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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.

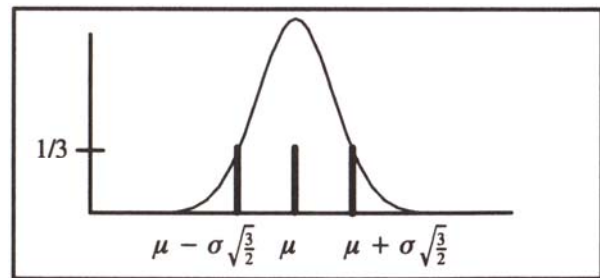


FIGURE 1. STANDARD TAGUCHI APPROXIMATION

The three levels are defined as:

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

$$center\ level = \mu_i \tag{1.b}$$

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

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:

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

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

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

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

$$\sqrt{\beta_1} = m_3 / (m_2)^{3/2} \quad \text{skewness coefficient} \quad (2.e)$$

$$\beta_2 = m_4 / (m_2)^2 \quad \text{kurtosis coefficient} \quad (2.f)$$

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:

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

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

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

The moments are calculated through

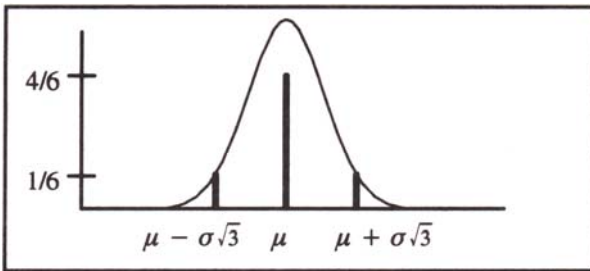


FIGURE 2. MODIFIED TAGUCHI APPROXIMATION

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

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

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.

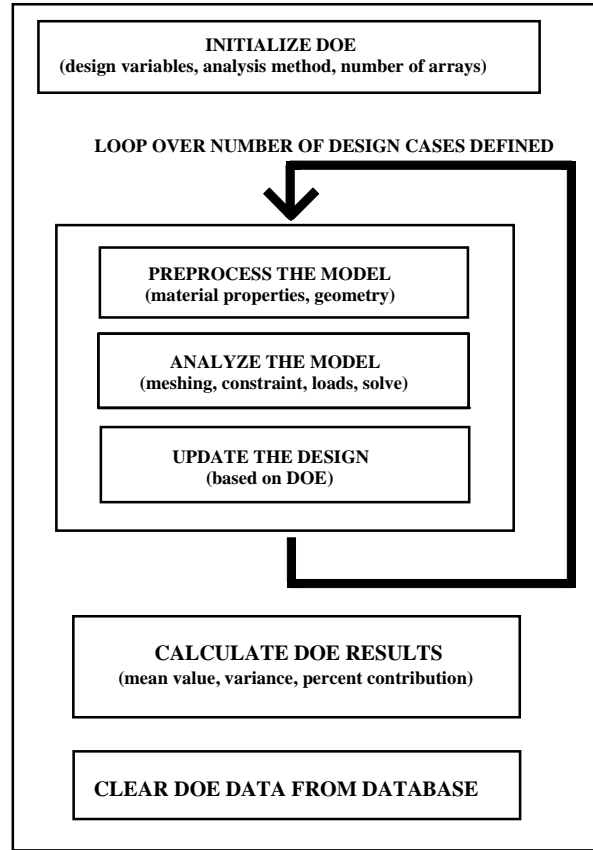


FIGURE 3. DOE BASED FE ANALYSIS

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 $r_o \in N(20,1)$.

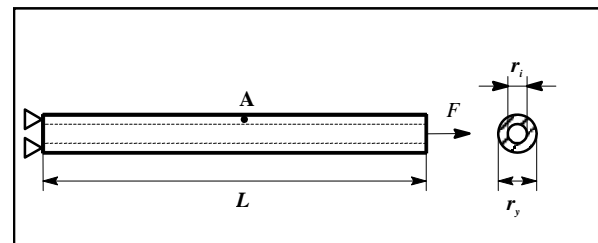


FIGURE 5. DIMENSIONS OF THE PIPE

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

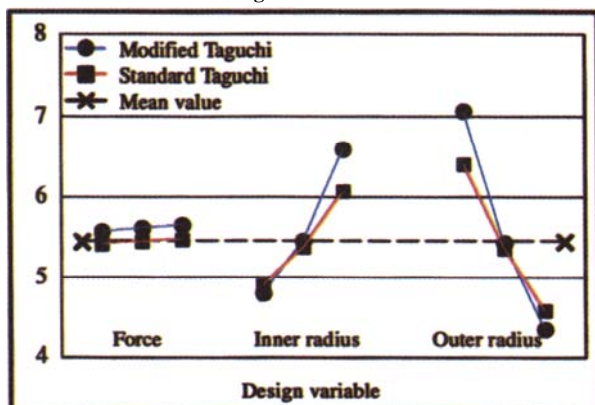
Table 4 shows the percent contribution of each design variable in the analytical case and in the FE analysis.

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.

Calculated stress at different design variable levels



Maximum stress in a beam

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

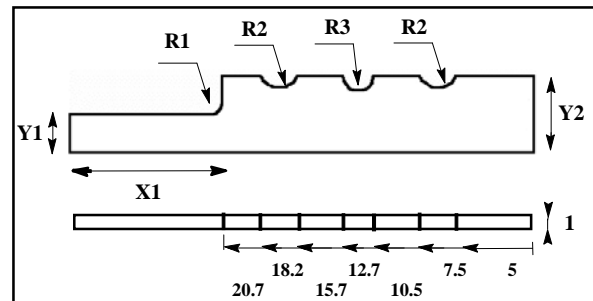


FIGURE 6. DESIGN

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 standard 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.

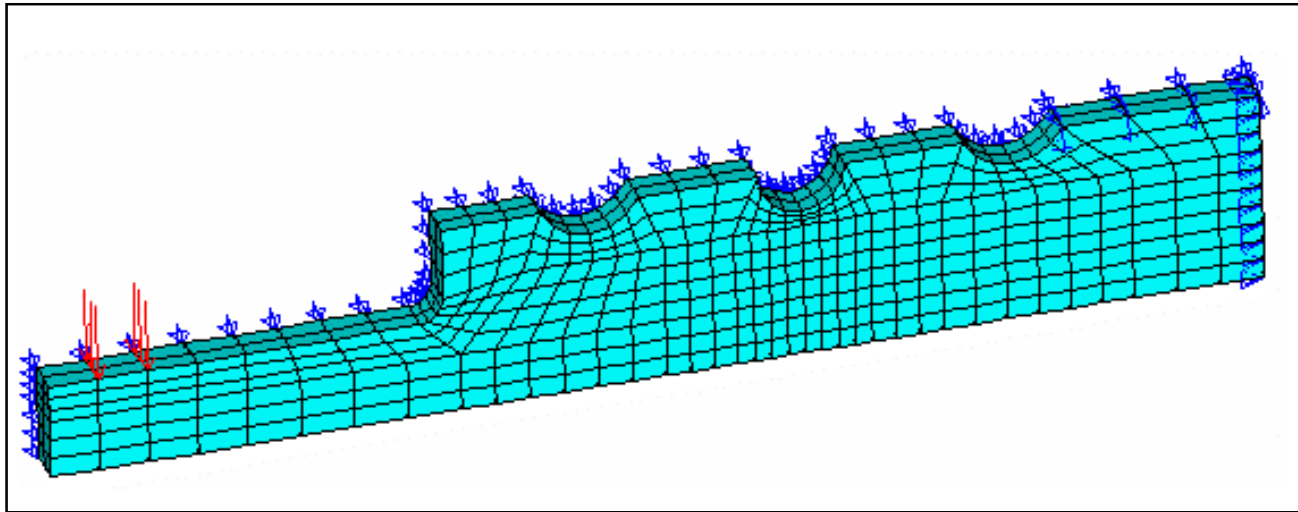


FIGURE 7. BOUNDARY CONDITIONS

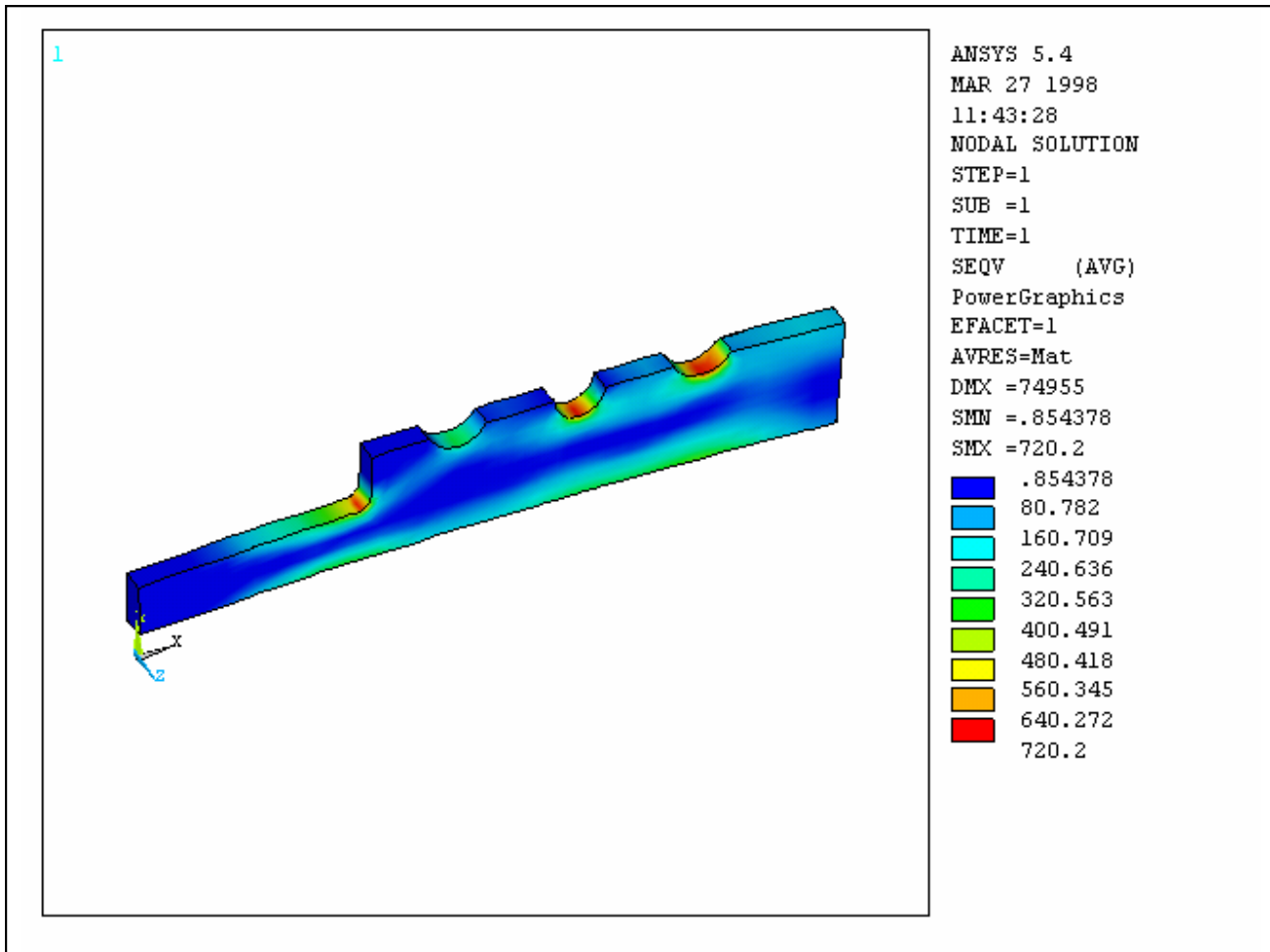


FIGURE 8. RESULT PLOT, SHOWING THE VON MISES EQUIVALENT STRESS

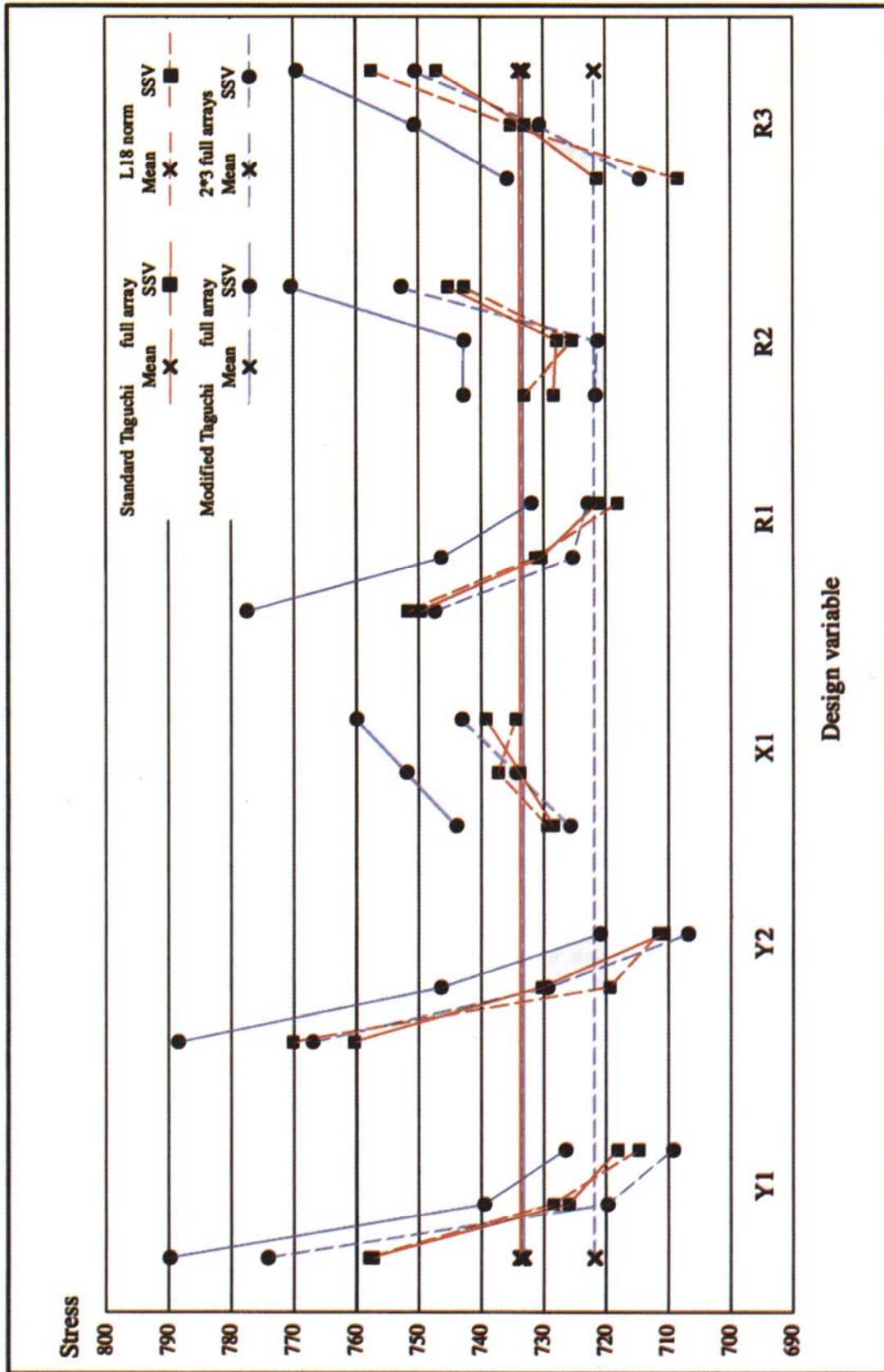


FIGURE 9. CALCULATED STRESS AT DIFFERENT DESIGN VARIABLE LEVELS

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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