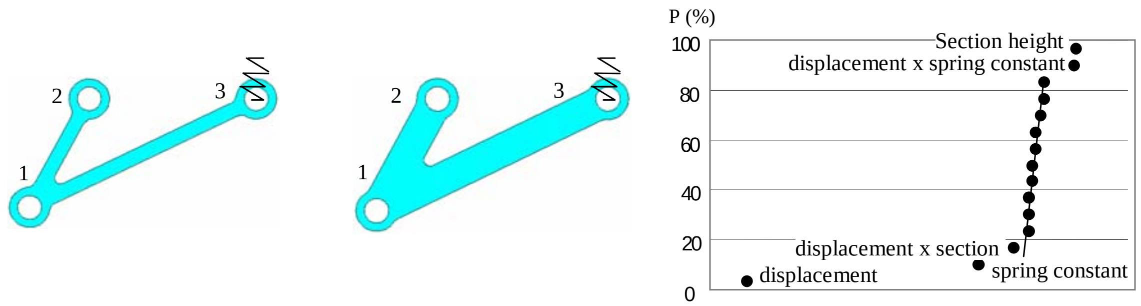


Figure 2. Embodiment design layout and the influences of studied variables on the displacement of point 3.

None of the studied variable combinations resulted in unacceptable stresses, and the stress is therefore not evaluated further. Figure 2 indicates that the displacement variable, the spring constant and the section height of the lever are active.

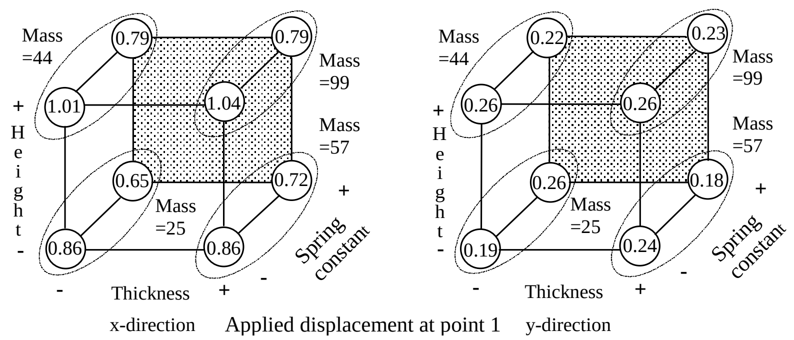


Figure 3. Cube plots of the displacement and the mass, both in unit of measurement, of point 3.

Figure 3 displays the relationship between the displacement of point 3 and the active design variables. The response is presented in two groups depending on the applied displacement at point 1. The values within each ellipse represent a constant mass of the lever. Based on the importance of the overall criteria, the engineering designer can use figure 2 and figure 3 to determine the final design. When, for instance, low mass is desired the lower values of height and thickness should be used. If the displacement at point 3 is not allowed to be less than e.g. 0.5, the displacement at point 1 should be in the x-direction. If on the other hand the influence from the spring constant should be minimized, the displacement at point 1 should be in the y-direction. Other variable configurations can be found in the same manner as described above.

5 Conclusion

This paper presents the value of using DOE together with PDA within design process to evaluate a product in the conceptual and embodiment phases. When more complex products are considered, the basic approach of PDA is the same. The implication would be that more parameters and other DOE algorithms have to be applied. By combining different evaluated responses into a decision table and assigning the responses relative weights based on their importance to the overall criteria, the optimum design variable configuration can be established. The total development and manufacturing cost of a product can also be evaluated by studying the quality level of different manufacturing processes. Combining studies of the significance of estimated factor effects with the PDA approach gives the engineering designer a tool that has a potential similar to that of the Robust Design concept for comparing the distribution of the strength and the prescribed load distribution.

References

[1] Bjärnemo, R., Burman, Å. and Anker, J. C., “FEA in the engineering design process", Computer Aided Design/Computer Aided Engineering (CAD/CAE) Techniques and Their Applications, volume 58, No. 1, Chapter 4, Academic Press, San Diego, 1993

[2] Johnson, D.H., Heald, E. E., “Design of experiments methods for a nonlinear buckling FEA study”, 1998 Ansys Conference Proceedings Vol.1, Ansys Inc., 1998, pp. 513-520

[3] Pahl, G., Beitz, W., “Engineering Design (2nd ed.)”, Springer-Verlag London, 1996

[4] Ullman D.G.,”The Mechanical design process (2nd ed.)”, McGraw-Hill New York,1997

[5] Bjärnemo R. Burman Å., ”Predictive Engineering – a Cornerstone in Tomorrow’s Product Development Process”, to be presented at ICED 99

[6] Eriksson, M., Andersson, P. O., Burman, Å.,”Using Design-of-experiments techniques for an efficient finite element study of the influence of changed parameters in design”, 1998 Ansys Conference Proceedings Vol.2, Ansys Inc., 1998, pp.63-72

[7] Bisgaard, S., “Quality Quandaries-Accommodating four-level factors in two-level factorial designs”, Quality Engineering, Vol. 10, No. 1, 1997, pp. 201-206

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