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Finite Element Analysis and Design of Experiments in Engineering Design

Eriksson, Martin

1999

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Citation for published version (APA):

Eriksson, M. (1999). *Finite Element Analysis and Design of Experiments in Engineering Design*. [Licentiate Thesis, Innovation]. Division of Machine Design, Department of Design Sciences, Faculty of Engineering LTH, Lund University.

Total number of authors:

1

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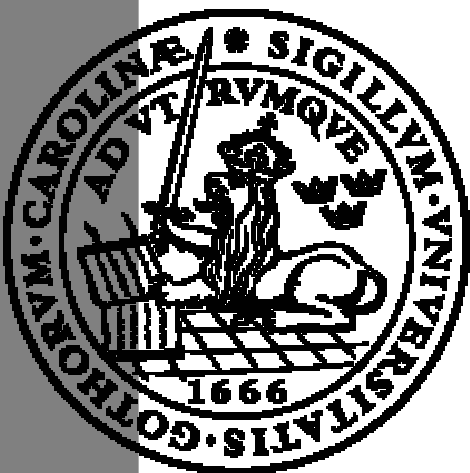
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Finite Element Analysis and Design of Experiments in Engineering Design

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Division of Machine Design
Department of Design Sciences
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Lund, Sweden
1999



Finite Element Analysis and Design of Experiments in Engineering Design

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Published by:

Division of Machine Design

Department of Design Sciences

Lund Institute of Technology

Lund University

P.O. Box 118

S-221 00 Lund, Sweden

ISRN LUTMDN/TMKT-99/1022-SE

ISBN 91-88536-06-8

Printed in Sweden

KFS AB

Lund 1999

To my family

Preface

The work documented in this report has been carried out at the Division of Machine Design, Department of Design Sciences, Lund University.

There are many people that have contributed to the completion of this Licentiate thesis. First of all I would like to thank my advisor and close friend Doctor Åke Burman for his comprehensive guidance during the work. In particular I would like to thank him for sharing his expertise in the field studied and for the boundless encouragement and support throughout the research work.

I would like to address a special thanks to Associate Professor, Robert Bjärnemo for all the stimulating discussions and informal lectures on research in general and Machine Design in particular. The insights gained have truthfully been essential for the completion of this research work.

Further, I would like to express my appreciation to all of the staff members, past and present, at the Division for their concern, friendly environment and for giving me lots of inspiration. Special thanks should go to my former colleague Pär-Ola Jansell who was not only a valued colleague in the beginning of this research project, but also is a great and valued friend.

Ric Fisher should be acknowledged for his thoroughly reviews of the language in this thesis (except for this section). Thank you for improving the English language of my scripts.

Last, but not least, I would like to express my deepest gratitude and love to my mother Inga-Kerstin, my brothers Magnus and Andréas and my sister Annica for their never-ending support and love, and for always being there.

Lund in November of 1999

Martin Eriksson

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The Body of this Report

This Licentiate thesis rests on the five publications listed below.

- A. **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., Canonsburg PA, 1998, pp. 63-72.
- B. **Andersson, P. O., Eriksson, M., Burman, Å.**, *A general tool for Finite Element Simulation of long-time sliding wear*, 1998 Ansys Conference Proceedings Vol.1, Ansys Inc., Canonsburg PA, 1998, pp. 137-145.
- C. **Eriksson M., Burman Å.**, *The Role of Design of Experiments in Predictive Design Analysis*, 1999 ICED Conference Proceedings Vol.1, WDK 26, Munich, 1999, pp. 385-388.
- D. **Eriksson, M., Burman, Å.**, *Statistical Predictive Design Analysis in an Internet Environment*, accepted for presentation at the 5th International Conference on Computer Integrated Manufacturing, Singapore, 2000.
- E. **Eriksson, M.**, Excerpt from the report *A survey of the literature on the use of design analysis and statistical methods in engineering design*, Division of Machine Design at the Department of Design Sciences, Lund University, Lund, 1999.

1 Introduction

Today the development of products is treated in a systematic manner where the goal is to efficiently and effectively develop products of high quality. The product requirements established are translated into technical criteria that are used to evaluate different candidate solutions. In the latter phases of the development process, analysis is today mainly utilized for verification purposes only. The main objective of analysis is to assist engineering designers in their work of simulating the behavior of the product-to-be as a basis for the subsequent decision making process, i.e. selection of "best" candidate solution.

Presently analysis is not regarded as a main part in the establishment of a generic product development procedure model. The consequence of this approach is, at least to some degree, a loss of the holistic perspective on product development. In order to overcome this shortcoming, analysis should not be treated only as a verification tool but as an effective tool that can be used to predict the final behavior of the product-to-be. In the holistic perspective it is also essential to enhance the view of the traditional deterministic analysis approach to the more general view of the stochastic approach where the robustness of a design can be studied.

In a historical perspective there has always been a search for establishing theoretically consistent algorithms and notations to fulfill the growing need for analysis. In addition, mechanical aids were also developed not only to

solve intellectual problems but also physical problems emerging from everyday life. The first documented mechanical aids to mathematical computing are the clay tablets used in Babylon over three thousand years ago.

The more philosophical approach to the foundation of analysis, mathematics, was introduced by the Greek philosophers, e.g. Pythagoras (560-480 BC) and Archimedes (287-212 BC). Pythagoras is most remembered for his famous theorem. Archimedes was not only interested in pure mathematics; he was also interested in the practical use of it. Some of his most famous accomplishments are the invention of the screw, Archimedes' Law of Buoyancy (also known as Archimedes' Principle), and the principle of the lever.

Many philosophers and scientists have contributed from the time of the Greek philosophers to the industrial revolution in the mid-18th century. One of the most famous scientists is the versatile Leonardo da Vinci (1452-1519) who besides being a skilled engineer was also successful as a painter, sculptor, architect, and inventor. As an engineer, Leonardo da Vinci took the startling approach of actually observing nature and asking deceptively simple scientific questions like, "How do birds fly?" He systematically recorded the solutions of nature in his, nowadays, well-known sketches, from which he created and developed new products which he built, at least in the form of prototypes.

With the industrial revolution the manufacturing of products shifted from handicrafts to mass production, which characterizes industrial production. As a result C. Babbage could develop the Difference Engine in 1820, which is considered as the birth of the computer as we know it today. Mathematics and engineering became more and more separated into different research areas, with the practical use of the theoretical research in mathematics being explored within engineering. Around the turn of the 20th century, knowledge was well spread over the world in both areas and many researchers contributed to the global knowledge. A stable industry structure evolved, though complex products were still developed facing numerous uncertainties. To ensure quality and reliability, all products had to be adjusted individually in order to work properly.

The problem of quality was obvious but the solution to the problem was not that obvious. It was, according to Bisgaard [8], the works of Shewhart and Tippet in the 1920s and 1930s that introduced quality control into the manufacturing process. They based their approaches on the idea of planned or designed experiments by Fisher [17], which he originally had developed for agricultural research. The novelty in the model by Fisher was the shift from the traditional one factor at a time experiments, where only one variable is altered at a time, to a planned approach where all variables are altered simultaneously in a systematic way. The one factor at a time experiments did give some indication of how to assign values to variables, but the crucial importance of finding the overall best values couldn't be detected since no interactions among the parameters could be studied. W. Deming [16] and J. Juran [18] introduced the idea of quality to Japanese industry, and they adopted the concept of active quality control within product development. This was later further developed and elaborated by G. Taguchi [33], who established an approach to quality that is frequently used in industry all over the world today.

Another research area focused on finding numerical methods to solve intriguing mathematical problems related to complex products. One of the first established methods that was used in solid mechanics was the Finite Difference method (FD) that is well suited for fluid and thermal analysis. The method had some drawbacks regarding the modeling of boundaries and boundary conditions since it required structured grids. Engineers wanted a more intuitive and forthright approach to the modeling than could be achieved with the FD. The research of discretization of a complex problem into a set of less complex problems that were easily solved began. This led to the development of the Finite Element Method (FEM) in the 1950s, see e.g. Argyris [6] and Clough [14]. The first implementations of FEM were used only for verification purposes. Development of the mathematics behind the technique has led over the years to a range of general formulations, which have been introduced into the mechanical engineering design process, or design process for short, to verify designs. The use of quantifiable methods, such as FEM, in design is referred to as design analysis in this thesis.

In parallel with the development of design analysis methods, the use of computers within design has increased. The real development of computers began with the Second World War and was first introduced in the ordnance industry. With the development of the transistor in 1956 the speed and efficiency of the computer increased. The research has since then resulted in smaller and faster computers. Along with the development of computers, their communication has been enhanced. Under the leadership of the United States Department of Defense's Advanced Research Project Agency (DARPA), ARPANET grew from a paper architecture into a small network in 1969 intended to promote the sharing of super-computers amongst researchers in the United States. The development of ARPANET into a global network of computers resulted in the Internet and WWW, containing the HyperText Markup Language (HTML) which was released in 1991 by CERN.

1.1 Background

Today design, manufacturing techniques and skills have become more and more sophisticated. This has led to the development of more reliable products, but their quality has not necessarily increased. Many issues of uncertainties still emerge during product development. Marczyk [23] categorizes these into two major areas, physical uncertainties and numerical simulation uncertainties. The first category contains load and boundary conditions, material and geometry problems. The latter category focuses on the implementations of numerical methods whereas problems arise in modeling, mathematical and discretization uncertainties, bugs and programming errors and numerical solution uncertainties (round off, convergence criteria). To address the problems mentioned above, non-commercial organizations such as The International Association for the Engineering Analysis community (NAFEMS) or the Nordic Association for Computational Mechanics (NoACM) have emerged. The purposes of these organizations are to promote and stimulate the research and practice of reliable and safe computational mechanics.

Methods, whether improvements on or combinations of known and well-established techniques or based on new methodologies, are developed to

handle the uncertainties addressed above. By integrating design analysis methods into Computer Aided Design (CAD) software environments, the influence of modeling and discretization errors can be decreased as an effect of the access to the CAD representation. A numerous of commercial solution packages are available, i.e. SDRC's I-DEAS, Dassault's CATIA and PTC's Pro/ENGINEER.

Other commercial software programs that work as general preprocessors and postprocessors are also available, see i.e. CADfix, FEMAP, HyperMesh. These programs interact with CAD programs with representations that are based on one of the two major CAD kernels Parasolid or ACIS, or they use some standard ASCII format such as IGES or STEP. The problem with the standard formats, however, is that they exist in many flavors, and thus the standards are unfortunately not very general. A fundamentally new technology approach has been introduced with the product Procision [5]. Procision is based on the External Approximation Method, and avoids the translation problem since the mathematical formulation works with the CAD representation.

Projects with the objective of introducing Finite Element Analysis (FEA) into the early phases of the design process have previously been carried out at the Department of Machine Design, see e.g. the Doctoral thesis by Burman [13]. These works clearly highlight the usefulness of introducing design analysis early in the design process. According to Bjärnemo and Burman [10] the most significant advantage of applying design analysis early in the design process was the shift from *verification* to *predictive* analysis. Based on these results the following objective has been established for Predictive Design Analysis (PDA), Bjärnemo and Burman [10]:

Development of computer based tools for generating features of the product-to-be that are computationally obtainable on all levels of concretization throughout the mechanical engineering design process.

The objective set forth for the research project reported here is to contribute to fulfilling the objective of PDA. More specifically, the objective set out for this thesis is:

To investigate and survey the state of the art of the utilization of statistical methods combined with design analysis methods within the early phases of the mechanical engineering design process.

Following a short account of the scientific approach utilized, the constituent parts of the objective, design methodology, design analysis methods and statistical methods are briefly elaborated upon.

2 Scientific approach

The use of scientific methods is one important characteristic of research. The vast variety of research disciplines implies that there also exist many different approaches to research. In natural science the *deductive method* (hypothesis testing) is frequently used. When working with this method, a hypothesis is established and if no implications that could lead to rejection of the hypothesis are found the hypothesis is strengthened. Another approach is the *inductive method*, which stipulates that all facts should be analyzed and classified. Based on inductive reasoning a hypothesis should then be generated. From the perspective of design it is often difficult to directly transfer these scientific methods because the objective is often to solve a problem. When studying a problem, researchers tend to focus on the development of tools or methods to be used within the solving process.

Since the basis of the research that this thesis is a result of is previous research carried out at the Division, a research approach that has an inductive nature is adopted. The results and conclusions found in earlier Doctoral theses by Burman [13], Bjärnemo [9] and Andersson [2] have been studied. The thesis “*On the Implementation of Finite Element Analysis in the Mechanical Engineering Design Process*” by Burman discusses the advantages of implementing design analysis, in his case Finite Element, early in the design process. In addition to Finite Element and design methodology, Bjärnemo focuses on evaluation techniques in the design process in the thesis “*Towards a Computer Implementable Evaluation*

Procedure for the Mechanical Engineering Design Process". In the thesis "*A Process Approach to Robust Design in Early Engineering Design Phases*" Andersson focuses on Robust Design and its positioning within the design process. The requirements of statistical methods within Robust Design are also discussed in this work.

This thesis is the result of studying the "state-of-the-art" of statistical and design analysis methods within the design process. The works documented here are subsequently to be used as a foundation for further research, which will aim at proposing hypotheses of how, when and why the studied approach to design analysis should be implemented in early phases of the design process.

3 Frame of reference

3.1 Design methodology

Several names and definitions have been associated with the work of developing product development processes over the years, and they have been interpreted differently by different people. Examples of expressions used are *Integrated Product Development*, *Concurrent Engineering*, and *Simultaneous Engineering* and a buzzword commonly connected with all these approaches is *concept design*. Although there are differences in names, the approaches are generally easy to deduce and they all have a similarity in focusing on the fulfillment of a need that initiated the development activity. Another important point of view that the approaches share is that the development of a product be organized and performed systematically. The methodologies proposed by researchers today have basically the same appearance as the model introduced by Krick [21] in 1969, see Figure 3.1.

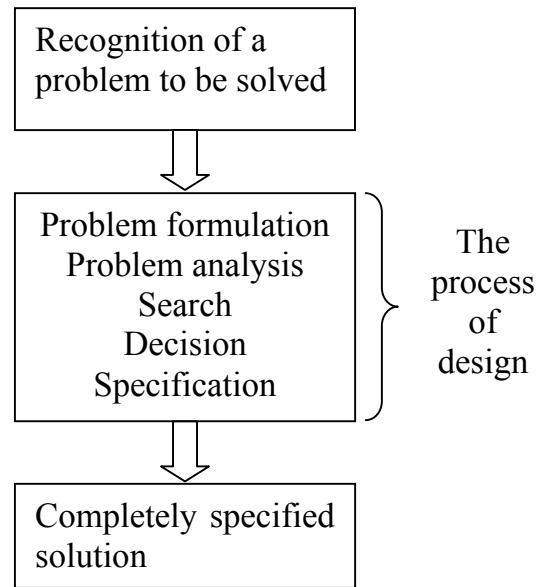


Figure 3.1 The design process model by Krick [21].

The difference between various procedure models for product development lies partly in how many functions within the company are included in the model; see for instance the procedure model *Integrated Product Development* by Olsson, Hein and Andreasen [26]. This work was extended, and today there exist two different models. One by Olsson [25] named *Integrated Product Development* that involves four parallel activity chains (marketing/sales, design, production, and management/financing). The other model, proposed by Andreasen and Hein [4], involves only three chains (marketing/ sales, design, and production). Apart from this obvious difference, these two models are similar in that the overall focus is on a problem-oriented activity and on the problem solver, i.e. the designer.

The approach by Pahl & Beitz [28] documented in *Engineering Design - A Systematic Approach* is one of the most utilized approaches. It is product oriented and focuses on the product-to-be, and their description of the general process for finding a solution, see Figure 3.2, shows significant influences from the model by Krick.

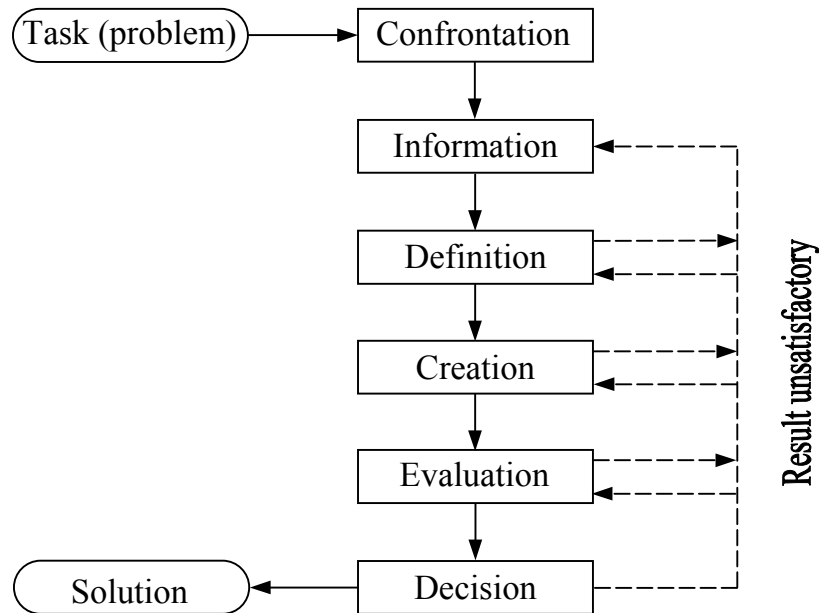


Figure 3.2 Model for finding solutions described by Pahl & Beitz [28].

Pahl & Beitz base their approach mainly on theory and give explanatory examples from their own experiences in industry. The method is documented in great detail, almost as a step-by-step guide to be used on all levels of the design process. Pugh [29], on the other hand, bases his *Total Design* mainly on his working experience in industry and gives an overview of practical aspects of design. This approach has an objective set out to satisfy a market or user need, where the focus is not only on the product but also on the process, people and organization. The approach by Ullman [34] documented in *The Mechanical Design Process* also discusses the designer's role in a design team and in the overall design process, and the importance of process planning. The approach is, however, focused on the development of a manufacturable product from the initial need. The approach of axiomatic design theory and methodology presented by Suh [31], in *The Principles of Design*, is the method that clearly differs from other approaches studied. In the perspective of the other approaches to design studied, Suh's can be seen as a wide methodology of evaluation theory.

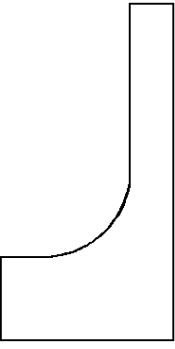
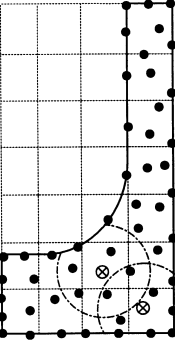
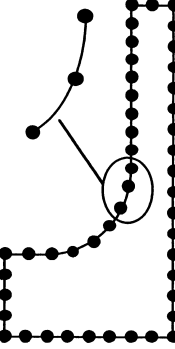
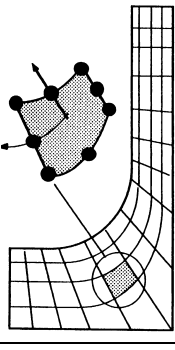
The starting point of all approaches is the establishment of criteria that must be fulfilled in order to satisfy the user requirements on which the criteria are based. In the concept design phase the objective is to generate different working principles, and combinations of those, that solve the overall function. The main activity in concept design can be characterized as synthesis. The concepts are then evaluated against the criteria that are mainly qualitatively oriented.

3.2 Analysis methodology

Design analysis can be divided into a couple of topics dependent on the nature and the purpose of the analysis, e.g. Multi Body Simulations (MBS), Computational Fluid Dynamics (CFD), magnetic and electrical field analysis, and structural and thermal analysis. To include all areas is beyond the scope of this research project. Two areas, structural and thermal analysis, are chosen to represent design analysis. These two types of analyses are similar in terms of the mathematical analysis approach and are also those most frequently used in design analysis.

The frames of reference of structural and thermal analysis are divided into different studied methods: the Finite Element Method (FEM), the Boundary Element Method (BEM), the Element Free Galerkin method (EFG) and the External Approximation Method. All methods have advantages, but also disadvantages, when compared to each other. Table 1 below shows a comparison of the methodologies.

Table 1 Studied Design analysis methodologies (Adapted from Kane [20]).

Method	External Approximation Method	The Element Free Galerkin Method	The Boundary Element Method	The Finite Element Method
M o d e l				
A d v a n t a g e s	<ul style="list-style-type: none"> • Requires only surface representation. • Sparse matrices, usually symmetric. • Modeling boundaries and boundary conditions very natural. • No defeaturing needed. 	<ul style="list-style-type: none"> • Sparse matrices, usually symmetric. • Integration cells can have very poor shape. • Effective in linear elastic fracture mechanic problems. • No defeaturing needed. 	<ul style="list-style-type: none"> • Modeling boundaries and boundary conditions very natural. • Requires only surface grids. • Ideal for infinite problems. • Resolution of response gradients not tied to volume mesh refinement. 	<ul style="list-style-type: none"> • Mature technology used extensively. • Integration of simple functions. • Sparse matrices, usually symmetric. • Modeling boundaries and boundary conditions natural.
D i s a d v a n t a g e s	<ul style="list-style-type: none"> • Immature technology, which only recently emerged as a commercially available numerical technique. • Different sets of functions for different types of geometry. 	<ul style="list-style-type: none"> • Immature technology that only recently emerged as a novel numerical technique. • Calculation of the stiffness matrix burdensome. • Modeling boundaries and boundary conditions unnatural. 	<ul style="list-style-type: none"> • Requires transformation to boundary formulation using fundamental solutions. • Requires substantial numerical integration of complex functions. • Generally unsymmetric matrices. • Defeating needed. 	<ul style="list-style-type: none"> • Requires volume grids. • Starting to approach final stages of accomplishment. • Resolution of response gradients tied to volume mesh refinement. • Defeating needed.

The frame of reference of FEM is based on books such as *The Finite Element Method* vol. 1 and vol. 2 by Zienkiewicz and Taylor [36], *Introduction to the Finite Element Method* by Ottosen and Petersson [27] and *Concepts and Applications of Finite Element Analysis* by Cook et al. [15]. Regarding BEM, the frame of reference is based the book *Boundary Element Analysis in Engineering Continuum Mechanics* by Kane [20]. The frame of reference of EFG is based on published research such as *Element-Free Galerkin Methods* by Belytschko et al. [7], *An Improved Element Free Galerkin Formulation* by Kaljevi'c and Saigal [19] and *The Element free Galerkin Method* by Andersson and Eriksson [3]. Regarding the External Approximation Method, the frame of reference is based on the technical white paper of Procision by the Russian Professor Apanovitch [5]. The above references are mainly concerned with the theoretical formulations of each method respectively.

EFG is the most recent of the methods developed, appearing in the early nineties. The idea of the method came from a research project aiming at finding a more efficient way of presenting and visualizing FEM results. The method is today mainly used for research purposes in specific areas, such as crack propagation. The development of the External Approximation Method in the early eighties in Russia was also related to FEM in the sense that the computer power in Russia at that time was inadequate to solve complex problems with FEM. A new and more efficient method was sought, and the development of the mathematics behind what is today known as the External Approximation Method was initiated.

BEM was developed in the mid- seventies and was introduced as an alternative to FEM. The use of FEM was too widespread in both academia and industry and therefore the development of BEM became more and more concentrated towards solving specific problems. Today BEM is mostly found in “in-house programs” solving contact problems.

The by far most commonly used design analysis software in design in industry today is based on FEM, as can be seen in the literature survey performed. The teaching at graduate levels at universities uses mostly FEM for the purposes of demonstrating design analysis. Based on the fact that

FEM is the most widespread technology in terms of practical use, it will be used throughout this work to represent design analysis.

Literatures that treat the use of FEA in the design process are rare and hard to find. However, three books that emphasize the practical issues of FEA have been studied. The book *Fem i praktiken* (in Swedish) by Sunnersjö [32] describes solutions to a number of practical problems and can be categorized as an engineer's handbook on FEA. Zahavi's book [35], *The Finite Element Method in Machine Design*, mainly addresses the analytical issues of FEM regarding studies of specific machine elements in the later design phases. The third book, *Building Better Products with Finite Element Analysis* by Adams and Askenazi [1], is focused on presenting a wide perspective of practical aspects related to FEA and only briefly discusses the use of FEA in design in terms of saved cost of early design changes. How FEA should be implemented in practice is left for the reader to decide.

3.3 Statistical methods

In design, the theory of probability and the theory of statistics are frequently used in a vast variety of engineering fields. The most frequent use is probably the selection of material properties from different standard textbooks. These data are often given in the form of mean values of some distribution. The selection of load cases, i.e. magnitudes and directions, is often based on some load spectrum. Other areas where the theories have been used are the study of fatigue data, Wöhler diagrams and in studies of reliability and quality. The method of Robust Design was established from the early studies of quality in design. By using the approach of Robust Design, the designer is able to compare loading and strength distributions and can thereby draw conclusions on whether a design will withstand a given load. A third area of interest to engineering designers is the Design for Manufacture where different quality aspects of manufacturing are considered. The probably most widespread statistical methodology used in quality research within the design process is the Design of Experiments (DOE).

The general idea of DOE is to perform as few analyses as possible, without compromising accuracy, to obtain a high-quality solution. DOE is based on fractional 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, i.e. stresses, displacements, design layouts, or working principles. Statistical evaluation methods are then used to extract vital information from DOE and also to organize and visualize it. The sensitivity of a product design to environmental factors can also be analyzed with DOE. Interactions between design variables and environmental variables might also be included in the study.

The use of DOE today can clearly be divided into two major groups depending on the basic approaches. The first group is based on the approach by the Japanese Professor Taguchi [33]. The frame of reference for the first group, besides Taguchi [33], is *A primer on the Taguchi Method* by Roy [30] and *Designing for Quality* Lochner and Matar [22]. The method is today widely deployed in industry as it is easy to adapt for engineers. In this approach it is preferred to consider design variables at three levels, and the evaluation of the experimental results is made of signal to noise ratios (S/N-ratios). Lochner and Matar [22] mention that Taguchi has introduced over seventy such ratios for different problems that are used to reduce the variance and keep the average response close to target. In practice the three ratios, called smaller-is-better, larger-is-better and nominal-is-best are used to handle most situations. Over the years there has been a lot of discussion regarding the efficiency and accuracy of the Taguchi method among western statisticians, see e.g. Box et al. [11]. They prefer to use an approach called two-level experiments where the design variables are treated on two levels. The frame of reference for this second group is *Statistics for Experiments* by Box et al. [12] and *Design and Analysis of Experiments* by Montgomery [24].

4 Summaries of papers appended

The first two papers show how extensions to a commercial FEA program can be made to increase the power of design analysis within the design process by adding capabilities of prediction. The third paper points out the potential of introducing PDA in the early phases of the design process. The fourth paper introduces a World Wide Web (WWW) interface to PDA. In the fifth paper the result of the literature survey regarding the objective set out for this thesis is presented. The survey has been performed throughout the work on the thesis.

Paper A : Using Design-of-Experiments techniques for an efficient Finite Element study of the influence of changed parameters in design

The paper presents a new approach of FE modeling including statistical aspects. The approach has been successfully implemented as a module in the FE software ANSYS. By describing the fluctuations in design parameters in terms of normal distributions with expectation and variance, the design in the examples is examined with the standard Taguchi statistical method and one variant of it.

This treatment of the design analysis demands several experiments, and to plan these experiments Design of Experiments (DOE) techniques according to Taguchi were used.

The module plans the FEM analysis and calculates the standard statistical moments of the FEM result. The errors in both the standard and variant method of Taguchi are of the same order as could be expected of an ordinary FE analysis of the problem.

This module serves as a powerful tool for the engineering designer or analyst when examining the influence of variance and mean value of different design variables as well as sorting out those parameters that have great influence on the response studied. The module can be implemented directly in the design for manufacture (DM) stage of the design process. Stress and strain results based on statistical finite element can be compared with the strength of the material used, which can also be treated as a normal distributed design variable in the implementation.

Paper B : A general tool for Finite Element Simulation of long-time sliding wear

In this paper, a wear module is presented which is implemented into the FE software ANSYS. The module is general, and can be used to perform long-time wear simulations of bodies in sliding contact, e.g. gear transmission analyses and biomechanics. The model is automatically updated, and no redefinition of data is needed. The implementation can be used by engineering designers to perform lifetime studies, design studies, studies of the behavior of different materials, and investigations of structural behavior due to mechanical wear. Both time and money spent on expensive lab rig experiments could be reduced significantly by using this tool.

Paper C : The role of Design Of Experiments in Predictive Design Analysis

This is the first paper based on the formalized Predictive Design Analysis (PDA) approach. The approach is illustrated with an example of how design analysis combined with statistical methods can be used in both the conceptual and the embodiment design phases. In the conceptual design

phase, four different concepts are established and evaluated only with respect to the results from the design analysis. The evaluation could, however, be extended to include other criteria that appropriately reflect other relevant requirements of the problem studied. The model in the conceptual phase was made with simple beam elements that result in a simplified and thereby fast analysis, but nevertheless describe the overall physical behavior of the concepts studied. The best concept was chosen for further evaluation, and the FE model was concretized further to a 2D model that allows the basic shape of the design to be evaluated.

Paper D : Statistical Predictive Design Analysis in an Internet Environment.

This paper shows the possibilities of combining PDA with tools for visualization and data communication. The application presented in the paper is built as a World Wide Web (WWW) Client/Server application. The client-side user interface interacts with the time-consuming FE analysis performed on the server through an Internet or intranet connection. The implementation consists of both of the statistical methods used in papers A and C. The use of Internet/intranet provides the possibility of the application presented to be used by design teams that are geographically separated. Design engineers from different teams can view and further evaluate the result for their specific area of interest. Another advantage of using a Client/Server application on the WWW is that the hardware platforms of the clients and servers are independent of each other.

Paper E : A survey of the literature on the use of design analysis and statistical methods in engineering design.

This paper presents the results of the literature survey. The survey covers only articles and conference papers, since monographs relevant to the topic are continuously updated and available at the Division. The databases used are INSPEC and COMPENDEX*. The objective of the survey was to determine the use of design analysis methods in combination with statistical

methods early in the design process. Participation and attendance at conferences and seminars have helped the activity of finding information.

The search in the literature survey discovered a large number of articles, and those that seemed to be best related to the general objective were selected and reviewed thoroughly. Based on the review it was concluded that the most frequently used design analysis method was Finite Element Analysis. The combinations of design analysis and statistical methods were presented for special applications, and few of the articles studied discussed the issue of introducing the methods into the early phases of the design process. Thus it was concluded that the implementation of design analysis methods together with statistical methods within the design process needs to be elaborated.

5 Conclusions

The literature survey clearly highlights that the use of design analysis methods is most frequently used in later stages of the design process. It further reveals that most research does not treat analysis in the context of the design process, and thus does not deal with how and when the techniques should be implemented. However, Burman's thesis [13] shows the advantages of introducing FEM into the early phases of 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.

The use of statistical methods in design today is merely concerned with the development of designs that are robust and have high reliability. Andersson's thesis [2] discusses the requirements needed for statistical methods to ensure robust designs. Another area where statistical methods have been introduced in recent years is in design analysis to plan and evaluate a number of analyses. Statistical approaches are very powerful and are used to extract the few vital variables from the many trivial ones.

To increase the use of both design analysis and statistical methods at the early phases of the design process, the proposed PDA approach will provide the designer with tools for using design analysis more effectively. The use of PDA will allow the designer to evaluate some of the criteria in the conceptual design phase using a quantitative approach, thus providing a

higher probability of success in the subsequent decision making procedure. This Licentiate thesis presents the “state-of-the-art” regarding research into the combination of design analysis and statistical methods in the early phases of the design process. The papers presented in the thesis show that the basic idea of PDA can be adopted into the design process.

Papers A and B presented in the thesis show how different modules can be added to commercial FEA software in order to increase the power and usability of that software.

The example shown in Paper C utilizes the PDA approach in the early phases of the design process. Although only the working principle is studied in the conceptual design phase, the paper demonstrates that design analyses can be used to study and evaluate concepts. The result is then reused in the embodiment design phase to determine the preliminary design layout.

A user interface to the PDA approach that is developed as a Client/Server application is presented in Paper D. The interface can be viewed and evaluated through the Internet simultaneously by design teams located all over the world.

This Licentiate thesis establishes that the combination of statistical methods and design analysis gives the designer powerful evaluation tools to be used in combination with other engineering tools at all phases of the design process.

5.1 Future research

Problems that occur when statistical methods are combined with design analysis are often related to lack of understanding of the theories of the techniques. The emphasis of future research should be to present an approach that can be understood and utilized by designers in their everyday work at all levels of abstraction in the design process.

To achieve this, an approach based on the results presented in paper C, that clearly addresses its applicability into different stages in the design process, has to be developed. The applicability of different design analyses techniques, FEM, BEM, EFG and External Approximation Method, or

combinations of these would be interesting to evaluate. Statistical methods used in this Licentiate thesis are based on DOE, but other statistical methods such as Monte Carlo simulation would be interesting to study. The interface presented in paper C can be considered as an embryo to an interface that could serve as an umbrella for the overall development process independently of which analytical or statistical techniques are used to perform the actual analyses and evaluations.

Another issue that is of interest when dealing with design analysis is to decrease the required resources. When dealing with statistical methods, a number of independent analyses have to be performed that will increase the total computational time approximately by a factor equal to the number of analyses performed. Performing the analyses in parallel, for example on a cluster of computers, will decrease the total computational time required. Another way to decrease computational time would be to perform the statistical evaluation by interpolating or extrapolating results from earlier design analyses.

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Paper A

A

**Using Design-of-Experiments techniques for
an efficient Finite Element study of the
influence of changed parameters in design**

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1998 Ansys Conference Proceedings
(Bryan, W. J. et al. eds.)
Ansys Inc., Canonsburg PA, 1998

USING DESIGN-OF-EXPERIMENTS TECHNIQUES FOR AN EFFICIENT FINITE ELEMENT STUDY OF THE INFLUENCE OF CHANGED PARAMETERS IN DESIGN

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ABSTRACT

All designs are marred by uncertainties and tolerances in dimensions, load levels etc. Traditionally, one has often over-dimensioned to take these uncertainties into account. The demand for optimized designs with high quality and reliability increases, which means that more sophisticated methods have been developed, see e.g. Lochner and Matar (1990). By describing the fluctuations in design parameters in terms of distributions with expectation and variance, the design can be examined with statistical methods, which results in a more optimized design. This treatment of the design often demands several experiments, and to plan these experiments Design Of Experiments (DOE) techniques, see e.g. Montgomery (1991), are often used. By using DOE methods the design variables are systematically altered, which minimizes the number of experiments needed. The output of the experiments is the results of a specified response function, giving an indication of the influence of design variable fluctuations. A FEM system is a suitable tool when performing repeated, similar analyses. Examples exist where the DOE process has been performed externally and then transferred to the FEM system in the form of parameter sets defining the analysis cases that are to be solved, see e.g. Summers et al. (1996) and Billings (1996).

This paper describes a statistical DOE module based on Taguchi's method that works within ANSYS. The module plans the FEM analysis and calculates the standard statistical moments of the FEM result. This module serves as a powerful tool for the engineering designer or analysts when examining the influence of variance and mean value of different design variables. It also serves as an exploration of where to concentrate an optimization process.

NOMENCLATURE

n = Number of design variables
 $X_{i \rightarrow n}$ = Values of the design variables
 μ_i = Mean value of the i :th design variable
 σ_i = Standard deviation of the i :th design variable
 w_i = Weight of the i :th design variable

L_i = Degree of freedom for the i :th design variable
 N = Number of calculations performed in the experiment
 N_{\min} = Minimum number of required calculations
 $Y_{1 \rightarrow N}$ = Response function for the experiments
 $\bar{\mu}$ = Mean value of response function
 $m_{1 \rightarrow 4}$ = Four moments in the statistical evaluation
 $\sqrt{\beta_1}$ = skewness coefficient
 β_2 = Kurtosis coefficient
 μ_{ik} = Mean value of level k for the i :th design variable
 SSV_i = Sum of square of the i :th design variable
 $SSTO$ = Total sum of square of a experiment

INTRODUCTION

Engineering design

FE analysis is commonly used as a tool by engineering designers to verify whether a product's design can withstand the loading and environment it is subjected to or not. Simple static analysis, where the stresses and displacement are investigated, as well as complicated optimization problems, where the goal is to find the best suitable design for the given premises, are performed. Failure investigation is another area where FE analyses have become a very important tool. These calculations are performed both on commercial products where the responsibility issue has to be determined and on prototypes developed within the product development process.

Both areas mentioned assume that at least a product design exists. It would be less time consuming and more cost effective to use FE analysis within the product design process. The approach where FE is treated as a product design tool and not exclusively as an analysis tool could be integrated with most known models of product development, for instance Pahl and Beitz (1996). Their model consists of three steps, conceptual design, embodiment design and detail design. In conceptual design the specification of principle is developed and the embodiment design results in a specified layout of the product. In detail design the final product is developed with specified dimensions, surface properties, production instructions and estimated costs.

It is in the detail design that the engineering designer could make use of the current implementation, DOE based FE analysis. Making use of the basic properties of DOE, planned experiments, the engineering designers can run a number of FE analyses to evaluate the influence different design variables have on a product. Before the theoretical formulation is outlined a brief history of quality in engineering design is discussed.

Statistical Methods in Engineering Design

In the early age of industrial manufacturing the product quality was often poor. Most products needed to be adjusted in order to work properly. A product tolerance was usually an outcome of the manufacturing process. Since then the manufacturing techniques and skills have become more and more sophisticated. These have led to more reliable products, but the quality of a product has not necessarily increased. This is probably due to higher competition among companies where the total cost of a product has become more and more important and the quality has sometimes been neglected. The “gurus” in quality engineering through the 1950s and 1980s, e.g. Dr. Juran and Dr. Deming, have based all their definitions on the word quality. Lochner and Matar (1990) have found that the definitions do not match entirely, but they say that there are some threads in the “guru’s” works.

- Quality is a measure of the extent to which customer requirements and expectations are satisfied.
- Quality is not static, since customer expectations can change.

With these comments in mind it is easy to see why quality was not the key issue among companies around the world.

Since the late 1980s the manufacturing process can meet most of the tolerance demands set by the engineering designer without raising the manufacturing price of a product. This makes it more interesting to take the work with tolerances into the product development process. Today these traditional methods for quality ensuring and tolerance analysis are becoming somewhat inadequate. Firstly, the tolerance was treated as limits on parameters on a parametric model. Secondly, the common practice has been to estimate tolerance by either worst-case methods that give results that are overly pessimistic or methods, e.g. root-sum-square methods, that give too optimistic results. To get more accurate results new methods have been introduced in the product development process in recent years. Statistical methods and DOE methods have often been used by scientists to evaluate their experiments and are now also introduced into the area of product development. Nigam and Turner (1995) presented a review of these methods in 1995. DOE are techniques to plan experiments in order to decrease the number of experiments performed while maintaining a reasonable accuracy level. In detail design FE analysis is a suitable tool for evaluating a products dimension and tolerances. Previous works, see Summers et al. (1996) or Billings (1996), are based on separate programs that collaborate to produce the final result. The data has to be transported between the two programs, this is time consuming and an old fashioned way of working with computer technology.

OBJECTIVE

The objective of this work has been to develop a code that integrates DOE, based on Taguchi, into the usual Finite Element environment in the ANSYS program. The code is written in such a way that an accustomed user of the program will find it easy to work with. The code is developed as an UPF, see ANSYS Programmer’s Manual (1996),

in ANSYS that, given a number of independent design variables of normal distributions with three levels, uses a Taguchi based DOE method to specify the layout of analysis cases to be solved. The FE results are analyzed statistically and calculated moments of the response are produced, and each design variable influence on the result is evaluated. The results calculated in the implementation could work as one of the decision rules in the detail design phase of the engineering design process.

THE TAGUCHI METHOD

The Taguchi method is suitable for conducting factorial experiments because the response function does not need to be known prior to the experiment. It can also handle design variables with two, three or more levels, and even mixed levels can be used. Finding the appropriate levels of each design variable is the key issue in the Taguchi method. Below are two methods that represent normal distributed variables in the Taguchi methodology described.

Traditionally full factorial experiments, all combination experiments, are performed. This tends to be very time consuming when the number of design variables increases. Taguchi has constructed different types of orthogonal arrays that limit the experiments performed. In this paper two different representation types of the normal distribution are used, firstly the standard Taguchi method introduced by Taguchi in the 1980s and then a modified Taguchi method presented by D’Errico and Zaino (1988). The design variables are normal distributed with mean value μ_i and standard deviation σ_i .

Standard Taguchi Method

In the standard Taguchi method three points with the same weight, 1/3 are used to represent the distribution. This means that they are equally represented in the calculations. Figure 1 shows the representation of the normal distribution in the standard Taguchi method.

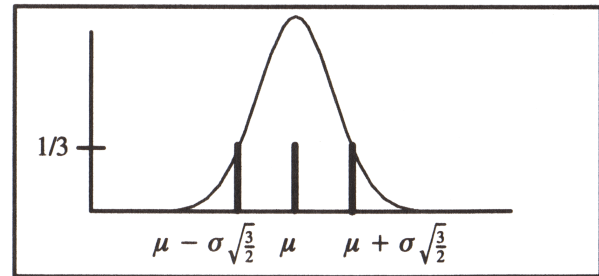


FIGURE 1. STANDARD TAGUCHI APPROXIMATION

The three levels are defined as:

$$\text{low level} = \mu_i - \sigma_i (3/2)^{1/2} \quad (1.a)$$

$$\text{center level} = \mu_i \quad (1.b)$$

$$\text{high level} = \mu_i + \sigma_i (3/2)^{1/2} \quad (1.c)$$

The system response function $Y = f(X_1 X_2 \dots X_n)$ is evaluated at the selected number of combinations of the design variables X_i .

The four moments, the skewness and kurtosis coefficients are computed directly from the response values as:

$$m_1 = \sum_{j=1}^N Y_j / N \quad \text{mean value} \quad (2.a)$$

$$m_2 = \sum_{j=1}^N (Y_j - m_1)^2 / N \quad \text{variance} \quad (2.b)$$

$$m_3 = \sum_{j=1}^N (Y_j - m_1)^3 / N \quad \text{third moment} \quad (2.c)$$

$$m_4 = \sum_{j=1}^N (Y_j - m_1)^4 / N \quad \text{fourth moment} \quad (2.d)$$

$$\sqrt{b_1} = m_3 / (m_2)^{3/2} \quad \text{skewness coefficient} \quad (2.e)$$

$$b_2 = m_4 / (m_2)^2 \quad \text{kurtosis coefficient} \quad (2.f)$$

Modified Taguchi Method

This method by D'Errico and Zaino NO TAG also uses three levels to represent the normal distribution as seen in Figure 2. Instead of treating all levels equally, the low and high levels are given the weight $(w_i) \frac{1}{6}$ and the center level is given the weight $\frac{4}{6}$

The three levels are defined as:

$$\text{low level} = \mu_i - s_i \sqrt{3} \quad (3.a)$$

$$\text{center level} = \mu_i \quad (3.b)$$

$$\text{high level} = \mu_i + s_i \sqrt{3} \quad (3.c)$$

The moments are calculated through

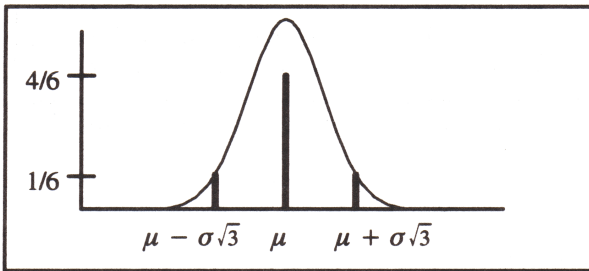


FIGURE 2. MODIFIED TAGUCHI APPROXIMATION

$$m_1 = \sum_{j=1}^N w_j Y_j \quad (4.a)$$

$$m_k = \sum_{j=1}^N w_j (Y_j - m_1)^k \quad (4.b)$$

When the experiment contains more than one design variable, the weights are simply multiplied for each factor.

FRACTIONAL FACTORIAL EXPERIMENTS

In full factorial experiments the response is calculated at every combination of design variable levels, which means that $N = 3^n$ calculations have to be performed. Fractional factorial experiments are based on arrays which define the order in which the design variables should be altered. They are commonly used with the standard Taguchi method to get a more time effective calculation. For example, a 3^4 factorial design requires 81 runs and a 3^{13} factorial design requires 1594323 runs. A fractional factorial experiment with the same number of design variables only requires 9 and 27 runs respectively. Thus when the number of design variables is increased the calculation time can be rapidly decreased by using fractional factorial experiments. In practice the task of finding a useful suitable array is easily reduced to selecting an already defined array which can be found in many reference books. Table 1 below shows some widely used orthogonal arrays, suggested by Taguchi, for three level design variables.

Table 1. List of Taguchi Orthogonal Arrays

Orthogonal array	Number of rows	Maximum number of factors	Maximum number of columns at these levels	
			2	3
L9	9	4	-	4
L18	18	8	1	7
L27	27	13	-	13
L36	36	23	11	12
L'36	36	16	3	13
L54	54	26	1	25
L81	81	40	-	40

All of these orthogonal arrays assume that the design variables are independent. The value "Number of rows" is the value of number of experiments to be performed. For instance the L9 array performs nine experiments with up to four design variables with three levels. The experiment results in nine different response values $Y_{1 \rightarrow 9}$ as seen in table 2.

Table 2. Taguchi L9 Array

Experiment	dv_1	dv_2	dv_3	dv_4	Response
1	1	1	1	1	Y_1
2	1	2	2	2	Y_2
3	1	3	3	3	Y_3
4	2	1	2	3	Y_4
5	2	2	3	1	Y_5
6	2	3	1	2	Y_6
7	3	1	3	2	Y_7
8	3	2	1	3	Y_8
9	3	3	2	1	Y_9

Minimum number of experiments to be performed

Which of the arrays must be conducted in order to use the Taguchi method can be calculated based on the degrees of freedom approach.

$$N_{\min} = 1 \pm \sum_{i=1}^n (L_i - 1) \quad (5)$$

where L_i denotes the degree of freedom for design variable i . In general the degree of freedom (df) associated with a factor is one less than the number of levels. Thus, the three level design variables each have $df = 2$.

STATISTICAL ANALYSIS OF THE FINITE ELEMENT RESPONSE

The response function as usually predefined when an experimental design is performed. In FE analysis, on the other hand, the analysts must define the response function. The choice of response function depends on the problem. In structural analysis, for instance, the weight, stresses and displacements can be chosen as response functions. The possibilities are many and the purpose of the analysis will be the guideline when the response function is selected.

Another issue when working with FE analysis is to decide how the result should be evaluated, in nodes (all or part of the model), in the elements or just as a maximum/minimum value of the whole model. Once again there is a choice to be made.

Whichever analysis and response function are chosen the basic procedure for analyzing the data is the same. First all necessary data have to be given by the designer. The design variables are then used in the usual FE environment as parameters. The modelling and equation solving phases have to be included in a loop where the design variables are altered according to the DOE layout. The chosen response is also collected within the loop for further statistical evaluation after all analysis cases are performed. Figure 3 shows a flowchart of a basic DOE FE analysis module.

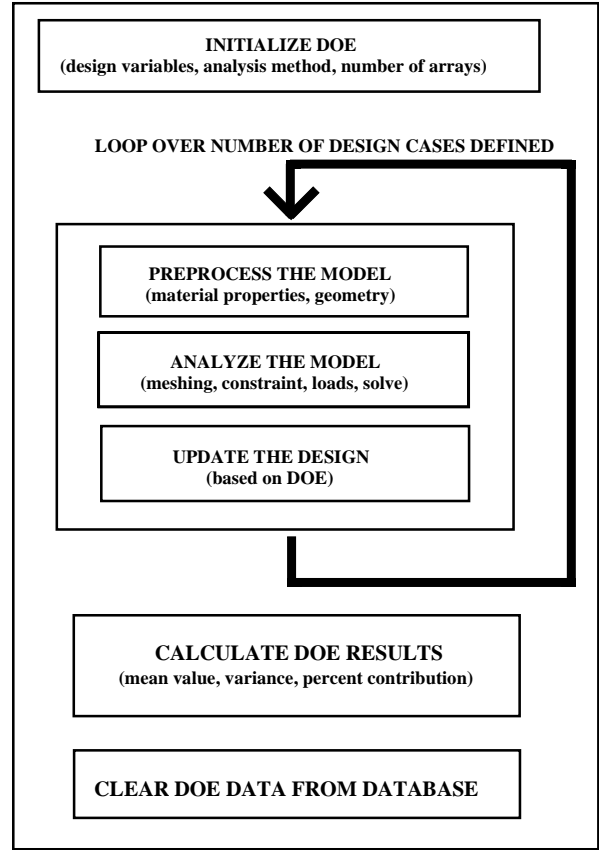


FIGURE 3. DOE BASED FE ANALYSIS

Analysis of means

To estimate the effects of the parameters from the experiments the following calculations, based on common statistical methods, are performed. The overall mean are calculated through eq. (2.a) or eq. (4.a) depending on which method is chosen. Each level of a particular design variable is used a specific number of times in the experiment. By summing up the response value corresponding to a specific level, all design parameter level means μ_{ij} can be evaluated, i.e. the mean value of level 2 of design variable 2 in an L9 array can be calculated as

$$\mu_{22} = \frac{(Y_2 + Y_5 + Y_8)}{3} \quad (6)$$

The other design variables and level means are treated in the same way.

The sum of square of design variable i (SSV_i) is calculated using the following equation

$$SSV_i = \sum_{j=1}^{L_i} (\bar{\mu} - \mu_{ij})^2 \quad (7)$$

where L_i is the number of levels for design variable i . The total sum of square ($SSTO$) is the sum of deviation of the design variables from the mean value of the experiment. This is calculated as:

$$SSTO = \sum_{j=1}^N (Y_j - \bar{\mu})^2 \quad (8)$$

The percent contribution of each design variable can now be evaluated. For design variable i it is calculated as the ratio of the sum of square for design variable i (SSV_i) to the sum of all sum of square values in the experiment. The ratio indicates the influence of the design variables on the response function due to change in level settings.

NUMERICAL IMPLEMENTATION

The implementation into ANSYS ver. 5.4 is based on the database functions provided by ANSYS INC, ANSYS Programmer's Manual (1996). By using these routines the data from the Finite Element (FE) analysis can be evaluated in a statistical manner within the FE program. The written FORTRAN routines were compiled and linked into ANSYS as user routines, resulting in a custom user ANSYS program. The routines are called as usual ANSYS commands. Five routines have been developed,

DOE,DV	Defines design variables, creates ANSYS parameters
DOE,TAGUCHI	Defines Taguchi method, orthogonal array to be used, response function and result location. Allocates the heap space.
DOE,CALC	Reads FE results and stores data. Updates model
DOE,RESULT	Statistical analysis of the FE results
DOE,CLEAR	Deallocates the heap space

A more detailed explanation of the commands is presented next. First the design variables have to be defined with the DOE,DV command. This command also writes the design variables to ordinary ANSYS parameters that can be used within ANSYS program. Next the statistical evaluation model (standard or modified) and the type of array have to be chosen. Based on the input to the DOE,TAGUCHI command the module will allocate memory in the database for the statistical evaluations, and the result that should be statistically evaluated is defined. The order in which the design variable will be altered is written to an *update vector*. The maximum number of analysis loops, MAXDOE that the specific problem will need is also written as a parameter to the ANSYS program.

A loop containing the preprocessor and solution processor is needed for the implementation to work properly. The command DOE,CALC is placed inside the loop after the solution processor. The locations (nodes or elements) where the result should be evaluated are defined the first time the command is called within the loop. The default result location is the selected nodes in ANSYS when the command DOE,CALC is called. This command also reads the FE results from the ANSYS database and writes them to the statistical arrays. Further, it clears the mesh and deletes the defined volumes or areas and everything associated with them, and finally it reads the *update vector* and updates the design variables. Based on the selected method in DOE,TAGUCHI the statistical evaluation is performed with the com-

mand DOE,RESULT. When all statistical calculations are performed the DOE,CLEAR command is used to retrieve memory back to the ANSYS program by deallocating the allocated database memory. Figure 4 shows the construction of a typical ANSYS input file that can be used with a DOE analysis module.

```
DOE,DV, name, mean value, standard deviation
DOE,TAGUCHI, type of method, type of array,
               response function, response location
DO-loop over the number of Design cases (MAXDOE)
  Pre-processor
  Solution-processor
  DOE,CALC,loop-#
END OF DO over Design cases
DOE,RESULT, result type
DOE,CLEAR
```

FIGURE 4. ANSYS INPUT FILE FOR A FE ANALYSIS WITH DOE

PRESENTATION AND RESULTS OF EXAMPLES

Tube in tension

The example has a very simple nature and can easily be evaluated analytically. The purpose of the example is to verify the implementation and compare the calculated results with the analytical results. The tube shown in Figure 5 is subjected to a normal distributed force in the axial direction $F \in N(5000,20)$. The inner and outer radii are also normal distributed with the following data $r_i \in N(10,1.25)$ and $r_o \in N(20,1)$.

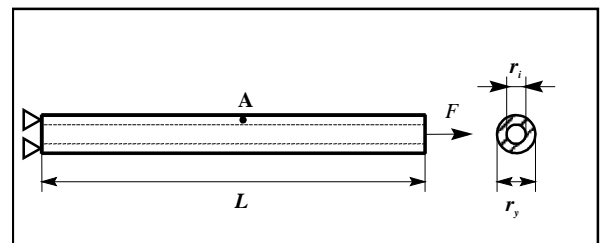


FIGURE 5. DIMENSIONS OF THE PIPE

The length of the tube is deterministic $L = 200$. The analytical expression for the stresses (S) in the pipe can be found in most standard computational mechanics handbooks, but is included here for convenience:

$$S = \frac{F}{\pi(r_o^2 - r_i^2)} \quad (9)$$

Statistical evaluation of the analytical results is based on the technique outlined in Andersson (1996). Both of the outlined Taguchi methods are used to evaluate the problem. In both cases full arrays are used; thus each FE analysis is run 27 times. The calculations are done with an axisymmetric model with forty linear four node elements (PLANE 42). The Von Mises equivalent stress in node A (see figure 5) is chosen as response function. Node A is the only node selected

when the DOE,TAGUCHI command is called. In Table 3 the mean values and the standard deviations for the different analysis cases are shown along with the analytical result.

Table 3. RESULT OF THE FIRST EXAMPLE

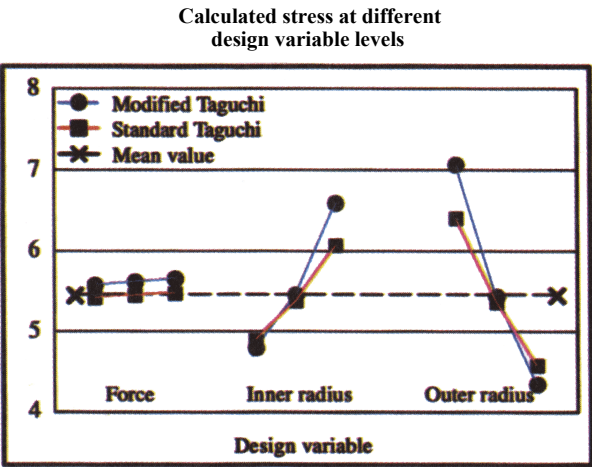
	Mean value	Variance
Analytical result	5.305	0.834
Standard Taguchi	5.454	0.896
Modified Taguchi	5.457	0.930

Table 4 shows the percent contribution of each design variable in the analytical case and in the FE analysis.

Table 4. PERCENT CONTRIBUTION OF THE DESIGN VARIABLES

	Outer radius	Inner radius	Force
Analytical result	71.86	28.07	0.064
Standard Taguchi	70.73	29.21	0.061
Modified Taguchi	67.96	30.54	1.49

The near optimum level values for each design variable can easily be found from the mean values of all design variable levels. The chart below says that the stresses will be minimal if the force and inner radius are kept at their low levels, and the outer radius should be kept at its large value. That this is correct is easily justified by the nature of the problem.



Maximum stress in a beam

This second example contains 6 design variables, as shown in Figure 6, that are all Normal distributed

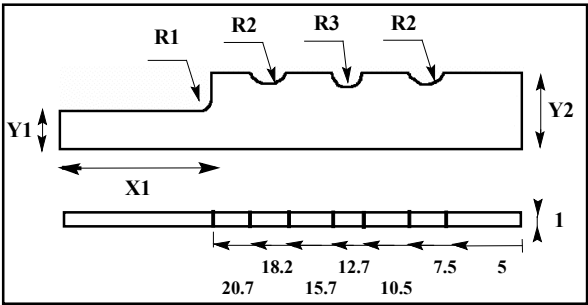


FIGURE 6. DESIGN

The values of the design variables are shown in table 5 below. All parameters are given the same standard deviation 0.1. The beam is loaded with a pressure as shown in Figure 7. There are two symmetry lines in the beam, and it is also constrained in the x and y direction at the larger part, as can be seen in Figure 7. The problem is treated as a 3D problem using linear eight node 3D elements (solid 45).

Table 5. Mean value and Standard deviation

	Mean value	Standard deviation
Y1	2.5	0.1
Y2	5	0.1
X1	10	0.1
R1	0.5	0.1
R2	0.75	0.1
R3	1.1	0.1

The overall maximum stress in the beam is taken as the response. Figure 8 shows a characteristic stress plot from one of the different analysis cases performed in the experiment. As in the first example, both Taguchi methods are used to evaluate the problem. Six design variables result in 729 FE analyses when full factorial analyses are performed. In order to reduce the analysis time an L18 norm is used together with the standard Taguchi method. Since the weights in the modified Taguchi method are not equally weighted the L18 can not be applied. Instead the analysis time is reduced by treating the problem as two full factorial experiments containing 3 design variables each. The experiments are chosen as: In the first design variables Y1, Y2, X1 are evaluated and in the second experiment R1, R2 and R3 are evaluated. This leads to a total of 54 analysis cases. Table 6 and shows the mean and standrad deviations for the different experiments. The full factorial experiments and the L18 experiment have a mean value that is almost the same. The modified method with 2*3 full arrays results in an answer that differs only 1.6 % from the others.

Table 6. RESULT OF THE SECOND EXAMPLE

	Mean value	Variance
Standard Taguchi full array	733.84	37.607
Standard Taguchi L18 norm	733.74	42.96
Modified Taguchi full array	733.17	41.327
Modified Taguchi 2*3 full arrays	721.83	29.05

In Table 7 the percent contributions of the different design variables are shown. The results vary depending on which of the Taguchi methods used. These changes can be explained by looking at the location of the response at each of the individual experiments. The maximum stress for the beam changes between three different locations in the beam, see Figure 8. The modified Taguchi method uses a bigger vari-

ance on the design variables than the standard method, and this leads to bigger variances in the response.

Table 7. PERCENT CONTRIBUTION OF THE DESIGN VARIABLES

	Standard Taguchi full array	Standard Taguchi L18 norm	Modified Taguchi full array	Modified Taguchi 2*3 array
Y1	27.6652	19.648	24.955	34.437
Y2	40.01	40.778	25.634	27.540
X1	1.8846	.6302	8.9793	7.422
R1	13.4988	11.548	16.216	7.9439
R2	6.3397	3.0336	11.880	11.354
R3	10.600	24.360	12.334	11.301

Figure 9 gives a more visual image of the different variable's influence on the result. The figure also indicates that the variances for the modified Taguchi method are bigger than for the standard method.

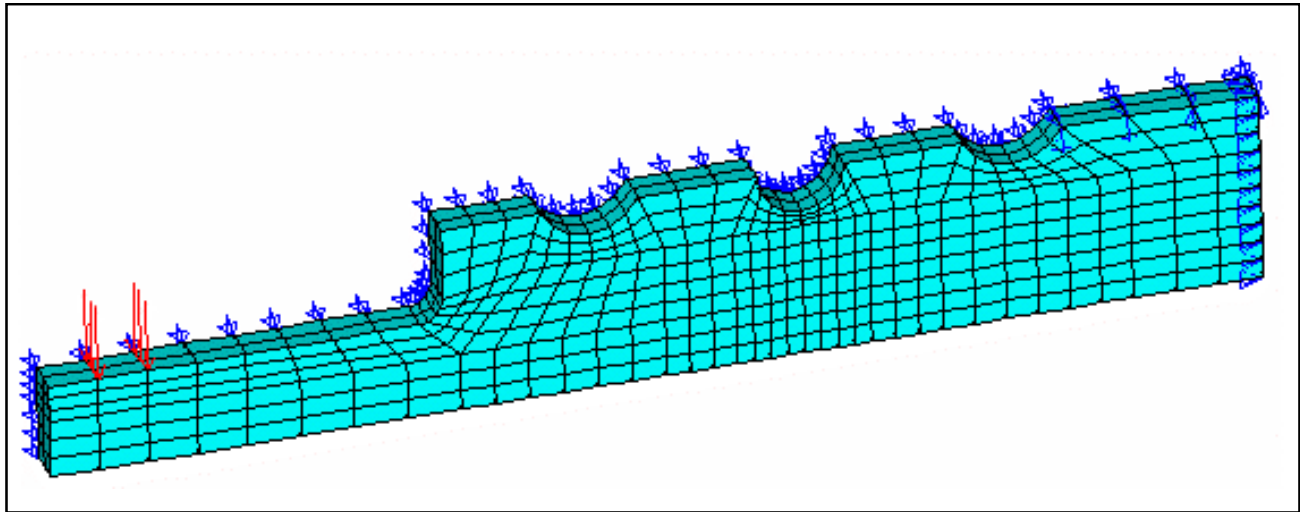


FIGURE 7. BOUNDARY CONDITIONS

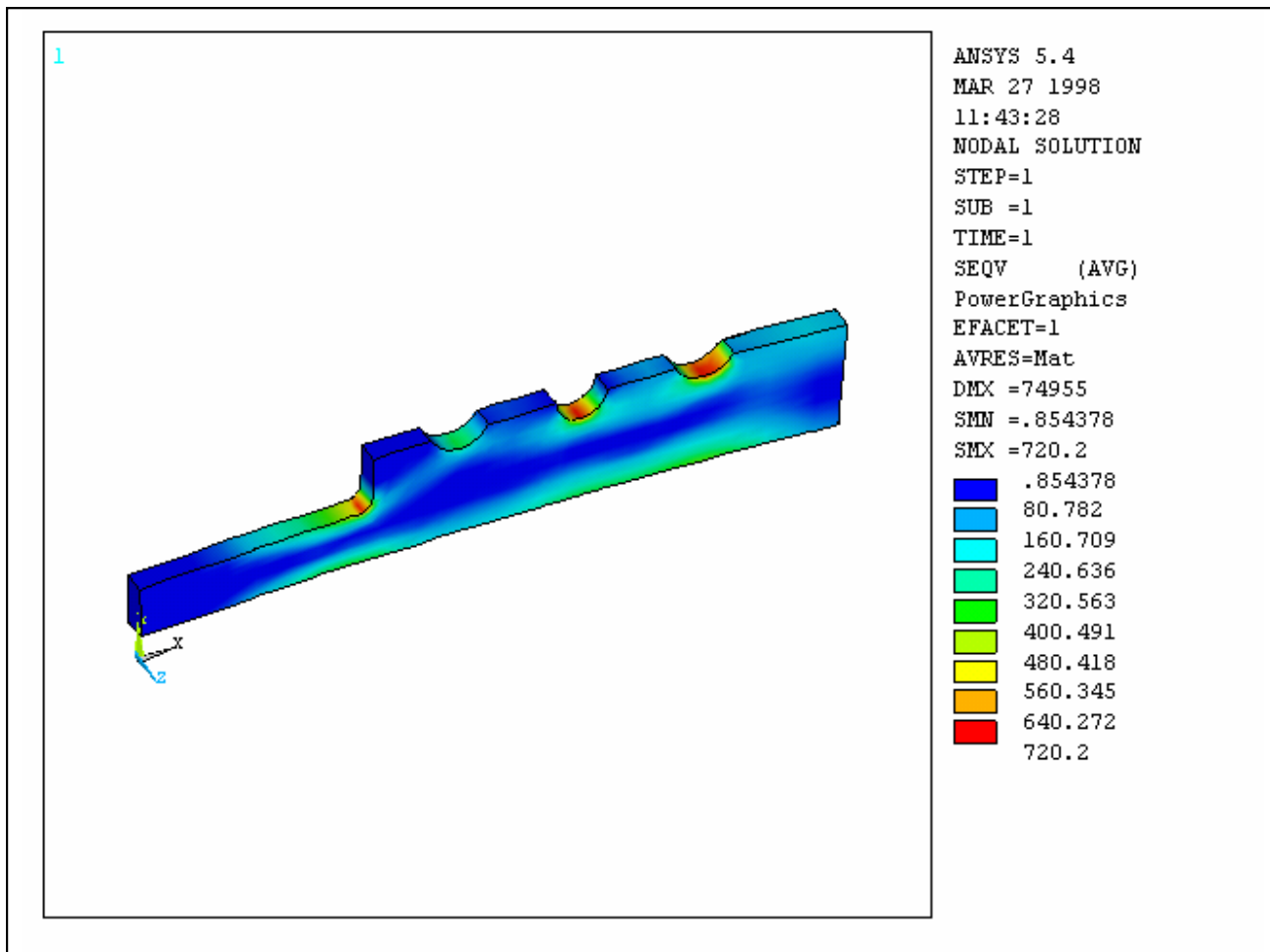


FIGURE 8. RESULT PLOT, SHOWING THE VON MISES EQUIVALENT STRESS

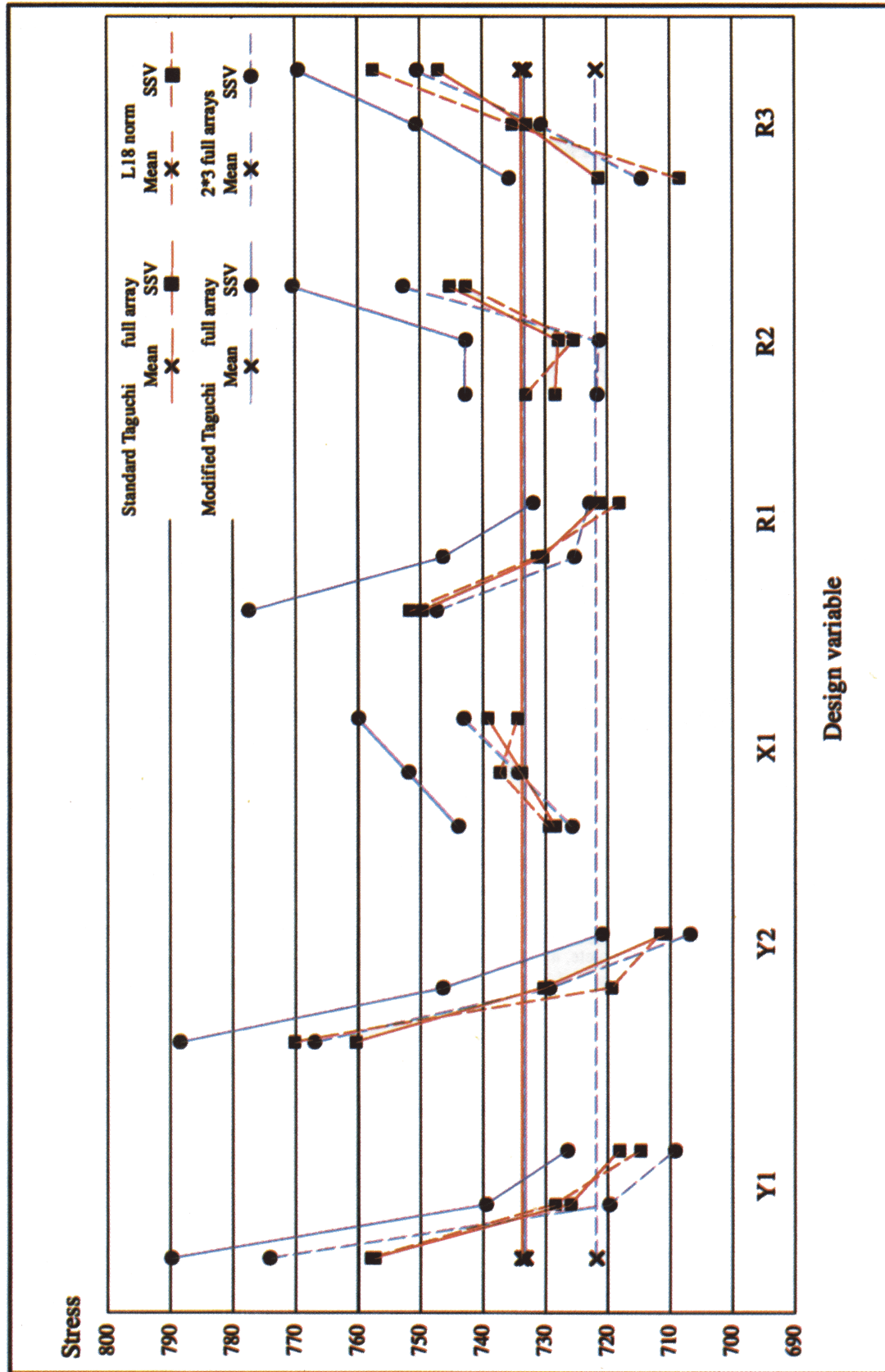


FIGURE 9. CALCULATED STRESS AT DIFFERENT DESIGN VARIABLE LEVELS

CONCLUSIONS AND FURTHER WORK

Conclusions

In this paper a new approach of FE modeling including statistical aspects has been successfully implemented into ANSYS. The example shows that the Taguchi method is a good statistical method to represent variables with normal distribution. The errors in both of the Taguchi methods are of the same order as could be expected of an ordinary FE analysis of the problem.

This FE module serves as a powerful tool for engineering designers studying the influence of different design parameters, geometric variables as well as load and material parameters. With very little extra work in the preprocessing phase of the analysis, the engineering designer will get a wider and better understanding of the analysis problem. Based on the results the engineering designer is able to determine which design variable should be considered in e.g. a design optimization.

Statistical finite element will be a useful tool in the detail design phase of the product development process, since the FE method can be used to analyze many different problems. By introducing dimensions with distributions, (tolerances), the manufacturing process is introduced. Loading condition with distributions gives a better reflection of the real life situation. Stress and strain results based on statistical finite element can be compared with the strength of the material used, which can also be treated as a normal distributed design variable in the implementation. The comparison of loading and strength is the main concern in the Robust Design, see e.g. Andersson (1996), where this type of FE analysis makes it possible to apply the Robust Design concept to many new problems. The lack of fractional factorial principles that works together with the modified Taguchi method makes this method somewhat more complicated. It makes it complicated in the sense that the engineering designer or analyst must choose which variables to treat separately.

Further work

The implemented module is a very interesting tool in the detail design phase. To make it even more useful and valuable to the engineering designer, the analysis of what a variation in the variance will have for influence on the result will be interesting to investigate (ANOVA). To make the statistical evaluation of the FE result more complete, a significance test of the design variables can easily be implemented. The modified Taguchi method has an interesting feature in its possi-

bilities to adjust to different distributions. It can easily be used to represent other distributions by simply choosing other levels and weights. Automatic design optimization based on the statistical finite element analysis implemented here will give the engineering designer an even more powerful design tool than this first implementation. The near-optimum value of the important design variables should be used as starting values in order to decrease analysis time. The percentage contribution factors and the results from a significance test are the basis for choosing the right design variables in the design optimization analysis.

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Paper B

B

A general tool for Finite Element Simulation of long-time sliding wear

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1998 Ansys Conference Proceedings
(Bryan, W. J. et al. eds.)
Ansys Inc., Canonsburg PA, 1998

A GENERAL TOOL FOR FINITE ELEMENT SIMULATION OF LONG-TIME SLIDING WEAR

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ABSTRACT

Finite Element (FE) modeling and simulation of long-time wear is an interesting topic with many fields of application, i.e. gear transmission analyses and biomechanics. The difficulties lies in the process of continuously updating and modelling the altered contact surface and contact pressure that result from unsymmetric wear over a long period of time. To do this, the geometry has to be changed due to the wear throughout the simulation. In this work, a wear-module is implemented into the FE software ANSYS, using User Programmable Features (UPF). The module is general, and can be used to perform long-time wear simulations of bodies in sliding contact. The model is automatically updated, and no re-definition of data is needed.

The wear theory used in the implementation is outlined, as well as the wear calculation procedure. To show on the capabilities of the module and to verify the implementation, two examples of long-time wear simulations are reported in the study. The implementation can be used by an engineering designer in lifetime studies, investigation of structural behavior due to mechanical wear etc.

NOMENCLATURE

F_N = applied normal load (N)

V = wear volume (m^3)

H = wear depth (m)

$H_0 = H / s_{total}$ dimensionless wear depth

$W(\bar{x})$ = Total wear vector in a point \bar{x} for one load cycle (m)

k_w = material and Surface dependent wear coefficient (m^3 / Nm)

n = number of cycles between nodal coordinates updating

$n(\bar{x})$ = normal vector in a point \bar{x}

\bar{p} = Normal contact pressure in \bar{x} (Pa)

$p_{applied}$ = applied pressure on structure

$p_0 = \bar{p} / p_{applied}$ dimensionless contact pressure

s = sliding distance (m)

s_{total} = Total sliding distance (m)

$s_0 = s / s_{total}$ Dimensionless sliding distance

\bar{x} = A set of coordinates (x_i, y_i, z_i) (m)

x_0 = Dimensionless x-coordinate ($-1 \leq x_0 \leq 1$)

INTRODUCTION

Wear of materials is a factor that plays a major role in life time expectations and the long term behavior of many mechanical structures. A mechanical structure or system exposed to an unsymmetric, cyclic loading can wear in way that ruins the initial functionality of the system. A good example of this is hip replacement prostheses, where the polyethylene femoral head cup has to be replaced after some time, due to wear. To avoid or delay these situations, the phenomena has to be studied when designing the eventually worn component. Doing this, the result is a high quality, robust design at a low cost. Today, recycling and life cycle analyses are important issues in the design process. By increasing lifetime and reliability of a product, these issues are both taken into account. This alone makes the study of long-time wear an important part of many design projects.

Traditionally, wear studies have been performed in laboratory rigs. However, these tests are both costly and time consuming. A computer tool that simulates long time wear of materials would reduce both time and money spent when evaluating the effects of wear. In order to simulate the wear process, a theoretical background and a reliable wear model are needed.

A lot of research has been performed to establish a theory of the wear process. The theory of sliding wear presented in (Archard, 1953) has been used extensively for wear estimations, and is a widely accepted theory of sliding wear.

An analytical approach can be used to estimate the wear in some simple cases, but generally this approach is not sufficiently accurate due to the simplifications that have to be made when studying a complex situation. Examples of situations that are hard to handle within the

scope of an analytical approach are changing contact surface due to propagating wear, or a nonuniformly distributed and changing contact stress over the contact surface. Also, a complex geometric shape of the contact surface introduces difficulties. To deal with a general problem a discrete, numerical approach is needed in order to analyze the problem accurately. In order to perform a numerical wear simulation, some modifications of classic wear theory need to be made, and such methods have been proposed, see e.g. (Marshek and Chen, 1989).

The Finite Element (FE) method is a well-established numerical method and widely used for performing structural analyses. Mechanical wear of materials occurs when two bodies are in sliding contact, and efficient modelling of contact problems is now a standard feature of most commercial FE softwares. This makes the FE method well suited for wear simulation analyses. Studies have been made where wear analyses have been performed using FE software and external scripts, see eg. (Maxian et.al, 1996a, 1996b). Most studies are problem based, though, and not general. A general long-time wear simulation module, where the geometry is continuously updated due to the wear, would be a good complement to general FE software. This could serve as a powerful tool to engineering designers evaluating different alternatives in detail design, or as a tool for lifetime studies of mechanical components, material wear studies etc.

OBJECTIVE

The main objective of this work has been to implement and verify a general long-time wear simulation module in the FE software ANSYS, using the User Programmable Features (UPF) of the program. The wear calculations are based on classic wear theory (Archard, 1953) and the tool can be used to simulate long-time wear where the worn surface is automatically updated at user given intervals. This is an example of tools that take the FE software from being a verifying analysis tool, to a design tool that can be used by the engineering designer in many situations. This work should also show that this kind of implementation is easily made in FE software.

WEAR THEORY

For both adhesive (sliding) and abrasive wear of an unlubricated surface the wear volume can be expressed as (Archard and Hirst, 1956)

$$V = k_w F_N s \quad (1)$$

where F_N is the applied load and s the sliding distance, see Figure 1.

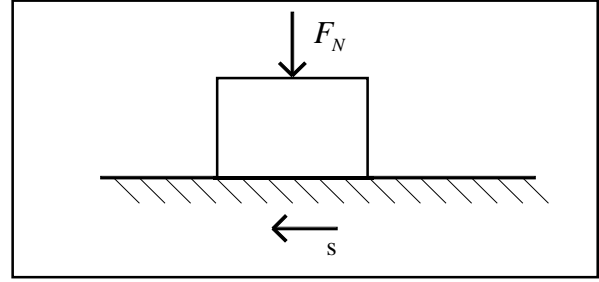


FIGURE 1. SCHEMATIC PICTURE OF BLOCK IN SLIDING CONTACT

k_w is a wear constant that depends on the materials used, and the surface conditions. The wear depth dH can be obtained from expressing the volume in terms of wear depth and rewriting Eq. (1) as

$$dV = \Delta x \Delta y dH = k_w (\bar{p} \Delta x \Delta y) ds \quad (2)$$

where \bar{p} is the local contact pressure, and $\Delta x \Delta y$ a discrete area. Now, the wear depth can be expressed as (Marshek and Chen, 1989)

$$dH = k_w \bar{p} ds \quad (3)$$

As the variables in Eq. (3) are time dependent, the total wear depth at a specified sliding distance S , can be written as

$$H(t) = \int_0^S k_w \bar{p}(t) ds \quad (4)$$

This expression can be used to calculate the wear of a contact surface in any structure, given that the contact stress and sliding distance are known as functions of time. Eq. (4) is the basic expression that have been used to calculate the wear in this work.

FEM IMPLEMENTATION OF WEAR SIMULATION PROCEDURE

The typical wear process consists of a cyclic loading, repeated several times. Thus, the problem is often limited to a number of repeated, identical load cycles. In order to evaluate Eq. (4) in a discrete analysis, each load cycle has to be divided into a number of load steps, over which the contact stress and wear coefficient is assumed to be constant. Making this discretization, Eq. (4) can be written as

$$\vec{W}(\bar{x}) = \sum_{i=1}^m k_w \bar{\sigma}_i(\bar{x}) s_i(\bar{x}) \bar{n}_i(\bar{x}) \quad (5)$$

where m is the number of load steps needed for one load cycle, and \bar{x} is a set of coordinates. Consequently, $\vec{W}(\bar{x})$ denotes the total wear vector in a point \bar{x} for one load cycle. Note that the normal direction in the point \bar{x} , $\bar{n}_i(\bar{x})$, can vary during the load cycle.

Wear Calculation

The wear vector, Eq. (5), is evaluated in each node of the contact surface/curve. In this way, the wear profile and mesh updating becomes relatively smooth.

The load cycle is usually repeated thousands of times in a real application, and therefore one must consider the frequency of which the wear is calculated and nodal coordinates are updated. The model can be updated every load cycle, as:

- Analyze load cycle 1
- Calculate the wear
- Update the nodal coordinates, due to the wear
- Analyze load cycle 2

etc.

A more computationally economic strategy is to update the model every n^{th} cycle:

- Analyze load cycle 1
- Calculate the wear and multiply it by n
- Update the nodal coordinates
- run the $n^{th} + 1$ cycle

etc.

As the wear contribution from one load cycle is very small, n could be chosen rather high, but care has to be taken so the total wear is being calculated accurately. Choosing a big n can result in large differences in total wear, compared to a simulation with a small n . This is due to the effect of local spots with high contact pressure that can occur as the geometry is changing. These spots can change the magnitude and direction of the wear considerable, an effect that is neglected if a too large n is used. Also, a big n could result in an unstable simulation, where the contact-stress peaks oscillates between different nodes that come in point contact after the geometry updates.

Consequently, what is needed from the FE contact solution after each load step in order to calculate the wear is:

- Contact pressure in the contact nodes
- Sliding distance in the contact nodes
- Normal direction of the contact nodes

The first two are easily obtained from the FE solution. The normal direction in the element nodes is calculated using the Jacobian of the element shape function. See e.g. (Ottosen and Petersson, 1992) for an explanation of the procedure.

Mesh updating

By continuously updating the coordinates of the contact nodes, the effect of the wear is automatically introduced in each new load cycle. Also, this approach eliminates the need of a remeshing of the FE model after each wear calculation. This method can be used as long as the wear is reasonable small, compared to the element size. If the wear is extensive, a remeshing procedure is needed in order to avoid badly shaped elements. An automatic remeshing when element shapes becomes too distorted is easily implemented in the wear simulation module, but as a remeshing procedure is not needed in this work, it has not been implemented. Consequently, the total wear must at least be less than the height of the underlying elements.

Contact modelling

Contact elements [CONTA171-174] together with the target elements [TARGE169-170] can be used to model the contact in the wear simulations, see (ANSYS Inc., 1997). Consequently, both linear and quadratic elements, in 2D or 3D models can be used. As the contact element solution gives the integration point solution, some approximations have to be made when calculating contact stress and sliding distance. The end node (2D) and corner node (3D) solutions are calculated as mean values of the nearest integration points. In the quadratic elements, the midside node solutions are calculated using a set of linear shape functions, based on the end/corner node solution.

In the 3D contact elements, only one sliding distance is given for each element, so the element size has to be sufficiently small in analyses where the sliding distance varies. Due to this, no general 3D wear module has been implemented at this stage.

As the updated nodal coordinates creates a gap between target and contact surface, which is numerically instable, the target surface has been modelled with an initial penetration, approximately one element layer large. Using real constants [PMIN, PMAX], see (ANSYS Inc., 1997), the target surface is automatically brought into "zero" penetration at the beginning of each load cycle, and singular stiffness matrices are avoided.

Wear simulation procedure

Based on the theory that leads to Eq. (5), a general long-time wear simulation procedure has been developed, outlined in Figure 2. This procedure assumes that the load history consists of repeated, identical load cycles, which is the most common wear situation. If such is not the case, the wear routines can be used separately to achieve a specific case. Further, the wear coefficient k_w is considered constant over each load cycle. n in Figure 2 is the number of cycles between the nodal coordinate updates.

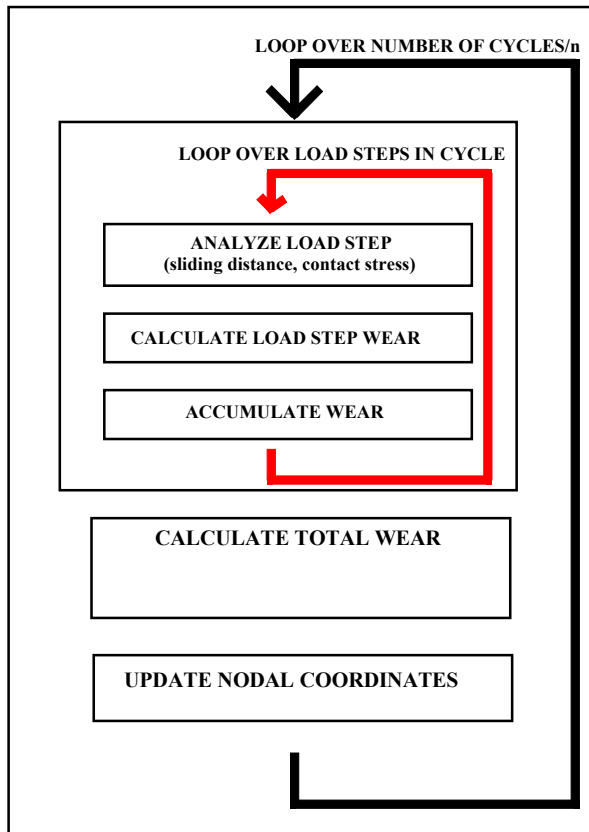


FIGURE 2. WEAR SIMULATION PROCEDURE

The procedure is fully automatic, and needs no user interference other than specifying the FE model and the load cycle. As the wear simulation proceeds, the nodal coordinates are automatically updated and a new geometry is analyzed in all load cycles.

Numerical implementation

The wear procedure has been implemented in ANSYS rev. 5.4. The wear calculation and geometry updating is implemented as FORTRAN routines, using many of the database and result access functions outlined in the manuals (see ANSYS Inc., 1996). The FORTRAN routines were then compiled and linked into ANSYS as user routines, resulting in a custom user ANSYS program. The routines are called as ordinary ANSYS commands. Four routines have been developed,

WEAR,INIT	allocates the heap space
WEAR,CALC	calculates and accumulates the wear of one load step
WEAR,MOVE	updates the nodal coordinates, due to the accumulated wear of one load cycle
WEAR,FINI	deallocates the heap space

Figure 3. shows the schematic constitution of an input file, is used in a typical wear simulation analysis.

```

WEAR,INIT,172
DO-loop over the number of load cycles / n
  DO-loop over each load step in the load cycle
    Apply load step load
    Apply load step BC's
    SOLVE
    WEAR,CALC
  END OF DO over load steps
  WEAR,MOVE, k_w , n
END OF DO over load cycles/N
WEAR,FINI
  
```

FIGURE 3. SCHEMATIC INPUT FILE SHOWING THE USE OF THE WEAR ROUTINES

EXAMPLES

Two examples have been analyzed in order to verify and show the capabilities of the implementation, a rectangular block in sliding contact and a cylinder in sliding contact. The first example has been used in other wear studies, which makes it a good example for verification of the implementation. The cylinder is an example of a problem type with a more arbitrary contact surface and resulting wear profile.

Rectangular block in sliding contact

A rectangular copper block sliding on a steel plate is considered in this first example. The copper block has the height $x1 = 0.1$ m and width $x2 = 0.065$ m, and the top of the block is subjected to a uniform pressure $p = 0.65$ MPa. A constant frictional coefficient $\mu = 0.3$ between the steel plate and copper block is assumed. The problem is treated as 2D plane strain. Further, the steel plate is considered as rigid with an infinite stiffness. The copper block is modelled as a flexible body, and the quadratic, 3-node contact element [CONTA172], see (ANSYS Inc., 1997), is used to model the contact. The FE model of the copper block used in the simulation is shown in Figure 4.

In each wear cycle, the block slides 0.125 m. The wear from each cycle is then multiplied by the factor $n = 400$, giving a sliding distance $s = 50$ m for each geometry update. A total of 30 wear cycles have been analyzed in this example.

The dimensionless contact pressure P_0 along the copper block at different sliding distances is shown in Figure 5: X_0 is the dimension-less x-coordinates of the contact surface, which runs from -1 to 1. As seen in the figure, the block is subjected to compression in the leading edge and stretching in the tail edge, due to the friction. As worn material is "removed" from the model, the stress curve flattens and a uniform stress distribution ($= p$) and wear rate are established.

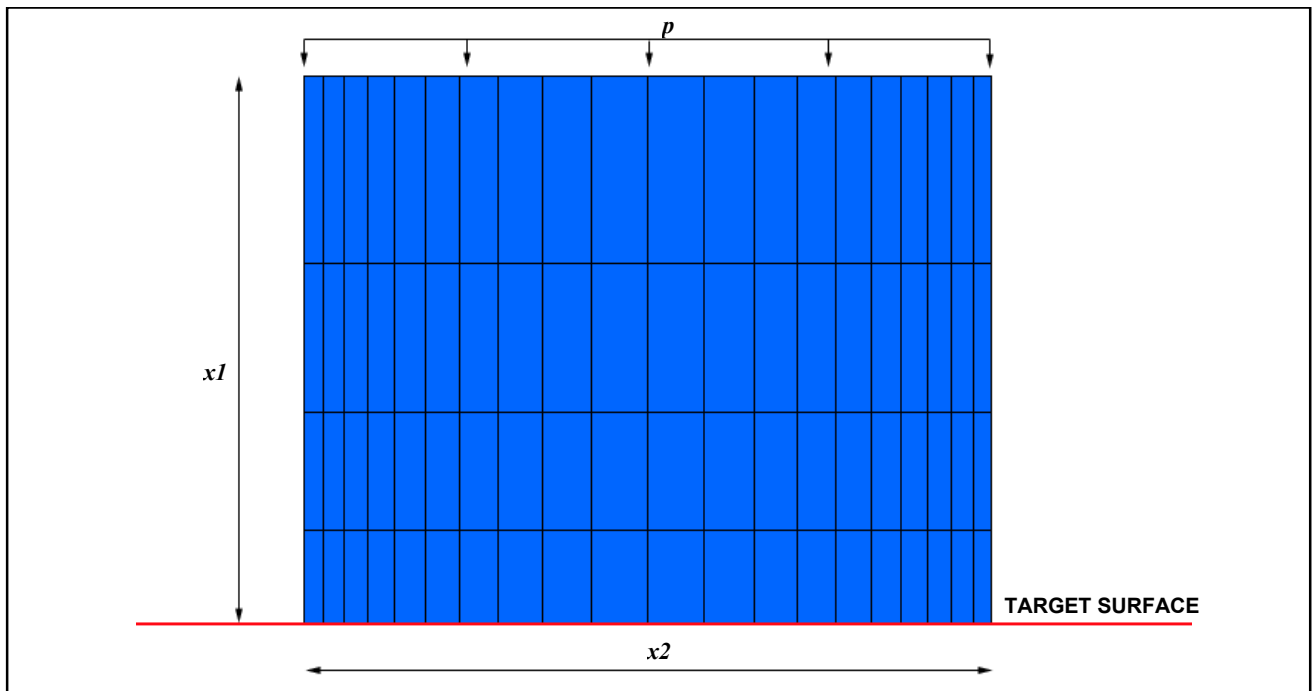


FIGURE 4. FEM MODEL OF THE COPPER BLOCK

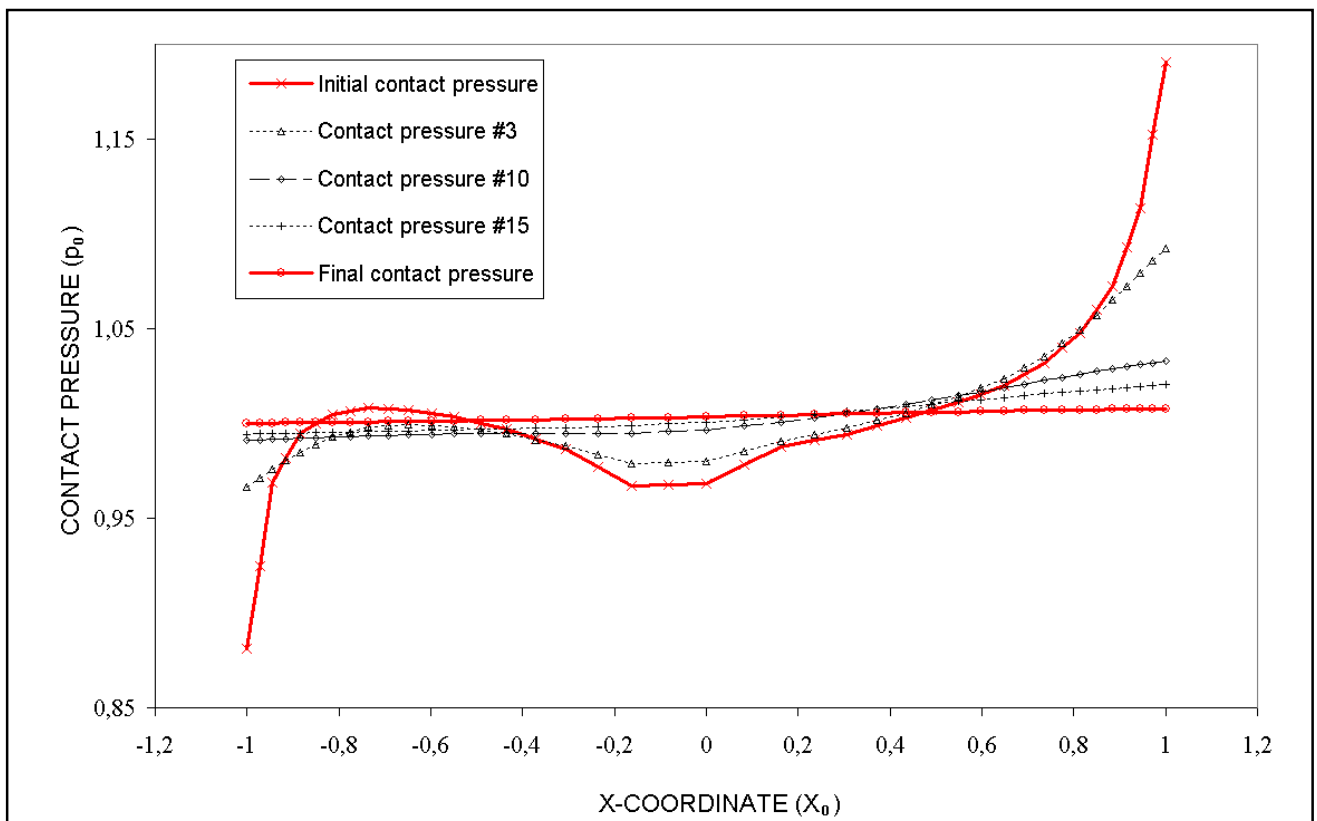


FIGURE 5. CONTACT STRESS DISTRIBUTION IN THE COPPER BLOCK AT DIFFERENT SLIDING DISTANCES

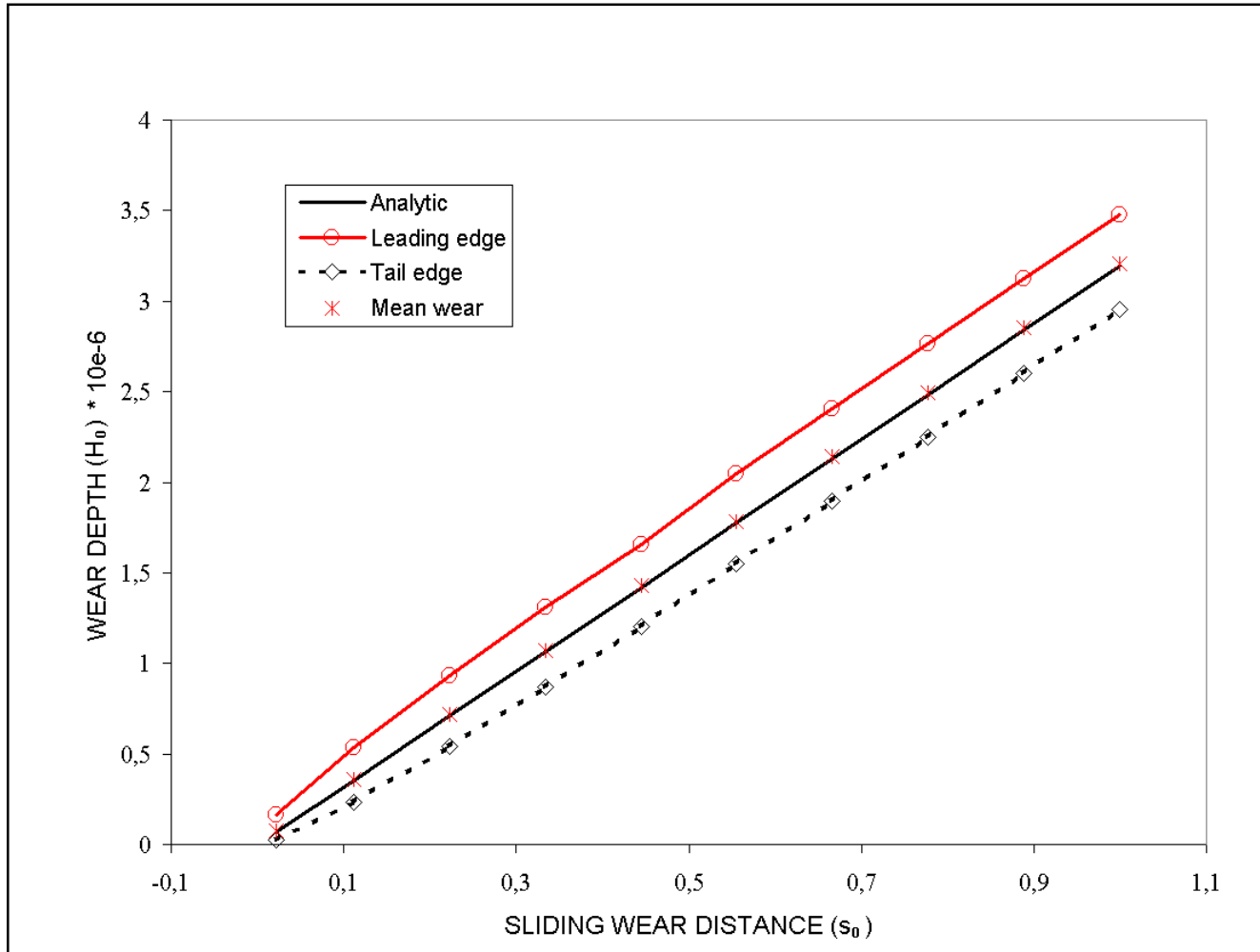


FIGURE 6. WEAR DEPTH AT DIFFERENT NODES IN THE BLOCK AS A FUNCTION OF SLIDING DISTANCE

The dimensionless wear rate H_0 in certain contact nodes as function of the sliding distance s_0 is shown in Figure 6. The different curves shows the maximum wear (leading edge), minimum wear (tail edge), average wear from all contact nodes and the analytical solution given by Eq. (1), assuming constant contact pressure. The average wear over the contact surface coincides with the analytical wear curve, which show that the implementation is correct. Further, the figure shows that all wear rates go towards the analytical one as the number of cycles rises. Consequently, the wear and contact stress levels stabilizes after a number of cycles (in this case, approximately 30 updates)

The results of this example show good agreement with other studies, see eg. (Marshak and Chen, 1989). Clearly, one can expect the wear and contact pressure to develop as shown in the example, where the sharp corners of the copper block are smoothed to achieve a constant contact pressure and wear rate. The example is also a verification of the correctness of the implementation, as shown in Figure 6.

Cylinder in sliding contact

A copper cylinder sliding on a steel plate is considered next. The copper cylinder has the radius $R = 0.0254$ m and is subjected to a force $F = 1000$ N. A constant frictional coefficient $\mu = 0.3$ between the steel plate and the copper cylinder is assumed. The problem is treated as 2D plane strain. The steel plate is considered as rigid with infinite stiffness, and the copper cylinder as a flexible body. Contact element [CONTA172], see (ANSYS Inc., 1997), is used to model the contact. The FE model of the copper cylinder is shown in Figure 7.

In each wear cycle, the cylinder slides 0.01 m. A wear factor $n = 350$ m has been used, which gives a sliding distance of 3.5 m between each mesh update. A total of 55 wear cycles have been analyzed.

The surface profile of the cylinder before and after the wear simulation is shown in Figure 8. As seen in the figure, the worn profile is

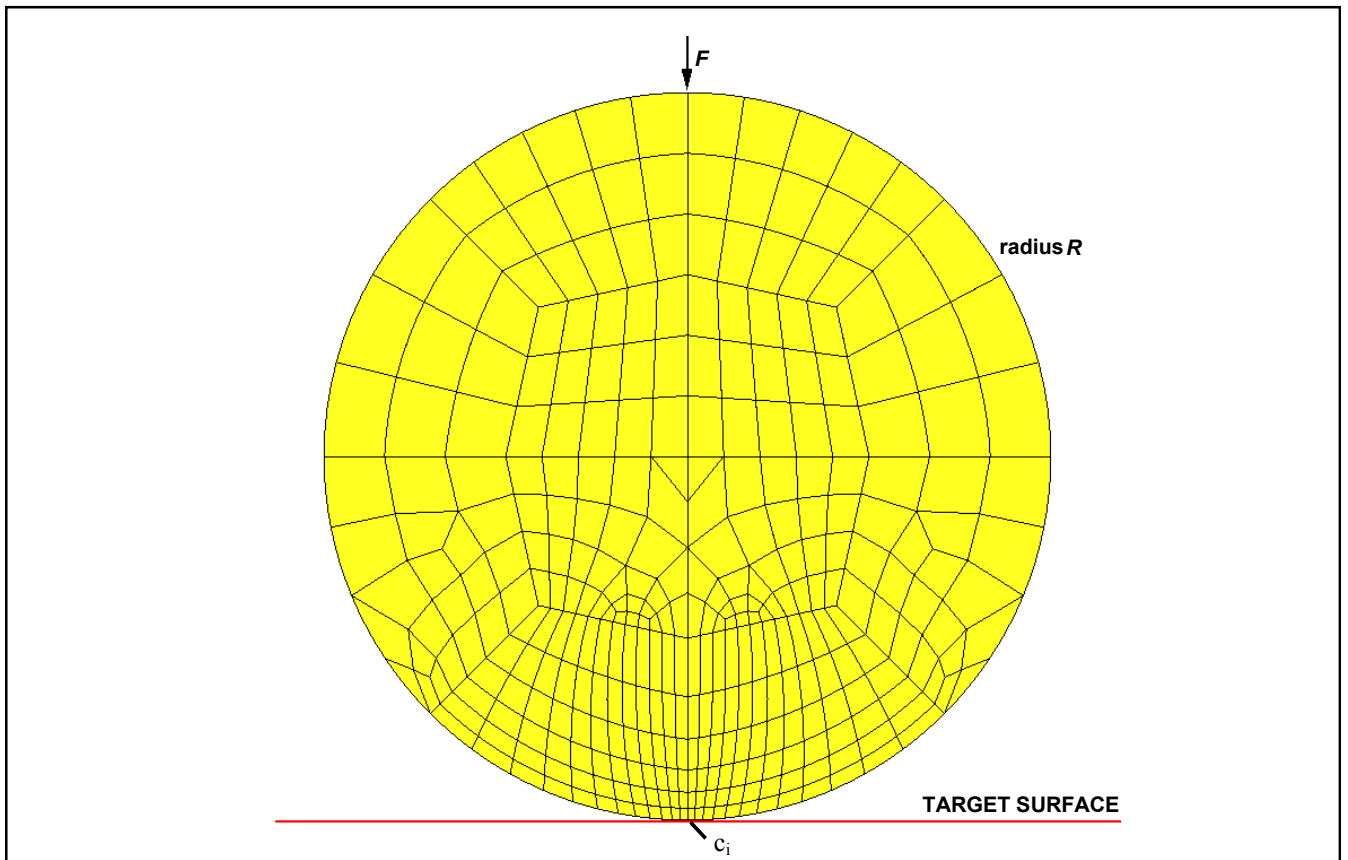


FIGURE 7. FE MODEL OF THE COPPER CYLINDER

flat, as can be expected. Note that the curvature is exaggerated in the figure, to better show the worn surface.

The dimensionless wear depth H_0 in the central contact node (marked c_i in Figure 7.) is plotted as a function of the dimensionless sliding distance s_0 in Figure 9. From the picture, one can see two different wear rates, where the initial one is higher than the final one. This is due to the higher initial pressure in the central node, which is reduced with enlarged contact surface.

Worth noting in this example is the fact that the contact nodes have different normal directions, both in reference to each other and also

from one wear cycle to another. As each nodal normal direction is automatically calculated (deformed position) in each wear step, this introduces no difficulties. This feature is important in a general wear simulation problem where complex geometry is present.

This example shows that the wear module can handle a general wear surface which changes during the simulation. However, the choice of wear update intervals is more crucial in this example. Too few updates tends to produce nonconvergence. Clearly, the contact elements have difficulties finding convergence when “rough” surfaces are analyzed.

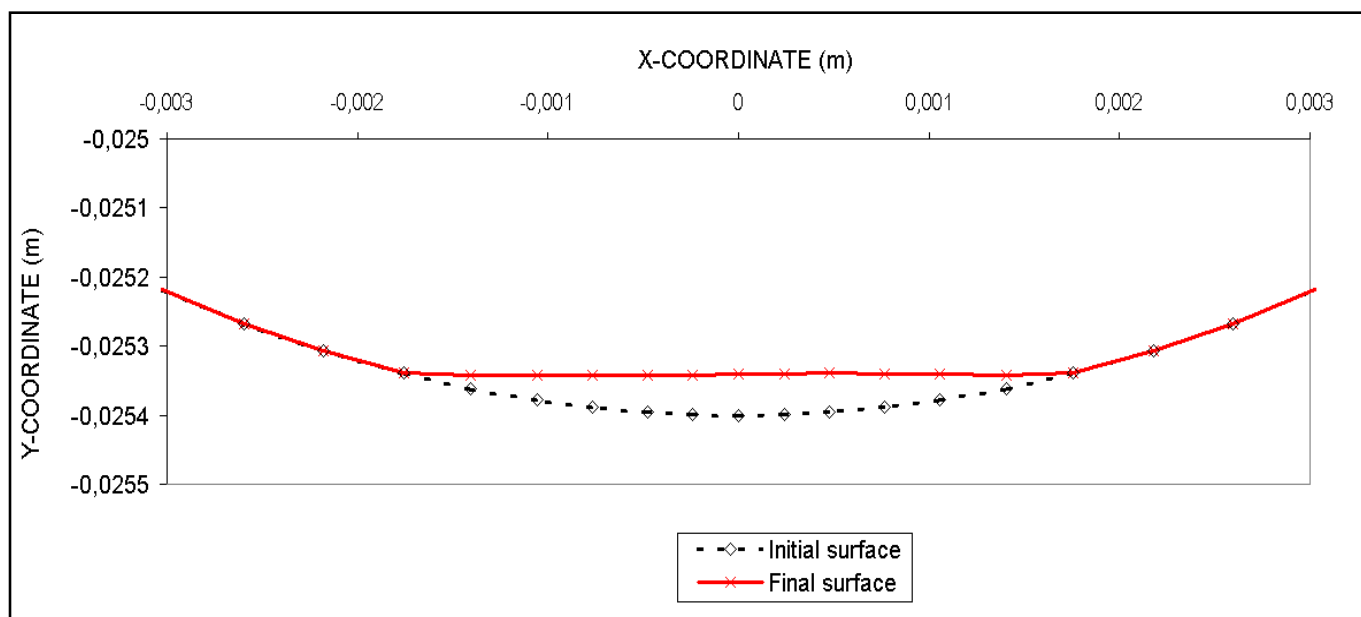


FIGURE 8. THE CYLINDER SURFACE PRIOR TO AND AFTER THE WEAR SIMULATION

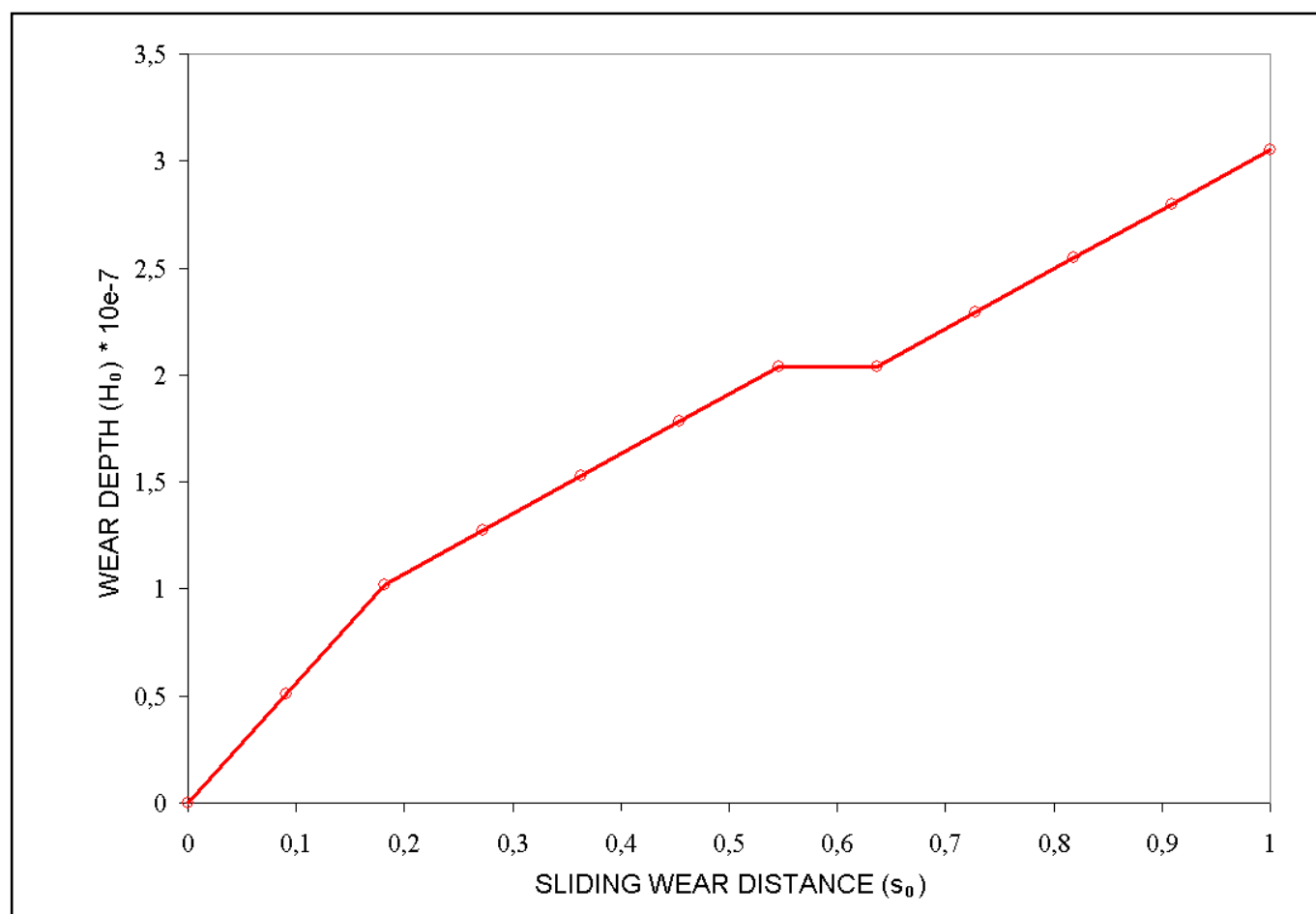


FIGURE 9. WEAR DEPTH AT THE CENTRAL NODE AS A FUNCTION OF SLIDING DISTANCE

CONCLUSIONS

2By implementing basic wear theory into the open ANSYS architecture, a general FE-module for long-time wear studies of general structures has been developed. The module is fully automatic, and needs no user input during the simulation. Two examples have been analyzed and show that the implementation gives reliable results, and can be used in a general case. Using this tool, the engineering designer can perform lifetime studies, design studies, study the behavior of different materials without having to use custom-written macros for each analysis. Both time and money spent on expensive lab rig experiments could be reduced significantly by using this tool. The FE software is used as an efficient design tool, and not only as a verification tool in the last stages of detail design.

Some questions have arisen during the work, and would be interesting to study further:

- is there a way to optimize the coordinate update intervals needed in order to avoid oscillation of the solution?

Clearly, some phases of the analysis, where the contact pressure varies a lot, are more critical than others. The most efficient simulation procedure would be to increase the update intervals when the contact stress levels are smooth, and decrease the intervals as the contact stress has big fluctuations.

- should the worn surface be mathematically smoothed, in order to achieve a more realistic solution, and minimize the risk of non-convergence.

Using a smoothing scheme as least-square fit of nodal coordinates could increase the performance of the implementation, and such a solution would be interesting to study.

There is a need for a general FE wear module, and this work has

shown that such a module is easily implemented in FE software and gives reliable results.

ACKNOWLEDGEMENTS

The Authors would like to express their gratitude to Dr. Yongyi Zhu, ANSYS Inc., for advice regarding the contact elements in ANSYS rev. 5.4.

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Paper C

C

The Role of Design of Experiments in Predictive Design Analysis

Eriksson, M., Burman, Å.

1999 ICED Conference Proceedings
(Lindemann, U. et al. eds.)
WDK 26, Munich, 1999

INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 99 MUNICH, AUGUST 24-26, 1999

THE ROLE OF DESIGN OF EXPERIMENTS IN PREDICTIVE DESIGN ANALYSIS

Martin Eriksson and Åke Burman

Keywords: Predictive Engineering, Predictive Design Analysis, Design Of Experiments, Mechanical engineering design process

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

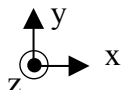
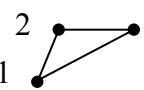
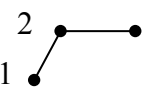
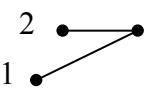
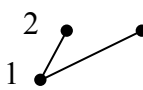
starting point of the majority of these models is the conceptual design phase. Traditionally the synthesis in the conceptual design phase is based on qualitatively oriented criteria. By using the proposed approach, the designer will be able to evaluate some of these criteria using a quantitative approach, 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.

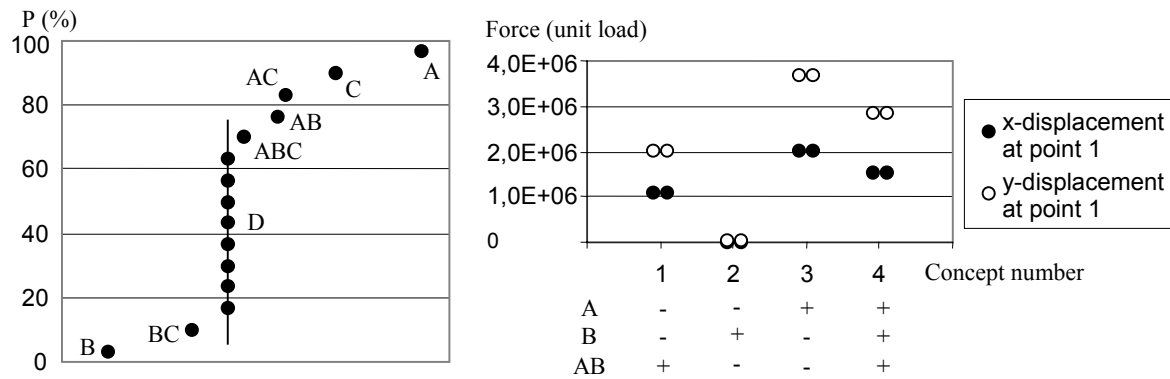


Figure 1. Evaluation of the different design concepts, normal probability plot and force versus concept number.

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.

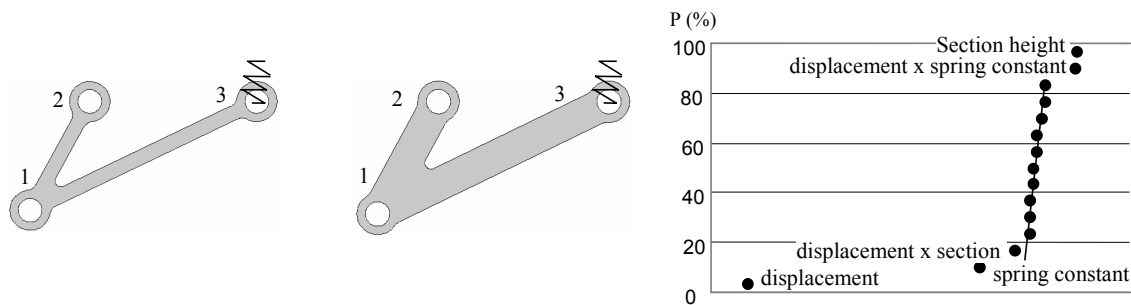


Figure 2. Embodiment design layout and the influences of studied variables on the displacement of point 3.

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.

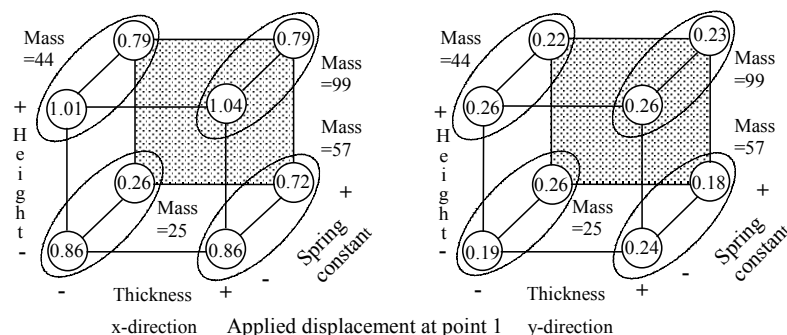


Figure 3. Cube plots of the displacement and the mass, both in unit of measurement, of point 3.

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.

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Paper D

Statistical Predictive Design Analysis in an Internet Environment

D

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Accepted for presentation at the 5th International
Conference on Computer Integrated Manufacturing
Singapore, 2000

Statistical Predictive Design Analysis in an Internet Environment

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Abstract. During recent years the increasing power of computers and communications has led to the use of more advanced analysis approaches within the mechanical engineering design process, or design process for short. Predictive Design Analysis (PDA), see [1], is an approach in which the final behavior of a product is predicted by combining information from different analysis techniques. This paper presents an application of PDA consisting of Design of Experiment (DOE) and Finite Element Analysis (FEA). The application is built as a World Wide Web (WWW) Client/Server application. The Client side User-interface interacts with the time-consuming FEA analysis performed on the server. This application serves as a powerful tool to the Designer or Analysts at all levels of abstraction in the design process, when examining the influence of different design variables on the product design.

1 INTRODUCTION

In the early age of industrial manufacturing, product quality was often poor. Most products needed to be adjusted individually in order to work properly. Since then the manufacturing techniques and skills have become more and more sophisticated, which has resulted in more reliable products. To increase the reliability even more, new methods have been introduced in the product development process in recent years. Statistical methods, i.e. DOE, have been used to evaluate experiments and numerical analyses. DOE are techniques to plan analyses, i.e. FEA, in order to decrease the number of analyses performed while maintaining a reasonable accuracy level. FEA is commonly used as a tool to verify whether or not a product design can withstand the loading and environment it is subjected to. The development of computers and communications has introduced new interesting possibilities in product development. Design teams can be geographically separated but still work close together on certain projects. Projects focusing on the possibilities and problems of new approaches of the design process are increasing [2-3].

2 OBJECTIVE

The objective set out for the work presented in this paper has been to provide the combination of design analysis methods and statistical methods with a user-friendly graphical interface. The implementation is developed as a Client/Server application,

where all time-consuming analysis and statistical evaluations are performed on the server. The client side is built up as a regular WWW browser application. The results calculated in the implementation could work as one of the decision rules to be used in the design process. Throughout the work, DOE is used to represent the statistical methods and FEA is used to represent design analysis.

3 HISTORY OF COMPUTING AND COMMUNICATION

The history of computing can be traced back over three thousand years, to Babylon and the clay tablets. But the real beginnings of computers as we know them today, however, lay with the "Difference Engine" in 1820 by the English mathematics professor, Charles Babbage. During the 1900 century the development was mainly pointed towards mechanical devices for office automation. By the Second World War the real development of computers began, with e.g. ENIAC, (Electronic Numerical Integrator Analyzer and Computer). It was used for preparation of firing tables for the Allied forces artillery. After the development of the integrated circuits in the seventies, the size of computers started to decrease and has done so ever since. Ultra-large scale integration (ULSI) increased the number of components on one chip into the millions. The numbers of personal computers in use more than doubled from 2 million in 1981 to 5.5 million in 1982. Ten years later, 65 million PCs were being used. Using either direct wiring, called a Local Area Network (LAN), or telephone lines, these networks could reach enormous proportions. The network is the key technology, linking PCs, workstations, and servers of various specialized kinds for printing and file storage. A buzzword of the early nineties has been Client/Server computing. Another approach to the network of workstations that is increasingly powerful but often under-utilized for much of the time is that of Cluster Computing, in which all the processing power on the network is viewed as a shared resource that can be applied to any computationally intensive task.

Along with the development of computers, the communication among computers has been enhanced. Under the leadership of the United States Department of Defense's Advanced Research Project Agency (DARPA), the architecture of a small network (ARPANET) was established to promote the sharing of super-computers amongst researchers in the United States. The first network of computers was established between Stanford Research Institute, UCLA, UC Santa Barbara, and the University of Utah. The second important development was the WWW containing the HyperText Markup Language (HTML), which was released in 1991 by CERN. In 1993 Mosaic was the first truly graphical, easy to use interface for the WWW that allowed the display of colors, pictures, graphics, even sound and videos. Sun Microsystems has in the mid-nineties released an Internet programming language called Java, which radically alters the way applications and information can be retrieved, displayed, and used over the Internet. Netscape developed Javascript, an extension to Java that enhanced the client side interactively even more. Other techniques released by the Microsoft Corporation in the late nineties are the Jscript and the Visual Basic VBscript, which interact, with WWW pages through the interface of ActiveX components. An extension to the original HTML is the

Dynamic HTML (DHTML), which builds upon existing HTML standards to expand the possibilities of WWW page design, presentation, and interaction.

4 WWW BASICS

Often confused with the Internet, the WWW is actually the sub-set of computers around the world that are connected with hypertext and WWW applications. A Web page's address on the Internet is called "URL", which stands for Uniform Resource Locator. HTML, which enables linking from page to page, sets the WWW apart from other networked computer files. The pages are accessed by a WWW browser that interprets the files and displays them graphically. A "plug-in" is an application set up within the browser, usually shareware that adds functionality to the Web browser. Another type of function that can either be embedded in the browser or on a server are imagemaps. Imagemaps allow users to click on a particular spot in an image to retrieve another HTML document or to run a specified script.

The coding that supports links to a variety of information is known as "hypertext". A WWW page designed using frames is divided into separate areas, which act independently of each other. An individual frame can be stationary or it can be a container for loading other pages. DHTML is somewhat of an umbrella term encompassing several ways in which Web developers can breathe life into pages that have traditionally been static portraits of information. Basically two different techniques, Common Gateway Interfaces (CGI) or some client side scripting language can achieve the interactivity of a WWW page. CGI can be used for a variety of purposes, the most common being the handling of FORM requests for HTTP (Hyper Text Transfer Protocol). Forms allow for user defined information to be passed along from a Web browser to a CGI program for processing. The program then returns the appropriate documents either by generating a document on the fly or by loading an existing document through the WWW via HTTP. CGI can be written in a vast variety of programming languages that produce an executable file, e.g. C, C++, Java or Perl. The client side interactivity is achieved with DHTML. This means that page modifications should appear immediately following a trigger, such as a user selection. By and large, DHTML describes the abstract concept of breaking up a page into manipulable elements, and exposing those elements to a scripting language, e.g. Java Script or VBscript, which can perform the manipulations. JavaScript is a compact, object-based scripting language that is embedded directly in an HTML page. VBscripts, on the other hand, are scripts that are placed on the server. To produce the interactivity, VBscripts use the connection to ActiveX controls. ActiveX components are then embedded in the HTML page. These statements can all recognize and respond to user events such as mouse clicks, form input, and page navigation.

5 THE PREDICTIVE DESIGN ANALYSIS APPROACH

The vast number of design procedure models have 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. [4]. 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 PDA 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. The result of PDA can then be evaluated further along with the remainder of the qualitative criteria by some known evaluation technique [5]. The process of developing the final design involves several iterations of synthesis, analysis, evaluation and decision making, where the totals cost of, and time consumed in, the project increase as the number of iteration increases. The PDA approach is very powerful in the way that it extracts the few vital variables from the many trivial ones and thus is able to extend the use of design analysis also to the early stages of the design phases. The sensitivity to environmental factors, interactions between design variables and environmental variables and uncertainty in design dimension can all be evaluated with PDA. The most significant advantage of applying this approach is the shift from verification to predictive analysis in the design process.

6 STATISTICALLY DESIGNED EXPERIMENTS

A general approach to design of experiment (DOE) is to perform factorial experiments, which means a systematic arrangement of the experiment. This approach considers not only the basic parameter problem as do the one factor at a time experiments; it also takes interactions among the studied parameters into consideration. When the number of parameters increases, the time and money spent on performing the large numbers of experiments would be unreasonably high. The fractional factorial arrays assume that the result consists somehow of redundancy and is performed by carefully choosing a piece (fraction) of the total experiment. Statistical layouts are used to organize the parameters in such fractional factorial analysis to ensure a reasonable accuracy level. Using just a fraction of a full design will introduce aliases effects to the response. A response that confounds main effects with two-factor interactions, but does not confound any main effects, is said to have resolution III. Design resolution IV confounds two-factor interactions with other two-factor interactions and main effects with three-factor interactions. The most suitable use of fractional factorial designs is for locating important variables. Early in the experimentation series interactions are more likely to be unimportant where one is often far away from the optimum values. At later stages of the experiments when the important factors are known, highly fractionated designs should not be used. In the statistical experiment society, two main approaches to performing statistical experiments have evolved.

Taguchi introduced the first approach that can handle design variables with two, three or more levels, and even mixed levels can be used. Taguchi has constructed different types of orthogonal arrays that limit the experiments performed, which are fractional factorial arrays based on independent variables. All of these orthogonal arrays assume that the design variables are independent, which can be difficult to verify in advance. The main effects are calculated through standard statistical formulae and plots of main effects can be produced. The second main approach is what is referred to as the methods of western statisticians. These approaches also use fractional factorial arrays. The chosen arrays are slightly different from those

presented by Taguchi in that they are not so complex and they are not based on independent variables. This means that interaction effects can be studied directly along with the main effects. A systematic way to calculate the response average, main effects and interaction effects is the Yates algorithm, which takes the response as input and calculates the effects. These effects can then be viewed and interpreted mainly through some types of graphs called normal plots and cube plots. There exist many examples on the use of DOE to organize a number of FEA, see e.g. [6].

7 CLIENT-SERVER IMPLEMENTATION

The implemented application is a further development of the PDA approach. The work is built up as a Client/Server application that makes use of the advantages of the internet/intranet. The time-consuming FEA are performed on the server while the pre and post processing are performed on the client machine. The first decision the designer or analyst has to make is to choose the appropriate statistical design layout. These layouts are standard DOE layouts that can be found in statistics literature see e.g. [7]. Figure 1 shows the result of choosing a 2^{4-1}_{III} layout, which is of resolution III and handles 4 variables in 8 analyses. To the right in Figure 1 the alternations of the design variables in the 8 analyses are shown along with the estimation of the statistical effects.

The screenshot shows a web browser window titled 'Test pages AZE - Microsoft Internet Explorer'. The page contains a form for setting up FEA analyses. The form is divided into two main sections: 'Complete the form' and 'Design layout'.

Complete the form

Choose input file to upload:

Assign Name and Values to the design variables

No.	Name	value1	value2
1	<input type="text"/>	<input type="text"/>	<input type="text"/>
2	<input type="text"/>	<input type="text"/>	<input type="text"/>
3	<input type="text"/>	<input type="text"/>	<input type="text"/>
4	<input type="text"/>	<input type="text"/>	<input type="text"/>

Crash response

☒ Total Mass (mass)

☒ Force history diagram (thrust)

Maximum axial contact force

☒ Maximal contact force evaluation

☒ Equivalent stress at max force (seqv)

☒ Total Displacement at max force (usum)

Minimum axial contact force

☒ Equivalent stress at final load (seqv)

☒ Total Displacement at final load (usum)

Select User and Projectname

User: Project:

Design layout

dv1	dv2	dv3	dv4
1	1	1	1
2	1	1	2
1	2	1	2
2	2	1	1
1	1	2	2
2	1	2	1
1	2	2	1
2	2	2	2

Effect and their aliases

$I_1 \rightarrow \text{mean}$

$I_1 \rightarrow A$

$I_2 \rightarrow B$

$I_3 \rightarrow AB+CD$

$I_4 \rightarrow C$

$I_5 \rightarrow AC+BD$

$I_6 \rightarrow BC+AD$

$I_7 \rightarrow D$

Generators: D=ABC

Figure 1. Input data setup for the FE analyses

The second step in the pre-processing phase is to fill out the FEA setup form shown in Figure 1. Firstly the location of the FEA input file on the client machine has to be specified. The appropriate name and values to the design variables also need to be assigned in this step. The name should correspond to those used in the FEA input file and the values are the levels to be evaluated statistically by the application. The third step is to choose the appropriate responses that are to be calculated in the analyses. The needed commands for producing the responses are appended to the

input file, when the submit button is pressed, to make the file complete. The last thing to define before sending the analysis request to the server is to fill out the correct username and project name. Each analysis project performed under a username has to have its own unique project name. Clicking on the submit button sends the data to the server and the CGI program starts the FEA with the input and output settings from the form data. After all the FEA are done the CGI program starts the statistical evaluation and presentation of the chosen responses.

The program sends a message back to the user when the analyses and evaluations are done, and the post-processing HTML page can be loaded. This page is built up from basically two frames. In the left, shown in the middle picture in Figure 2, a Java applet is loaded that contains all the user projects. The right frame is used to view selections made in the applet. The applet has a tree structure similar to the structure of file manager that engineering designers meet in their everyday work.

Every project contains a listing of the analysis data, see left top picture in Figure 2, defined in the pre-processing phase. A new project with different input data can easily be established. There are possibilities to choose another level for the current design variables or to test new design variables. If new design variables are chosen, the input file has to be rewritten and uploaded to the server. There is also a possibility to test the current design variable configuration on a different design product; hence a new input file has to be uploaded to the server. Submitting the new form data to the CGI application user will extend the Java applet tree with a new project. Further, the applet contains a subfolder named *result* containing another subfolder for each of the chosen response functions. The result folder includes a subfolder, named *runs*, with the FEA results and graphical presentations of the statistical evaluations. The FEA results are visualized through Virtual Reality Modeling Language (VRML) files for each analysis performed, which can be seen in the left bottom picture in Figure 2. The VRML is a file format for describing interactive 3D objects and worlds that can be dynamically modified through a variety of mechanisms. The user has such possibilities as to rotate, zoom, translate and seek certain model locations of the model with the built-in mechanism in the browser's plugin for handling VRML files.

The statistical calculation is also available for further evaluation. These HTML pages are built up from two vertical frames, in which the right one is divided into two horizontal frames. The different statistical result charts are shown in the left of these frames. The upper right frame displays the name conversions between the defined design variables and the letters shown in the result charts, along with buttons for further statistical evaluation. Depending on the method chosen for statistical analysis layout, different types of graphical representations will be available. If the Taguchi analysis layout is chosen, the result charts will be as shown in the right-hand pictures in Figure 2. The main effects shown in the top chart are the responses of each design variable that is created on the fly by the application. The mean value and the standard deviation of the response are also shown along with the result of each FEA. By clicking the Interaction plot button a form is created based on the current design variables. Choosing the relevant design variables, in the form creates the interaction plots between different design variables as shown in the bottom right picture of Figure 2.

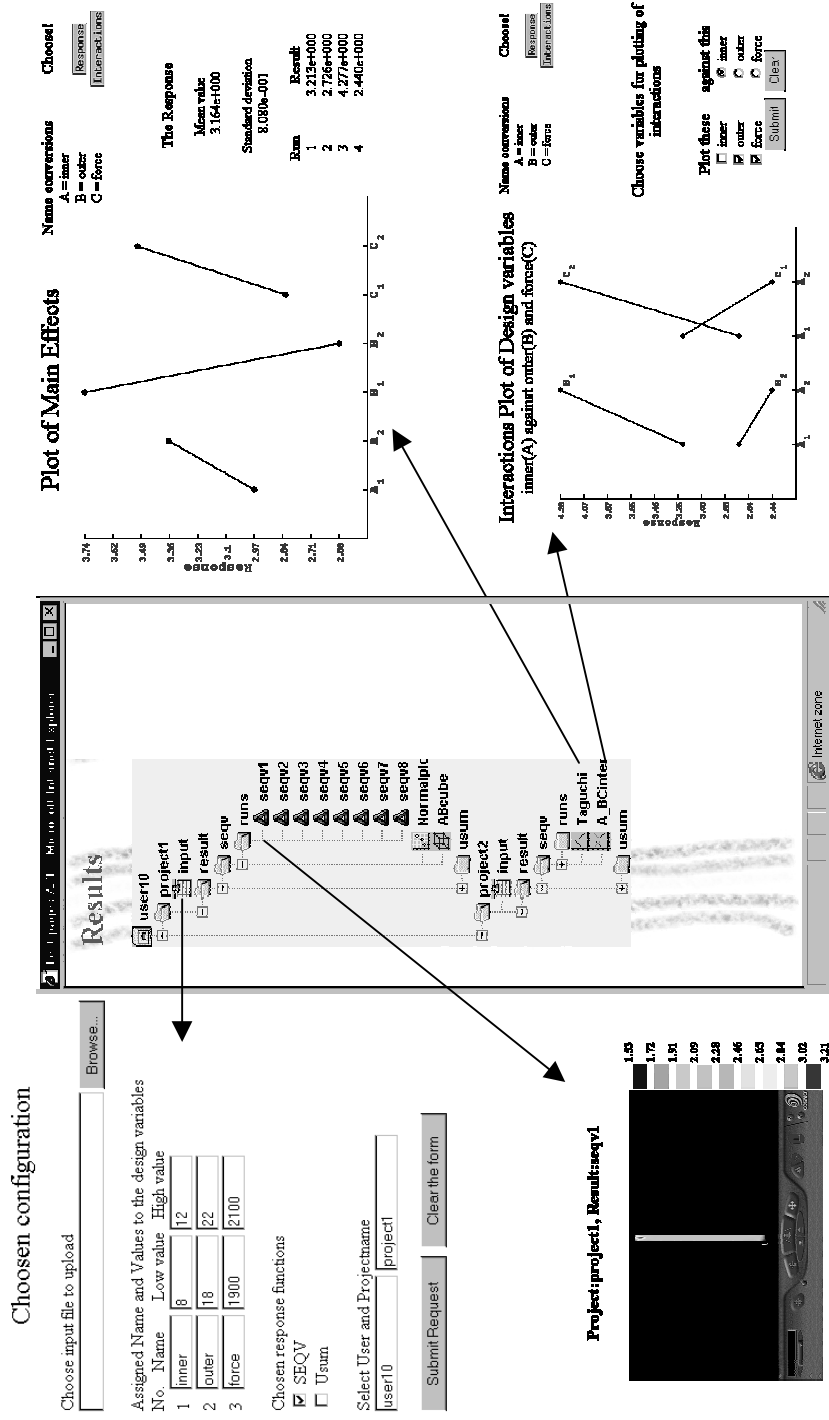


Figure 2. Post-processing interface: The left pictures display chosen FEA data and the corresponding VRML picture of the response. The middle picture shows the Java applet organising the result. The right charts display the resulting statistical evaluation.

8 AN EXAMPLE

The example chosen to exemplify the application is a component in a transportation device. The beam is a critical component in the device since the operator of the device is located close to the component. The beam has to behave in a controlled manner in case any structural load is applied. To ensure the behavior, different types of load cases are tested on the beam. The loadcase shown in this example is a direct side impact (crash) in the axial direction of the beam. The criterion is that the final design of the component must be able to withstand a load of 30 kN. The design layout of the component and visualisation of the design variables is illustrated in Figure 3.

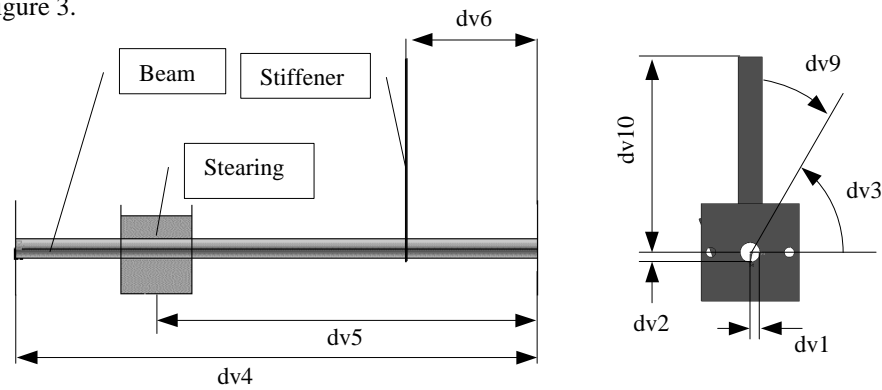


Figure 3. Visualisation of the chosen design variables.

To sort out the important design variables, a design layout for ten variables in sixteen runs is chosen. The chosen layout, 2_{III}^{10-6} , is of resolution III and handles 10 variables in 16 analyses. One of the generators is J=AB, which means that the effects from J and interaction effect from AB cannot be separated in the statistical evaluation. Further, the analysis layout and the estimation of effects along with the aliases can be seen in Figure 1b. The variables selected and their assigned values are shown in the table below.

Table 1 Design variable definitions for the performed analyses.

Design variable	Description	Low Value	High value	16 Runs	8 Runs
1	Radius 1 of beam section (m)	20e-3	22e-3	A	A
2	Radius 2 of beam section (m)	20e-3	22e-3	B	B
3	Angle of beam section (°)	0	45	C	
4	Length of beam (m)	1.1	1.15	D	
5	Location of steering (m)	0.6	0.62	E	
6	Location of stiffener (m)	0.275	0.28	F	C
7	Thickness of beam section (m)	2e-3	2.5e-3	G	D
8	Thickness of the stiffener (m)	2e-3	2.5e-3	H	
9	Angle of stiffener (°)	0	15	I	
10	Length of stiffener (m)	0.3	0.35	J	

All available options for Crash analyses (Crash response), see Figure 1, are selected. The graphical result presentation includes such things as stress and total displacement plots at the time of maximum contact force; see Figure 4.

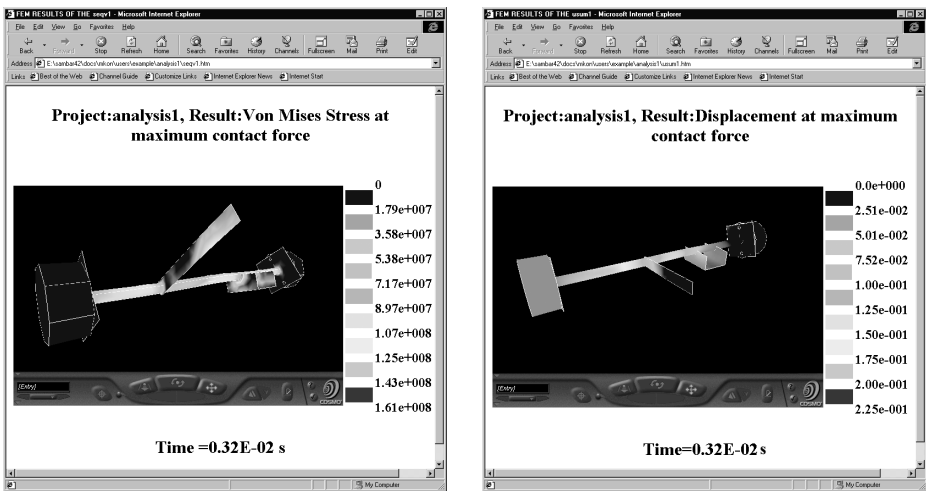


Figure 4. VRML plots at the maximum contact force

For each analysis a history plot of the contact force is produced; see Figure 5. As can be seen from the two graphs, the behavior of the component is quite dependent on the design variable settings. Furthermore the maximum force also differs for the two graphs shown. These behaviors, along with the component mass, are evaluated statistically.

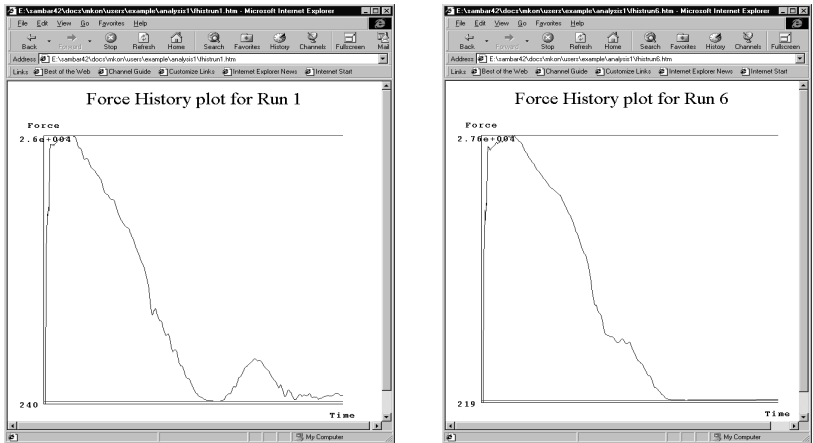


Figure 5. Force history diagrams for analyses 1 and 6.

The normal plot in Figure 6 indicates that the important factors are the effects G+BI+FJ, A+FI+BJ, B+GI+AJ. In Figure 6 the mean value and standard deviation are shown along with the individual responses from each analysis. The mean value is above the criterion of 30 kN, but not all the analyses are above this value.

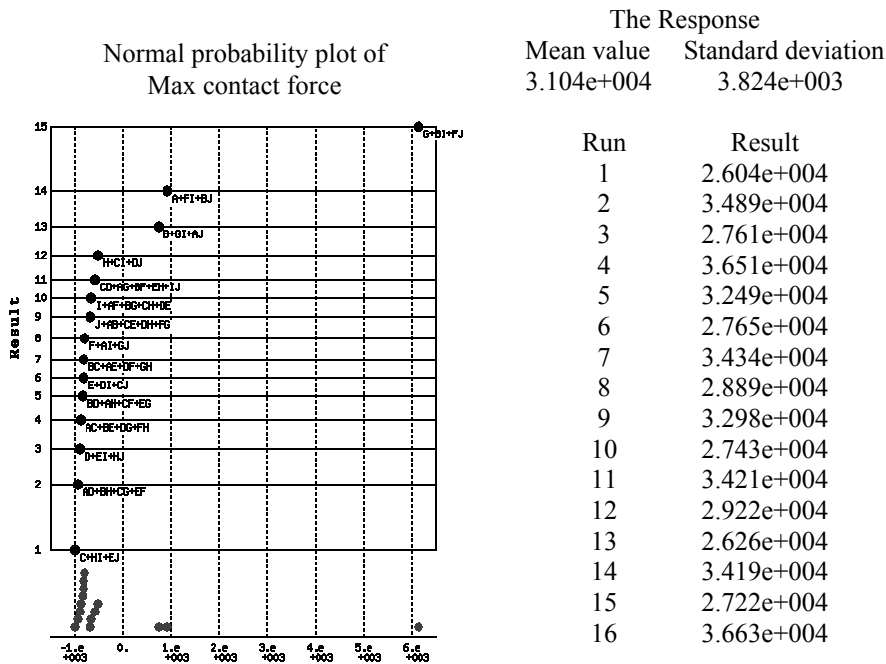


Figure 6. Normal plot of the maximum contact and responses from each analysis.

A normal plot similar to the one shown above for the components' total mass indicates that the effects A+FI+BJ, B+GI+AJ, G+BI+FJ and H+CI+DJ have influences. To be able to get even more information, eight new analyses are performed with the variables A, B, F and G. The layout 2^{4-1}_{IV} , which is of resolution IV, is chosen to manage the 4 design variables in 8 analyses. The new set of variables is given new letters (A, B, C, and D) according to the *column 8* runs in Table 1. The layout is of resolution IV, which means that all main effects can be estimated without any aliases. The remaining variables are held at their lower values.

By studying the results of the maximum contact force in the second set of analyses, see figure 7, it can be seen that the important effects found in the first set of analyses still have substantial influence. The new analysis once again results in a mean value of 31 kN with a standard deviation of 3.8 kN. To highlight the actual response of each of the variables, a cube plot is constructed, see figure 7. As can be seen from the cube plot, the criterion value of 30 kN is only fulfilled when the beam thickness (D) is at its high level independent of the combinations of the radiuses.

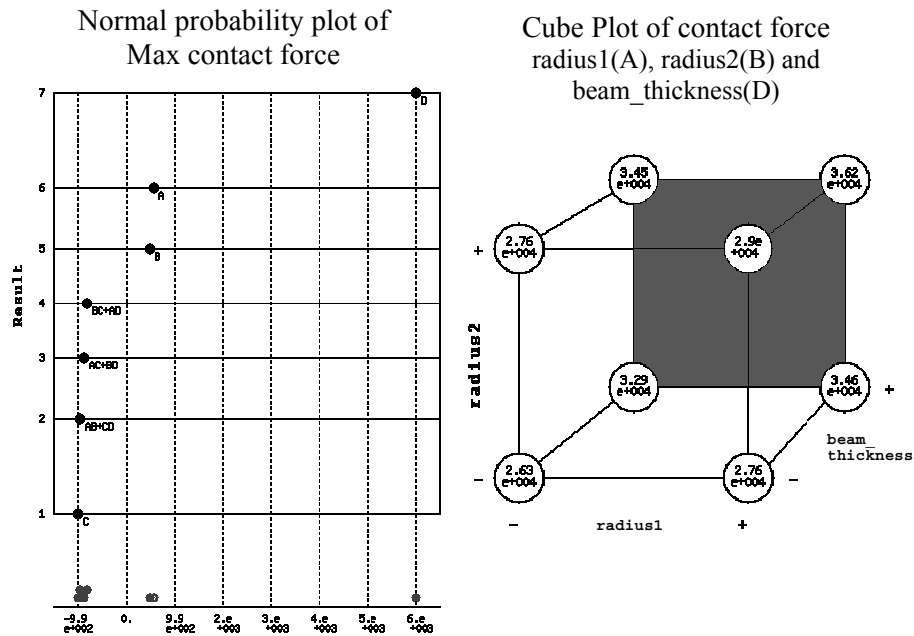


Figure 7. Normal plot of the maximum contact force and a cube plot of the design variables A, B and D.

This also indicates that the shape of the beam has negligible influence and a simple circular section can be used. The total mass of the component is of course also dependent on the above studied variables. The cube plot in Figure 8 also shows that the small circular beam has the lowest weight, which is desirable in the transportation device.

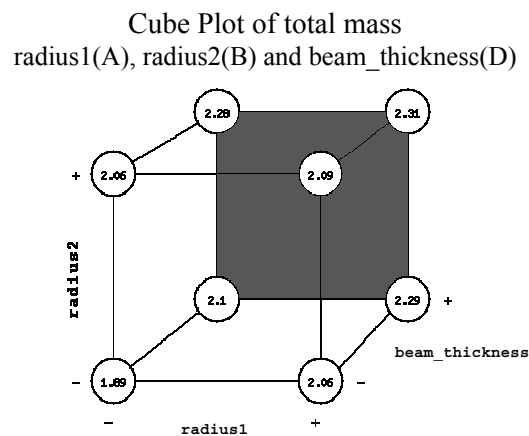


Figure 8. Cube plot of the component mass from the last set of analyses.

The example studied illustrates how PDA decreases the number of design variables, from ten to four, that an engineering designer has to take into consideration when designing the component. In the remaining variables, only one variable setting would be important to fulfill the demand on the component. The other variables can be useful in trying to fulfill certain wishes, e.g. low mass, on the component.

9 CONCLUSION

The combination of DOE and PDA gives the designer a powerful analysis tool for evaluating the product, along with other engineering tools, at all phases of the design process. Based on the results the designer is able to sort out the important variables for further evaluation along with other criteria on the product. The optimum design variable configuration can be established by weighting the different evaluated responses in a decision table. The deployment of Internet or intranet makes it possible to use the application presented here by design teams that are geographically separated. Designers from different teams can view and further evaluate the result for their specific area of interest. Another great advantage of using a Client/Server application on the WWW is that the hardware configurations of the clients and servers are independent.

To make the application more interactive and more dynamic the language of XML (Extensible Markup Language) will be interesting to investigate. XML provides a formal syntax for describing the relationships between the entities, elements and attributes that make up an XML document, which can be used to recognize the component parts of each document.

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Paper E

Excerpt from the report

**A survey of the literature on the use of
design analysis and statistical methods in
engineering design**

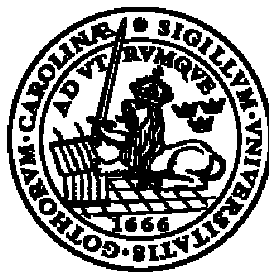
Eriksson, M.

Division of Machine Design,
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Lund University, Lund, Sweden, 1999

E

A survey of the literature on the use of design analysis and statistical methods in engineering design

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Summary

This survey has been carried out within the framework of a research project whose objective is

To investigate and survey the state of the art of the utilization of statistical methods combined with design analysis methods within the early phases of the mechanical engineering design process.

This survey covers only articles and conference papers, since monographs relevant to the topic are continuously updated and available at the division. The databases used were INSPEC and COMPENDEX*. The search was aimed at finding information about the use of design analysis methods in combination with statistical methods early in the design process. The number of articles found in the database search was 502.

The articles that seemed to be best related to the general objective were selected and reviewed thoroughly. Based on the review it was concluded that the most frequently used design analysis method was Finite Element Analysis. The survey concludes that implementation of design analysis methods together with statistical methods in the engineering design process needs to be elaborated.

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1 Introduction

Design analysis methods are commonly used as tools to verify whether a product's design can withstand the loading and environment it is subjected to or not. By combining design analysis with statistical methods, a more solid foundation for evaluation of reliability and robustness is achieved. To make use of the techniques even at early stages of the engineering design process, an approach that shifts from verification to predictive analysis has to be established.

Studying relevant literature from each discipline makes it possible to review the “hits” from database searches in an adequate way to establish the “state-of-the-art”. The literature studied concerning the engineering design process is [1-5], design analysis [6-9] and statistical methods [10-12]. The literature survey is a part of a research project with the following objective:

To investigate and survey the state of the art of the utilization of statistical methods combined with design analysis methods within the early phases of the mechanical engineering design process.

The literature survey has been performed, and updated, continuously during the work on the research project. This report presents the current status of the subjects as of October 1999.

1.1 Objective

The main objective of the literature survey was to obtain information about the “state-of-the-art” concerning the use of design analysis tools and statistical methods within the early stages of the engineering design process. The search covered only articles and conference papers. Monographs regarding design analysis, the design process and statistical methods have been reviewed earlier at the division and are frequently updated.

2 Survey Approach

This section presents the databases used in the survey and the search-profiles used. Two different databases were used in the survey, INSPEC and COMPENDEX*, but the overall search approach is the same in both databases. The search was carried out by treating design analysis as four different topics based on their different mathematical formulations. The four categories were the Finite Element Method (FEM), the Boundary Element Method (BEM), the Element Free Galerkin (EFG) method and the External Approximation Method. These four categories were then combined with statistical methods, and finally the engineering design process was added to the search.

2.1 INSPEC

INSPEC is one of the most respected databases in the information business, due mainly to the quality of its indexing.

INSPEC contains citations, with abstracts, to the worldwide literature in physics, electronics and electrical engineering, computers and control, and information technology. The primary coverage is of journal articles and papers presented at conferences, although significant books, technical reports, and dissertations are also included.

The database contains over 5 million records, and approximately 300,000 records are added annually. Sources include more than 4,000 journals and more than 2,000 conference proceedings, books, and reports corresponding to the following publications:

Physics Abstracts, Electrical & Electronics Abstracts, and Computer & Control Abstracts.

INSPEC

Database type:	Bibliographic plus abstracts
Producer:	Institution of Electrical Engineers (IEE), UK
Online Service:	Lund University library; Internet
Content:	Bibliographic plus abstracts from over 4,000 journals and some 2,000 published conference proceedings as well as numerous books, reports and dissertations
Number of Records:	over 6,000,000 (October 1999)
Records Added Annually:	over 330,000 (October 1999)
Subjects:	Artificial Intelligence Astronomy Communications Computers Energy Engineering Information Sciences Nuclear Energy Oceanography Physics Science & Technology Telecommunications
Time span:	1969-Present (October 1999)
Update:	Weekly

2.2 EI COMPENDEX WEB

CompendexWeb is the internet version of Engineering Index, the world's premier source of engineering abstracts. With backfiles through 1970, it is the most comprehensive interdisciplinary engineering database in the world, offering over five million summaries of journal articles, technical reports, and conference papers and proceedings in electronic form. Ei Compendex®Web also includes in its indexing Web sites from Engineering Information Village .

Compared to the other leading databases in their fields, Ei is No.1 in Mechanical Engineering, No.1 in Chemical Engineering, No.1 in Civil Engineering, No.1 in Computer & Electrical Engineering, and No.1 in Engineering Management. EiCompendexWeb also includes the Ei Compendex® database.

The database adds about 220,000 abstracts yearly. Abstracts come from 2,600 engineering journals, conferences, and reports. All areas of engineering are covered. Approximately 22% of the database is conference literature, and 90% of the source documents are in English.

EI Compendex web

Database type:	Bibliographic; abstracts from 1990
Producer:	Engineering Information Village.TM
Online Service:	Lund University library; Internet
Content:	References to ca. 2,600 journals, conference proceedings, reports, and books
Number of Records:	over 5,000,000 (October 1999)
Records Added Annually:	220,000+ (October 1999)
Subjects:	Chemical and process engineering (15%) Computers and data processing (12%) Applied physics (11%) Electronics and communication (12%) Civil engineering (6%) Mechanical engineering (6%)
Time span:	1970-Present (October 1999)
Update:	Weekly; ca. 4,000 records per week

2.3 Search Profiles

The search can be divided into four main categories with a total of twelve actual searches:

I. FEM as design analysis method combined with statistical methods within the design process.

1. $(fem \cup fea \cup \text{finite element}) \cap (\text{engineering} \cup \text{model} \cup \text{product design} \cup \text{theory} \cup \text{reaserch} \cup \text{programming})$
2. $(fem \cup fea \cup \text{finite element}) \cap ((\text{doe} \cup \text{design of experiment}^*) \cup (\text{factorial}^* \cup \text{fractional factorial}^* \cup \text{two level} \cup \text{three level}))$
3. $(fem \cup fea \cup \text{finite element}) \cap (\text{engineering} \cup \text{model} \cup \text{product design} \cup \text{theory} \cup \text{reaserch} \cup \text{programming}) \cap ((\text{doe} \cup \text{design of experiment}^*) \cup (\text{factorial}^* \cup \text{fractional factorial}^* \cup \text{two level} \cup \text{three level}))$

II. BEM as design analysis method combined with statistical methods within the design process.

4. $(bem \cup bea \cup \text{boundary element}) \cap (\text{engineering} \cup \text{model} \cup \text{product design} \cup \text{theory} \cup \text{reaserch} \cup \text{programming})$
5. $(bem \cup bea \cup \text{boundary element}) \cap ((\text{doe} \cup \text{design of experiment}^*) \cup (\text{factorial}^* \cup \text{fractional factorial}^* \cup \text{two level} \cup \text{three level}))$
6. $(bem \cup bea \cup \text{boundary element}) \cap (\text{engineering} \cup \text{model} \cup \text{product design} \cup \text{theory} \cup \text{reaserch} \cup \text{programming}) \cap ((\text{doe} \cup \text{design of experiment}^*) \cup (\text{factorial}^* \cup \text{fractional factorial}^* \cup \text{two level} \cup \text{three level}))$

III. EFG as design analysis method combined with statistical methods within the design process.

7. $(\text{meshless method}^* \cup \text{efg} \cup \text{element free galerkin}) \cap (\text{engineering} \cup \text{model} \cup \text{product design} \cup \text{theory} \cup \text{reaserch} \cup \text{programming})$
8. $(\text{meshless method}^* \cup \text{efg} \cup \text{element free galerkin}) \cap ((\text{doe} \cup \text{design of experiment}^*) \cup (\text{factorial}^* \cup \text{fractional factorial}^* \cup \text{two level} \cup \text{three level}))$
9. $(\text{meshless method}^* \cup \text{efg} \cup \text{element free galerkin}) \cap (\text{engineering} \cup \text{model} \cup \text{product design} \cup \text{theory} \cup \text{reaserch} \cup \text{programming}) \cap ((\text{doe} \cup \text{design of experiment}^*) \cup (\text{factorial}^* \cup \text{fractional factorial}^* \cup \text{two level} \cup \text{three level}))$

IV. External Approximation Method as design analysis method combined with statistical methods within the design process.

10. $(\text{procision} \cup \text{external finite element}) \cap (\text{engineering} \cup \text{model} \cup \text{product design} \cup \text{theory} \cup \text{reaserch} \cup \text{programming})$
11. $(\text{procision} \cup \text{external finite element}) \cap ((\text{doe} \cup \text{design of experiment}^*) \cup (\text{factorial}^* \cup \text{fractional factorial}^* \cup \text{two level} \cup \text{three level}))$
12. $(\text{procision} \cup \text{external finite element}) \cap (\text{engineering} \cup \text{model} \cup \text{product design} \cup \text{theory} \cup \text{reaserch} \cup \text{programming}) \cap ((\text{doe} \cup \text{design of experiment}^*) \cup (\text{factorial}^* \cup \text{fractional factorial}^* \cup \text{two level} \cup \text{three level}))$

3 Results

This section contains the results, that is the so-called “hits”, found in each of the thirteen searches. Brief comments on the articles that were found to be of most interest are also given.

3.1 Inspec

The numbers of hits from each search in INSPEC are listed in Table I.

Table I: Hits from the searches in INSPEC

Main categories	Search No.	No. of Hits
$\text{FEM} \cap \text{Engineering design}$	1	6966
$\text{FEM} \cap \text{statistics}$	2	456
$\text{FEM} \cap \text{Engineering design} \cap \text{statistics}$	3	297 *
$\text{BEM} \cap \text{Engineering design}$	4	456
$\text{BEM} \cap \text{statistics}$	5	19
$\text{BEM} \cap \text{Engineering design} \cap \text{statistics}$	6	12 *
$\text{EFG} \cap \text{Engineering design}$	7	9
$\text{EFG} \cap \text{statistics}$	8	2
$\text{EFG} \cap \text{Engineering design} \cap \text{statistics}$	9	1 *
$\text{External Approximation Method} \cap \text{Engineering design}$	10	0
$\text{External Approximation Method} \cap \text{statistics}$	11	0
$\text{External Approximation Method} \cap \text{Engineering design} \cap \text{statistics}$	12	0

The search resulted in 310 articles and those marked with * in Table I are listed in Appendix A.

19 Abstracts were ordered on the basis of the article's titles. The titles of these articles are listed in tables II and III and the complete abstracts are listed in Appendix B.

Table II Title of ordered article abstracts from INSPEC

Hsien-Chen-Li; Fuyau-Lin	Process improvement using design by experiments
Syed-AR	Significance of design parameters on the thermal fatigue life of plastic ball grid array packages
El-Sawy-K; Moore-ID	A two-level iterative FEM technique for rigorous solution of non-linear interaction problems under large deformations
Evans-JW; Evans-JY; Yu-BK	Designing and building-in reliability in advanced microelectronic assemblies and structures
Dyck-D; Lowther-DA; Malik-Z; Spence-R; Nelder-J	Response surface models of electromagnetic devices and their application to design
Papadrakakis-M; Kotsopoulos-A	Parallel solution methods for stochastic finite element analysis using Monte Carlo simulation
Van-Campen-DH; Schoofs-AJG; Roozen-Kroon-PJM	Structural optimization and experimental design
Chatterjee-A; Volakis-JL; Windheiser-D	On the optimization of a finite element code for 3D scattering computation
Brandisky-K; Belmans-R; Pahner-U	Optimization of a segmental PM DC motor using FEA, statistical experiment design method and evolution strategy
Pucik-TA; Curry-TF; Dziuban-ST; Senseny-PE	The use of experimental design in large-scale finite element simulations
Piazek-J; Banas-K; Kitowski-J; Boryczko-K	Exploiting two-level parallelism in FEM applications
Wong-TE; Kachatorian-LA; Tierney-BD	Gull-wing solder joint fatigue life sensitivity evaluation
Mantell-SC; Chanda-H; Bechtold-JE; Kyle-RF	A parametric study of acetabular cup design variables using finite element analysis and statistical design of experiments

Table III Title of ordered article abstracts from INSPEC (cont.)

Lam-TF	FEA applications in DOE and design optimization
Chen-JT; Leu-S-Y	Finite element analysis, design and experiment on solid propellant motors with a stress reliever
Zahn-BA	Using design of experiment simulation responses to predict thermal performance limits of the heatsink small outline package (HSOP) considering both die bond and heatsink solder voiding
Allegre-JM; Marchand-C; Razek-A	Identification of thermal parameters in a coupled magnetic-thermal model with the experimental designs method
Heuer-N; Stephan-EP; Tran-T	Multilevel additive Schwarz method for the h-p version of the Galerkin boundary element method

3.2 Compendex web

The search in Compendex web is carried out in different time spans (1970:s, 1980:s, 1990-current). The numbers of records shown below is the total sum of all four timespans.

The number of “hits” from each search in Compendex web are listed in Table IV.

Table IV: Hits from the searches in Compendex web

Main categories	Search No.	No. of Hits
FEM \cap Engineering design	1	1+24+7077=7102
FEM \cap statistics	2	0+0+206=206
FEM \cap Engineering design \cap statistics	3	1+41+140=182*
BEM \cap Engineering design	4	0+2+527=529
BEM \cap statistics	5	0+0+13=13
BEM \cap Engineering design \cap statistics	6	0+2+7=9*
EFG \cap Engineering design	7	0+0+7=7
EFG \cap statistics	8	0+0+0=0
EFG \cap Engineering design \cap statistics	9	0+1+0=1*
External Approximation Method \cap Engineering design	10	0+0+0=0
External Approximation Method \cap statistics	11	0+0+0=0
External Approximation Method \cap Engineering design \cap statistics	12	0+0+0=0

The search resulted in 192 articles and those marked with * in Table IV are listed in Appendix C.

20 Abstracts were ordered on the basis of the article's titles. The titles of these articles are listed in Table V and VI and the complete abstracts are listed in Appendix D.

Table V Title of ordered article abstracts from Compendex web

Marcincavage, Thomas A.	DESIGN OPTIMIZATION: APPLICATION OF TAGUCHI METHODS TO FINITE ELEMENT ANALYSIS.
Leung, A. T.; Wong, S. C.	TWO-LEVEL FINITE-ELEMENT METHOD FOR THIN PLATES SUBJECT TO CONCENTRATED LOADS.
Mantell, S.C.; Chanda, H.; Bechtold, J.E.; Kyle, R.F.	Parametric study of acetabular cup design variables using finite element analysis and statistical design of experiments
Fai, Lam Tim	FEA applications in DOE and design optimization
Zahn, Bret A.	Using design of experiment simulation responses to predict thermal performance limits of the heatsink small outline package (HSOP) considering both die bond and heatsink solder voiding
Vo Van, Andre; Chtourou, Hedi; Guillot, Michel; Gakwaya, Augustin	Simplified approach to predicting dimensional changes during sintering using Finite Element Analysis (FEA)
Johnson, David H.	Open section buckling study using design of experiments and response surface methodology techniques
Kashiwamura, T.; Shiratori, M.; Yu, Q.	Statistical optimization method
Horstemeyer, Mark F.	Structural analysis of a submarine using statistical design of experiments
Rizzo, Anthony R.	Quality engineering with FEA and DOE
Ramappan, Vijay; Dasgupta, Abhijit	Simulation of the influence of manufacturing quality on reliability of vias
Edwards, M.J.; Sandifer, J.B.; Duffy, S.F.; Brown, T.S.	High-temperature life prediction of monolithic silicon carbide heat exchanger tubes
Di Pasquale, Fabrizio; Gaibazzi, Alberto; Zoboli, Maurizio	Analysis of erbium doped fiber amplifiers by combined Runge-Kutta and finite-element methods
	DOE Facilities Programs, Systems Interaction, and Active/Inactive Damping

Table VI Title of ordered article abstracts from Compendex web (cont.)

Leung, A.Y.T.; Su, R.K.L.	Body-force linear elastic stress intensity factor calculation using fractal two level finite element method
Chiang, Y.J.; Lee, Y.-L.	Evaluation of modeling accuracy of 20-node solid elements by statistical factorial design
Papadrakakis, M.; Kotsopoulos, A.	Parallel solution methods for stochastic finite element analysis using Monte Carlo simulation
Sobieszczanski-Sobieski, Jaroslaw; Kodiyalam, Srinivas	BLISS/S: a new method for two-level structural optimization

3.3 Articles ordered

Based on abstracts from the articles above in Table VIII-VI, the articles shown in Table VII and VIII were ordered and reviewed.

Table VII Articles reviewed

Hsien-Chen-Li; Fuyau-Lin	Process improvement using design by experiments
Syed-AR	Significance of design parameters on the thermal fatigue life of plastic ball grid array packages
Evans-JW; Evans-JY; Yu-BK	Designing and building-in reliability in advanced microelectronic assemblies and structures
Papadrakakis-M; Kotsopoulos-A	Parallel solution methods for stochastic finite element analysis using Monte Carlo simulation
Van-Campen-DH; Schoofs-AJG; Roozen-Kroon-PJM	Structural optimization and experimental design
Pucik-TA; Curry-TF; Dziuban-ST; Senseny-PE	The use of experimental design in large-scale finite element simulations
Wong-TE; Kachatorian-LA; Tierney-BD	Gull-wing solder joint fatigue life sensitivity evaluation
Mantell-SC; Chanda-H; Bechtold-JE; Kyle-RF	A parametric study of acetabular cup design variables using finite element analysis and statistical design of experiments
Lam-TF	FEA applications in DOE and design optimization

Table VIII Articles reviewed (cont.)

Marcincavage, Thomas A.	DESIGN OPTIMIZATION: APPLICATION OF TAGUCHI METHODS TO FINITE ELEMENT ANALYSIS.
Zahn, Bret A.	Using design of experiment simulation responses to predict thermal performance limits of the heatsink small outline package (HSOP) considering both die bond and heatsink solder voiding
Kashiwamura, T.; Shiratori, M.; Yu, Q.	Statistical optimization method
Rizzo, Anthony R.	Quality engineering with FEA and DOE
Ramappan, Vijay; Dasgupta, Abhijit	Simulation of the influence of manufacturing quality on reliability of vias
Edwards, M.J.; Sandifer, J.B.; Duffy, S.F.; Brown, T.S.	High-temperature life prediction of monolithic silicon carbide heat exchanger tubes
Chiang, Y.J.; Lee, Y.-L.	Evaluation of modeling accuracy of 20-node solid elements by statistical factorial design

3.4 Review of articles

Based on a thorough investigation of the articles ordered they could be divided into four different categories.

Group 1

Articles that utilize statistical methods to enhance and/or validate FEA as an engineering design tool.

Group 2

Articles that are focused on life prediction analyses. The FEA and statistical methods are used to establish a prediction of the studied product.

Group 3

Articles dealing with different kinds of optimization where FEA is used as design analysis tool and the optimization is based on the statistical results.

Group 4

Articles that address quality and reliability in the later stages of the design process.

Group 5

Articles that cannot be directly categorized into one of the four groups above. The contents of these articles handle everything from screening analysis to description of very specific implementation.

The articles are distributed into Tables IX-XIII based on the categorization above.

Table IX Articles in Group 1

Papadrakakis, M.; Kotsopoulos, A.	Parallel solution methods for stochastic finite element analysis using Monte Carlo simulation
Fai, Lam Tim	FEA applications in DOE and design optimization
Chiang, Y.J.; Lee, Y.-L.	Evaluation of modeling accuracy of 20-node solid elements by statistical factorial design

Table X Articles in Group 2

Syed-AR	Significance of design parameters on the thermal fatigue life of plastic ball grid array packages
Wong-TE; Kachatorian-LA; Tierney-BD	Gull-wing solder joint fatigue life sensitivity evaluation
Zahn, Bret A.	Using design of experiment simulation responses to predict thermal performance limits of the heatsink small outline package (HSOP) considering both die bond and heatsink solder voiding
Edwards, M.J.; Sandifer, J.B.; Duffy, S.F.; Brown, T.S.	High-temperature life prediction of monolithic silicon carbide heat exchanger tubes

Table XI Articles in Group 3

Marcincavage, Thomas A.	DESIGN OPTIMIZATION: APPLICATION OF TAGUCHI METHODS TO FINITE ELEMENT ANALYSIS.
Kashiwamura, T.; Shiratori, M.; Yu, Q.	Statistical optimization method
Van-Campen-DH; Schoofs-AJG; Roozen-Kroon-PJM	Structural optimization and experimental design

Table XII Articles in Group 4

Hsien-Chen-Li; Fuyau-Lin	Process improvement using design by experiments
Rizzo, Anthony R.	Quality engineering with FEA and DOE
Ramappan, Vijay; Dasgupta, Abhijit	Simulation of the influence of manufacturing quality on reliability of vias
Evans-JW; Evans-JY; Yu-BK	Designing and building-in reliability in advanced microelectronic assemblies and structures

Table XIII Articles in Group 5

Pucik-TA; Curry-TF; Dziuban-ST; Senseny-PE	The use of experimental design in large-scale finite element simulations
Mantell, S.C.; Chanda, H.; Bechtold, J.E.; Kyle, R.F.	Parametric study of acetabular cup design variables using finite element analysis and statistical design of experiments

4 Conclusions

The articles studied showed that statistical methods have successfully been used to extract vital information from FE Analyses. It was obvious that the extracted information enhanced the probability of successful decisions regarding the problems studied. However, few details on the issue of how and when statistical and design analysis methods should be implemented into the design process were given.

One of the two major areas of investigation was life prediction analysis, where DOE was used to extract the few vital design parameters used in the FE Analyses, which then were used to predict the fatigue life. The other area was optimization studies where DOE was utilized to establish the foundation for the optimization, and in some cases Monte Carlo Simulations were used to control the optimization procedure.

The conclusion of the survey is that the articles studied do not treat design analysis and statistical methods thoroughly enough to supply sufficient information regarding implementation of these methods in the engineering design process.

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