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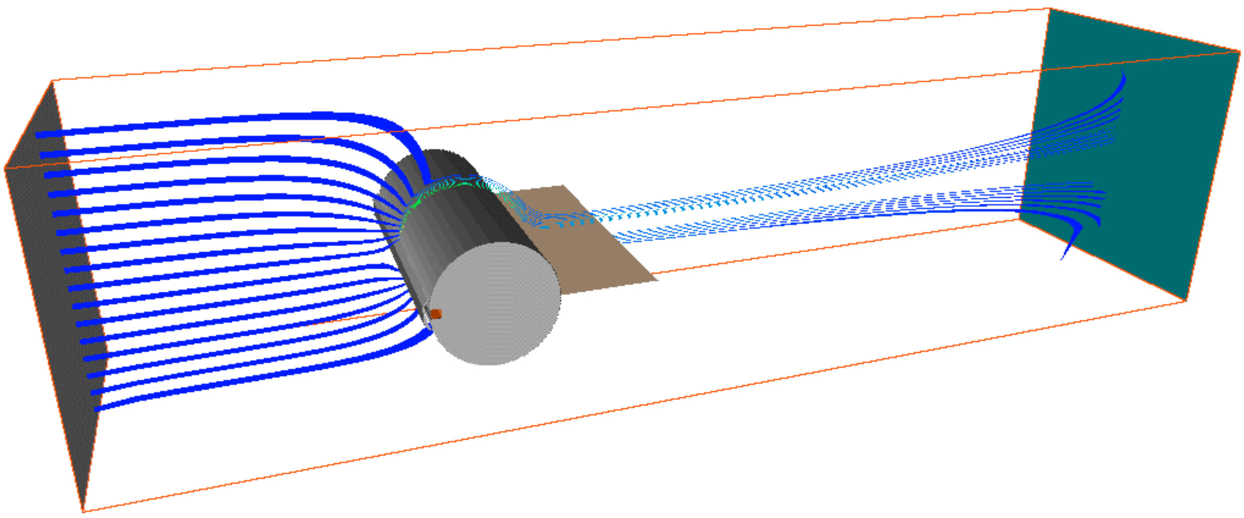
DESIGN OPTIMISATION OF THE ZETA LINEAR COANDA UTILISING TAGUCHI METHODS



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Abstract

Taguchi methods utilised in conjunction with the CFD package PHOENICS-VR 3.4 to find the optimum design of a piece of hardware known as the Zeta Linear Coanda Unit (ZLCU). The ZLCU is a non-mechanical pump device, which utilises the *Coanda* effect – the attachment of flowing liquids to a curved surface.

The major device driver for this optimisation process was the ability of the ZLCU to move sand. Analysing the entrainment factor of the device tested this ability. The various features affecting the amount of entrainment included a number of dimensional and feed factors.

The technique of using Taguchi methods with CFD analysis can cut down considerably on the number of runs required to test a specific phenomenon. This technique was also able to highlight the factors with the strongest relations so that additional man-hours were not misspent.

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Introduction

Time and cost restraints on product development usually mean that it is not a practical option to test every single combination of factors at every experimental level. Any method which would allow a reduction in the number of experiments while at the same time not compromising on accuracy to give the required optimum performance would be valuable. The Taguchi Method is one way of achieving this consistently.

The Zeta Linear Coanda Unit[1] (ZLCU) is a patented design of a non-mechanical pump, which utilises the Coanda effect to entrain the inherent flow of the surrounding fluid.

It was proposed that the Zeta Linear Coanda (ZLC) design be optimised dimensionally for moving sand by utilising CFD techniques before manufacturing experimental models due to the costs relating to each model. The problem with the optimisation of the ZLC is that the number of dimensional factors would make a standard approach of changing one variable at a time unfeasible.

It was therefore decided that another experimental technique should be utilised to cut down on the number of necessary runs and therefore the cost. The Taguchi Method was chosen due to its suitability for this scenario.

The Taguchi Technique is extremely valuable as a statistical aid in identifying numerical factors and flow regimes of interest. A large number of CFD studies, including this case, involve a considerable number of driving factors. Therefore, an industry wide appreciation of this technique would provide CFD analysts with an invaluable tool for research studies.

Large-scale changes are relatively easy to see, for example how the entrainment ratio varies with the primary feed flow. However, they cannot always display the relative effect between the important factors, which impact entrainment calculations in order to improve predictions in the future. In such a case a statistical picture is a novel way to see the relationships between the factors of the CFD runs, which are actually just a series of numerical experiments. In these numerical experiments all independent factors are external to the solver itself since no code variables were changed other than the chosen turbulence model.

Taguchi Techniques have traditionally been used in the industrial sector to analyze hardware experiments and to determine what design factors have the greatest effect on the out-come.

Taguchi Techniques can relate the relative importance of each of these to the final value for the entrainment ratio as well as the level of interactions between the factors and flow regimes of importance. Such information might be important in determining optimum test conditions or areas for code development in the smallest number of computer runs.

1 - In the 1930's the Romanian aerodynamicist Henri-Marie Coanda (1885-1972) observed that a stream of air (or other fluid) emerging from a nozzle tends to follow a nearby curved or flat surface, if the curvature of the surface or angle the surface makes with the stream is not too sharp. Examples: attachment of a jet *originally parallel to a wall, re-attachment* *after a boundary layer has separated, attachment of two flows to each other. The Zeta Linear Coanda Unit (ZLCU) utilises this phenomenon of wall attachment to create a pump with no moving parts.*

Definition of the Problem

When attempts are made to optimise a process or device, the most common approach is to use the *COST* (Change one separate factor at a time). This method leads rarely to improvement of a complicated process, even when an improvement is possible, but very often to the wrong conclusion that the process is already running at its optimum. This is due to the inability of COST to identify *interactions* among the factors that influence the process. If there are no interactions between the critical factors then the COST can be applied. Still there is another considerable disadvantage with this approach and that is the need for great amount of experimental work in order to optimise one variable at a time.

Thus if the process is complicated and there are interactions between the factors that are important, one should consider to use statistical designs as an optimisation tool. These are basically mathematical schemes in which all important factors are changed simultaneously, thereby leading rapidly to the real process optimum.

An example of a widespread form of statistical design is the modified *Taguchi* method. The method is used mostly in industrial process design, where it is applied to generate enough information to establish the optimal conditions for a particular process, using the minimal amount of experimental work conceivable.

A number of progressive trials are performed by the Taguchi method. An initial experiment is made to find the most influential of a number of potentially important factors. These "control parameters" are then used to predict a combination that will make the investigated system optimal with respect to some given criterion. If these results are satisfactory then no further studies are needed. However, if an additional improvement is desirable then the subsequent experiments may be performed using a narrower range of settings for each control parameter.

Let us assume that we want to look at four reaction components, such as deflector spacing, laminating plate length, jetting plate angle and deflector angle with respect to entrainment ratio using three levels for each component. Normally it would require a test with 81 (i.e. 3^4) separate experiments to be able to investigate the effects and interactions of the chosen components. With Taguchi methods the same answer may be achieved using just nine reactions.

$$E = 2.k + 1$$

E : the number of experiments required

K : the number of components to be tested

'E' must be a multiple of three otherwise the required number of experiments is the next multiple. When looking at more components the reduction in the amount of experiments needed becomes more obvious; e.g. to test 8 factors would require 6561 (3^8) reactions to analyse fully, whereas using Taguchi methods this may be limited to only 18 ($2\times 8 + 1 = 17$, next integer divisible by three is 18). The control factors are arranged in an orthogonal array.

The orthogonal array has such properties that between each pair of columns, each combination of levels (A, B or C) occurs an equal number of times. By using a quadratic loss function it is then possible to estimate the effects of individual components on entrainment ratio.

The following quadratic loss function is recommended by Taguchi:

$$SNL = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)$$

SNL : signal-to-noise ratio

n : number of levels

y : entrainment ratio

The most optimal conditions give the largest *SNL*.

Taguchi Method Technique

Experimental Methods

In any technical study, enough relevant data has to be obtained from each experiment so that the science behind the observed phenomenon can be inferred. This can be done by:

1. Trial-error approach:

   Creating a random experiment and then analysing the data to create a new experiment, and so on – it is impossible to tell when the optimum has been achieved

2. Design of experiments:

   A planned set of experiments, in which all parameters of interest are varied over a specified range – requires a large amount of experiments and resources

3. Taguchi Method:

   "Orthogonal Array" experiments which gives much reduced "variance" for the experiment with "optimum settings" of control parameters

Taguchi method is a scientifically disciplined mechanism for evaluating and implementing improvements in products, processes, materials, equipment, and facilities. These improvements are aimed at improving the desired characteristics and *simultaneously* reducing the number of defects by studying the key variables controlling the process and optimising the procedures or design to yield the best results.

In Taguchi Method, the word "optimisation" implies "determination of best levels of control factors". In turn, the best levels of control factors are those that maximise the Signal-to-Noise ratios. The Signal-to-Noise ratios are log functions of desired output characteristics. The experiments, that are conducted to determine the best levels, are based on "Orthogonal Arrays", are balanced with respect to all control factors and yet are minimum in number. This in turn implies that the resources (materials and time) required for the experiments are also minimum. In this case the number of experiments was reduced to 8 for each set, instead of 128 using a typically designed series.

The method is applicable over a wide range of engineering fields that include processes that manufacture raw materials, sub systems, products for professional and consumer markets. In fact, the method can be applied to any process be it engineering fabrication, computer-aided-design, banking and service sectors etc. Taguchi method is useful for 'tuning' a given process for 'best' results.

Taguchi Matrices

Below are Taguchi Method related tables. Utilising this technique, a number of conditions can be varied at once. B.C and A.E represent possible interactions between the conditions. After analysis, it can be seen that reducing the base displacement is the only improvement from this set of variables. In this way, it was possible to create a theoretical optimised ZLCU that could then be constructed for verification physically.

Variable Number / Run Number	Base Displacement	Deflector Spacing	Deflector Angle	Laminating Plate Length	Guiding Plate Angle	Interactions		Results
	mm	mm	deg.	mm	deg.			
	A	B	C	D	E	F	G	Entrainment
1=	35	12	130	55	14			
2=	25	18	150	25	7	B.C	A.E	
1	1	1	1	1	1	1	1	1.248
2	1	1	2	2	2	2	2	-0.037
3	1	2	1	1	2	2	2	0.859
4	1	2	2	2	1	1	1	0.519
5	2	1	1	2	1	1	2	1.374
6	2	1	2	1	2	2	1	0.747
7	2	2	1	2	2	2	1	0.996
8	2	2	2	1	1	1	2	0.631

Table 1 Taguchi Matrix

Variable	Effect
Effect of Base Displacement	0.290
Effect of Deflector Spacing	-0.082
Effect of Deflector Angle	-0.654
Effect of Laminating Plate Length	-0.158
Effect of Guiding Plate Angle	-0.302
Effect of the Interaction B.C	-0.302
Effect of the Interaction A.D	-0.171

Table 2 Effects table

The method involves setting up an interaction table that determines which factors are measured against the others in a series of experiments. Taguchi has constructed several of these tables depending on the number of factors and how many levels the factor will take during the experiment. In this work for example, the model has a two level factor. As the number of factors and their interactions increase, these tables can grow quite large and complex. For this study the main factors have been the deflector plate spacing, the laminating plate length, the angle of the jetting plate and the deflector angle.

The Taguchi method also allows the computation of the effects of interactions between the factors. Depending on how the experimental factors are assigned to the columns of the interaction table, (called an Orthogonal Array in the Taguchi Technique) we can study not only the relative importance of the factors in each numerical experiment but, say, the importance of the interaction between deflector spacing and deflector angle. It will not indicate how they interact but it will show how important this interaction is to the final answer and it shows under what experimental conditions the factor is important. *Table 2* shows an interaction table for eight experiments with seven possible factors, A-G. The number in the table indicates which level of factor to use in each of the eight experiments. Note that these eight experiments are statistically equivalent to running up to 2^7 (128) separate runs.

Some factors in this research and other possible projects may have more than two levels. However, the experimental complexity increases greatly with the number of different levels so it is recommended that some engineering judgment be used both to reduce the number of important factors as much as possible and to use no more than two levels until the most important factors are highlighted, at which time more experiments can be run with a lower number of more important factors.

To use a Taguchi Method to aid in evaluating a CFD code requires sound engineering judgment since so very many measurements can be made. The user should be aware that the information gained would depend upon what is being used as the experimental ‘result’. Incorrect conclusions could be drawn if the wrong experimental results (what Taguchi calls ‘quality characteristics’) are used. Note that this does not mean the answer is wrong but that a result not reflecting the experimental factors is being reported.

Besides the Orthogonal Arrays and interactions between factors, one of Taguchi’s most important contributions was the analysis of noise. If, for example, a particular hardware experiment was conducted under differing environmental conditions that the experimenter had no control over and which may or may not affect the outcome of the experiment, these environmental factors would be examples of experimental noise. Perhaps the temperature of the gasket affects the results of the leaky pump experiment. But the pump manufacturer has no control over how his pump is used so temperature would be an example of noise while the pump is operating. Taguchi showed that by correct application of experimental conditions, an engineer can discover those factors which are not only significant to the outcome of the experiment but those which are relatively unaffected by noise parameters. By concentrating design efforts on these components, a better product is developed.

Taguchi Method and ISO-9000:

The ISO-9000 aims at improving the capability of an organisation as a whole to manufacture products to specified technical specification and quality standards and to deliver them to the customer on time. Taguchi Method, on the other hand, attacks the product design itself. Through product and process design optimisation it improves product quality and reduces costs drastically. Taguchi Method and ISO-9000 thus complement each other.

Conclusion

Taguchi Method is a new engineering design optimisation methodology that improves the quality of existing products and processes and simultaneously reduces their costs very rapidly, with minimum engineering resources and development man-hours. The Taguchi Method achieves this by making the product or process performance "insensitive" to variations in factors such as materials, manufacturing equipment, workmanship and operating conditions. Taguchi method makes the product or process robust and therefore is also known as *robust design*. Some of the advantages are listed below.

- Competent R&D engineers can easily apply it.
- Results are achieved quickly - within 4 to 6 weeks.
- Solutions given by Taguchi Method can be implemented at an affordable cost.
- It is readily amenable to computerisation.

Taguchi method is an experimental engineering tool and hence the success of its application does not depend on the company environment - cultural changes are not really required.

The Taguchi method coupled with CFD represent a powerful tool that can be used to rapidly predict trends in factors, or assess whether a case is viable or not.

In this case, the ZLCU entrainment ratio was increased via an optimisation process, thus its sand handling abilities were improved. The ZLCU prototype was then manufactured and tested to verify the experimental CFD results.

It could be seen that the CFD solutions used in conjunction with the Taguchi method of analysis, have successfully predicted the optimum combination of factors to give a maximum entrainment ratio.

However the Taguchi prediction of the entrainment ratio for the optimum combination was somewhat different from that predicted from the CFD analysis. This could be due to a lack of cells in the computational domain or the experimental imperfections inherent with the physical tests.

The time taken to construct, solve and complete the Taguchi analysis involved about 8 man-days. To complete the same analysis without Taguchi Techniques would have taken approximately 2 months and in the laboratory it was conservatively estimated to take around 6 man-months. The savings in time have been shown in this case are over 15 fold.

This application of a statistical tool has also been applied to the CFD solver itself, rather than the hardware designed with the help of CFD. The Taguchi Techniques can directly predict areas where the inputs to the solver have significant (or insignificant) effect. In the presence of noise, which is defined as an experimental input that the developer has no control over, the Taguchi Technique can highlight solver parameters and flow regimes that may be insensitive to changes in the calculation environment, making them good candidates for off-design calculations. Other groups of factors and quality characteristics in CFD experiments may yield further conclusions about improving solver performance or behavior over wide regions.

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