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Random design: A design of experiment method to integrate geometrical deviations throughout the product lifecycle into performance simulation

Dinh Son Nguyen, Frédéric Vignat, Daniel Brissaud

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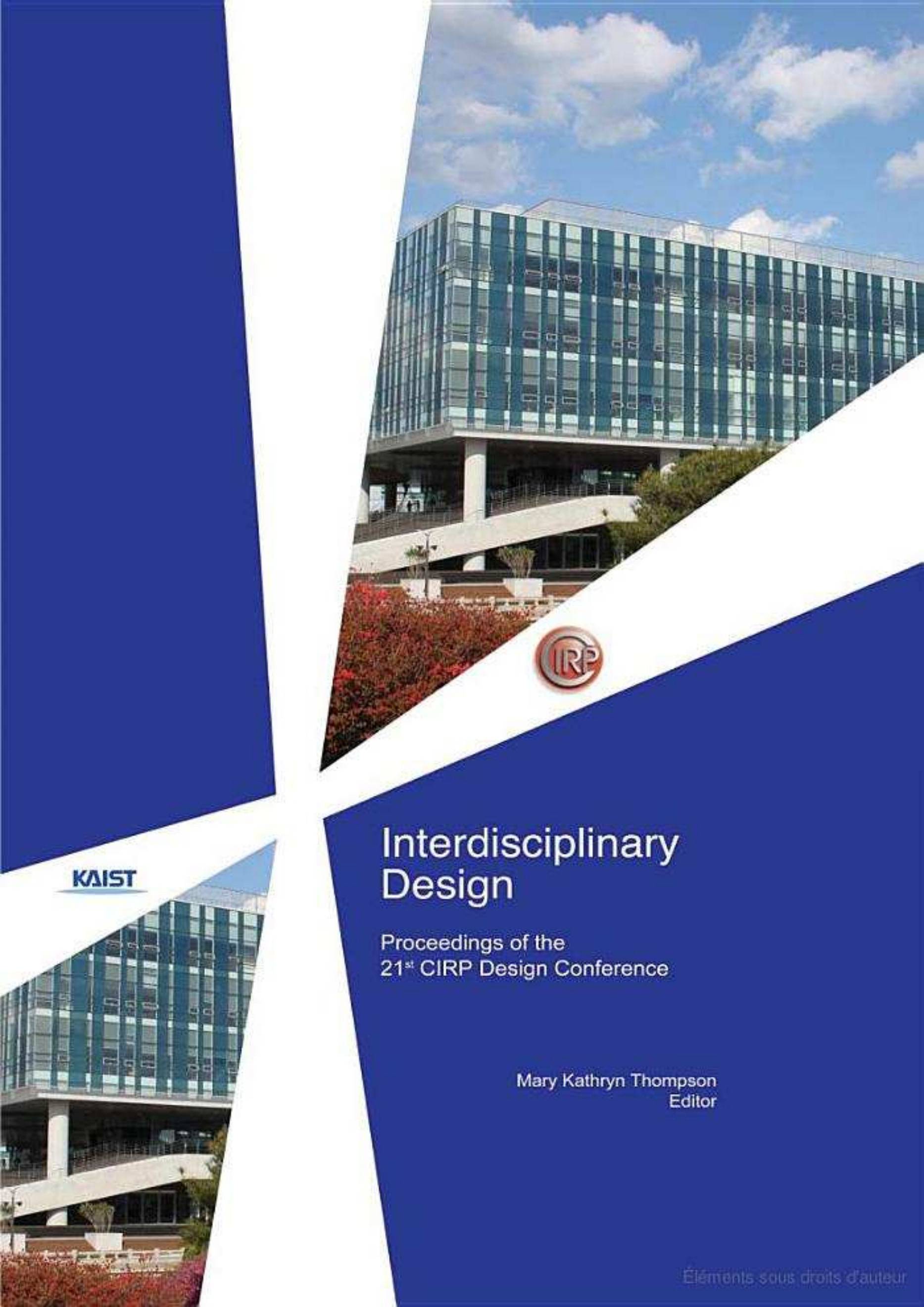
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KAIST

Interdisciplinary Design

Proceedings of the
21st CIRP Design Conference

Mary Kathryn Thompson
Editor

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Forward

The first CIRP Design Conference was held at MIT in 1990. A great deal has been achieved in design research for production and manufacturing since that first meeting. This can be seen in the dramatic increase in the number of research papers written on the subject in the past two decades and in the continued success of meetings such as this. This field has also seen, and will continue to see, many changes.

In today's world, system design and issues associated with large systems such as complexity and integration are critical. As such, the importance of cooperation, collaboration, integration and exchange of information between different elements of these systems (particularly between hardware and software), different parts of the design team, and different phases of the design process will only increase. Academic research must rise to address these new challenges.

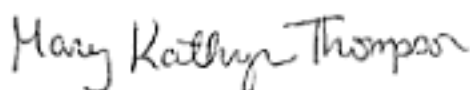
These changes are also causing engineering design research, which has always spanned the silos of technical knowledge, to reach beyond engineering and become truly interdisciplinary. For this reason, the theme of the 21st CIRP Design Conference is Interdisciplinary Design.

The 21st CIRP Design Conference features 35 technical papers and 2 keynote presentations by leading scholars from academia and industry from 17 countries around the world. The meeting will discuss research topics from production and manufacturing, mechanical engineering, biomedical engineering, industrial design, and architectural engineering including: cost, value, complexity, sustainability, integration, computation, information, robustness, creativity, collaboration, rapid prototyping, virtual design, and green transportation. The papers included in this book include contributions from the CIRP community and beyond.

We would like to take this opportunity to thank the CIRP STC Dn and the leadership of the CIRP for their support of this conference. We would also like to thank all of the authors for sharing their exceptional research with us, the members of the international program committee for their support in reviewing the papers, and the local organizing committee for their assistance with conference preparations. We would especially like to thank Ms. Jieun Choi, Ms. Monica Pena, and Mr. Harvey Rosas for their tireless efforts. Finally, we would like to thank the Korea Advanced Institute of Science and Technology, the KAIST Department of Industrial and Systems Engineering, and the Daejeon Convention and Visitor's Bureau for their financial and logistical support for the conference.



President Nam P. Suh



Professor Mary Kathryn Thompson
Chairmen, 21st CIRP Design Conference

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Random Design: A Design of Experiment Method to Integrate Geometrical Deviations throughout the Product Lifecycle into Performance Simulation

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Abstract

Robust performance is one of the most important keys in product design when many variation sources exist throughout the product lifecycle such as material defects, machining errors, and use conditions of the product. However, most of the performance simulation of the product is traditionally carried out by using the numerical model created in the CAD system. This model only represents the nominal information of the product. Thus, it is difficult to determine the relationship between the performance of the product and the variation sources, especially geometrical variation sources. A method is proposed in this paper to allow modelling the geometrical variations generated during the product lifecycle and integrating ones into the product performance simulation. As a result, the relationship between the performance and the geometrical variation sources can be established.

Keywords:

Product Lifecycle, Geometrical deviations, Performance Simulation, Robust performance

1 INTRODUCTION

Robust performance is one of the most important keys in product design since many variation sources exist in the real environment, including the manufacturing operations, material properties and operating environment. If these variations are not considered in the design process, they will prevent the performance of the designed product from meeting the requirements of clients. Furthermore, most of the product designers can easily create a numerical model of the product and the manufacturing process by a variety of computer aided tools, such as CAD/CAM system, CAE systems, product data management (PDM) and product lifecycle management (PLM). The current computer aided tools are actually effective to reduce the time for designing and developing a new product. However, the numerical model of the product is a nominal representation that does not take into account the variations generated all along the product lifecycle such as geometrical variations generated during the manufacturing and assembly stage. Moreover, most of the product performance simulations are carried out on the nominal model of the product created in the CAD system. The real performance of the designed product is different from the nominal performance and the geometrical variability obviously has an influence on it. The risk is then that the designed product doesn't satisfy the requirements of the users. In this case, the product-process design has to be considered as not good or at the least not robust.

There are therefore important issues that have to be considered:

- How to model the geometrical deviations of a product generated in the successive stages its lifecycle?
- How to manage the causes and consequences of deviations at the design stage?
- How to establish the relationship between the performance and geometrical deviations of the product?

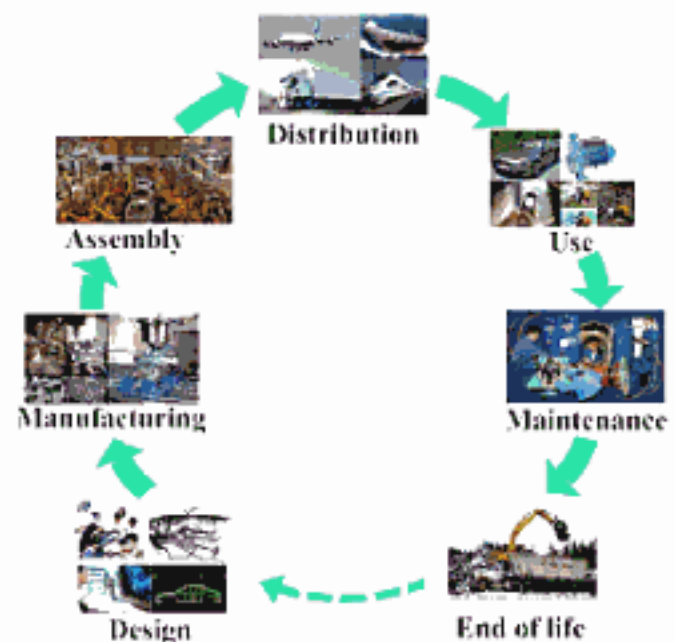


Figure 1: Closed loop product lifecycle

In this paper, a method to establish the relationship between the product performance and the geometrical deviations of the product surfaces is proposed. This method is based on the geometrical deviation model already proposed by the authors [1-2] and an original design of experiment method based on random selection of factor values. This method allows fast determination of the expected relationship even in the case of high number of factors and long calculation time.

2 LITERATURE REVIEWS

2.1 Manufacturing stage

Much research for modelling geometrical deviations generated during manufacturing stage has been done. These projects can be classified into two different

approaches. The first one is based on the concept of state space model that is, firstly, mentioned by [3]. The models to describe dimensional variation propagation along multistage machining processes using this approach are proposed by [4-5]. A state vector $x(k)$ is used to describe workpiece deviations at k^{th} stage. These deviations are accumulated and transformed onto the workpiece during previous stages ($1...k-1$) of the multistage machining process. The set of state vectors $x(k)$ describes the workpiece deviations relative to the nominal one resulting from the whole machining processes. This model provides a quantitative relationship between the fixture locator errors and the final workpiece geometrical error and has great potential to be applied to fault diagnosis and process design evaluation for complicated machining processes.

The second approach is based on the concept of small displacement torsor (SDT) that is proposed by [6]. The method based on the SDT approach to perform 3D manufacturing tolerancing for mechanical parts is, firstly, proposed by [7]. Thereafter, a model of manufactured parts (MMP) based on the SDT for simulating and storing the manufacturing defects in 3D has been developed by [8]. It permits the collection of deviations generated during a virtual manufacturing process. The defects generated by a machining process are considered to be the result of two independent phenomena: the positioning and the machining deviations accumulated over the successive set-ups. The positioning deviation is the deviation of the nominal part relative to the nominal machine. The positioning operation of the part on the part-holder is realized by a set of hierarchically organized elementary connections. The manufactured deviations of the surface relative to its nominal position in MMP are expressed by the parameters of the SDT. [9] proposed a graph representation of the manufacturing process. This graph models the successive set-up and for each set-up the positioning surface and their hierarchy and the machined surfaces. This graph makes it possible to highlight the influential paths. They propose then two analysis methods. The first one is based on the concept of SDT. The second one is based on the use of CAD software in which they model a manufacturing process with defects. They then virtually measure the realized part and check its conformity

2.2 Assembly stage

A product is made up of parts assembled by the way of connections. Each part has already passed through the manufacturing stage where geometrical deviations have been generated. Then the product passes through the assembly stage of its life cycle. The assembly stage of the product life cycle is an essential stage, and it obviously brings its share of deviations to the product. In general, models for mechanical assembly can be categorized into two different approaches. The first one is based on the state space model. Some models representing this approach are proposed by [10-11] with Stream-of-Variation Model (SOVA) for 3D rigid assemblies dimensional variation propagation analysis in multi-station processes. The deviations accumulated at i^{th} assembly station are described by a vector $X(i) \in R^{n \times 1}$. The state space model of a multistage assembly process is represented by equations (1).

$$\begin{cases} X(i) = A(i-1)X(i-1) + B(i)U(i) + W(i) \\ Y(i) = C(i)X(i) + V(i) \end{cases} \quad (1)$$

Where $U(i) \in R^{m(i) \times 1}$ is the fixture/part deviation contribution from station i , $Y(i) \in R^{q(i) \times 1}$ is the

measurement obtained on station i , $W(i)$, $V(i)$ are mutually independent noise and $A(i)$, $B(i)$ and $C(i)$ are transformation matrix.

The second approach is based on the SDT concept. [12] introduced the geometrical behaviour laws based on the SDT for modelling geometrical deviations in the mechanism. Thereafter, [13] proposed a model to analyse part deviation in assembly. The positioning variation of the part relative to its nominal position in the global coordinate system is expressed by equation (2).

$$D(A/R) = E(A/S_A) + T(S_A/S_B) + E(S_B/B) + D(B/R) \quad (2)$$

Where :

$D(A/R)$ is the variation of part A relative to its nominal position in global coordinate system.

$E(A/S_A)$ is the variation of surface S_A of the part A relative to its nominal position.

$T(S_A/S_B)$ is the variation of link between the surface S_A of the part A and the surface S_B of the part B.

$E(S_B/B)$ is the variation of surface S_B of the part B relative to its nominal position.

$D(B/R)$ is the variation of part B relative to its initial nominal position in global coordinate system.

A linear system of equations is created from the contribution of each connection between part A and part B. The positioning variation of part A is determined by the resolution of the linear system of equations based on the Gauss-elimination method.

The main principle of the models proposed by [10-11,13] is to model the variation of the part at each stage along the assembly process. However, they do not link the geometrical deviations of the surfaces of the parts to the parameters of the manufacturing process. These parameters are those of the MMP [8] that can be measured from the manufacturing process as proposed by [9]. That is the reason why the authors have already proposed a model using the small displacement torsor in order to model geometrical deviations generated during the manufacturing stage and accumulated in the assembly stage.

2.3 Design stage

The geometrical deviations generated and accumulated during the product life cycle affect the performance of the product. It is thus necessary to manage their causes and consequences at the design stage in order to reduce their effect on the product performance all along its life cycle.

[14] proposed to use engineering models for developing robust design in order to reduce the variance of the design under variation of sources, such as manufacturing operations, variation in material properties, and operating environment. [15] addressed the impact of the manufacturing errors on the performance of the product. He defined the Manufacturing Variation Pattern (MVP) to represent the manufacturing characteristics and investigated its effects on the performance of the product. [16] presented a theory that offers an analytical and geometrical description of the performance sensitivity distribution of a product in the variation space. The theory can be applied to find a robust design that is less sensitive to the dimensional variation due to manufacturing errors or product wear. [17] proposed a new Probabilistic Sensitivity Analysis (PSA) approach for design under uncertainty based on the concept of relative entropy. This approach provides valuable information about the impact of the design variables on the performance of the product and whole range or a partial range of the performance distribution. [18] proposed a statistical approach in order to evaluate the impact of the geometrical variations on the

angular rotational velocity between two bevel gears. Monte-Carlo simulation method is used to consider the geometrical behaviour simulation and tooth contact analysis. [19] proposed to integrate material and manufacturing process uncertainties in the design in order to consider their impacts on the performance of the product. They developed a procedure for uncertainty propagation from the material random field to the end product performance based on the product finite-element mesh.

These studies examine the impact of the variation sources or the geometrical variations on the product performance variation. Their approaches are, however, based on the nominal model of the product. They do not take into account the real variations coming from whole stage of the product life cycle. In addition, the concurrent product modelling technology, such as CAD/CAM, PLM, etc., is unable to model geometrical deviations generated during the product life cycle. Most of the relationship approximations between the performance and the design variables are only based on the nominal model of the product. Thus, a method that models the geometrical deviations of a product during its life cycle and integrates them into the performance simulation is proposed in this paper. The aim is to manage the geometrical variability throughout the product life cycle and its impact on the performance.

3 SIMULATION OF PRODUCT PERFORMANCE WITH GEOMETRICAL DEVIATIONS

The geometrical deviations of each surface of the product are generated and accumulated along its lifecycle. They will obviously have an influence on its performance. The geometrical deviation model, as presented in [1], can model them. The Monte-Carlo simulation method is used to create a set of m products with geometrical deviations. The product designers can be aware of distribution and variation of each surface of the product from the simulation result [2]. It is, however, unable to integrate all of them into a performance simulation of the product. Thus, we propose, in this section, to use the design of experiments (DOE) approach to integrate more geometrical deviation parameters into the performance simulation and to determine the relationship between the performance and the geometrical deviation parameters of the product (see figure 2).

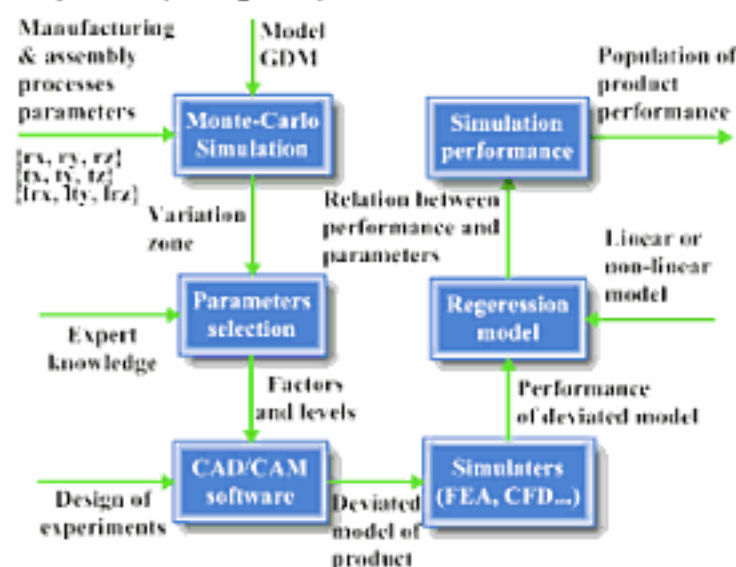


Figure 2: Performance simulation of the product with geometrical deviations

Full factorial designs are used to establish the relationship between the performance and the geometrical deviation parameters of the product, as presented in [20]. However,

the experimental runs will be very large when the numbers of the selected factors and the levels have more than two. For example, there are $3^4 = 81$ runs in the case of four factors and three levels.

Another solution, proposed by [21], is to use Taguchi orthogonal arrays. Taguchi's orthogonal arrays are highly fractional orthogonal designs proposed by Taguchi. They are used to estimate main effects by only a few experiments. They are applicable to investigate main effects with many factors and levels. The factors are similarly selected by the expert knowledge in order to eliminate the factors that have small effects on the performance of the product. The numbers of levels of each factor are also defined by the result of geometrical deviation simulation [2]. The numbers of new nominal models of the product will be created by using Taguchi's orthogonal arrays. The number of runs is chosen corresponding to the number of factors and levels. For example, it is necessary to create 27 new nominal models of the product for the performance simulation in the case of 10 factors and 3 levels. In comparison with the factorial design, we need to create $3^{10} = 59049$ nominal models for simulating the performance of the product. This is one of the advantages of the method.

In the case of increasing complexity alongside with factors number, the number of necessary simulations to determine the relationship between performance and deviations can become too large and thus time consuming even using Taguchi design. Moreover, the use of expert knowledge to determine key factors filters the deviation sources and can reach to the lost of some influential factors. Factorial design and Taguchi's orthogonal arrays are not effective in this case. Thus, we propose a random design method in order to address these issues. All product geometrical deviations parameters, called factors $\{p_i\}_{i=1..n}$ that have small effects on the performance of the product are taken into account. The variation range of each factor is determined based on the results of geometrical deviations Monte-Carlo simulations, as presented in [2].

The random design approach is realized in 4 steps (see figure 3):

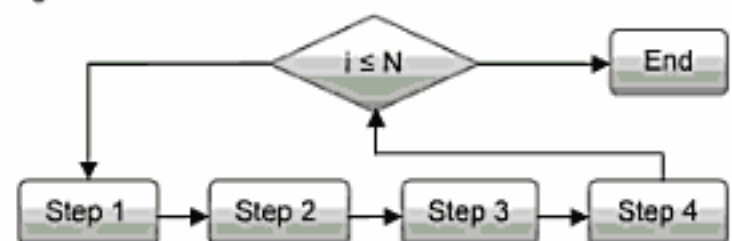


Figure 3: Algorithm diagram of random design method

- Step 1. Draw randomly a product with geometrical deviations in the set of products collected from the Monte-Carlo simulation.

A k^{th} product with geometrical deviations is randomly drawn in a set of M products collected from the results of the geometrical deviation simulation. The value of each factor $\{p_i\}_{i=1..n}$ is calculated based on the drawn product deviation parameters values. The set of values of the factors $\{p_i\}_{i=1..n}$ is added into the k^{th} row of the design matrix P , as given in equation (3).

$$P = \begin{bmatrix} p_{11} & p_{21} & \dots & p_{n1} \\ p_{12} & p_{22} & \dots & p_{n2} \\ \vdots & \vdots & \ddots & \vdots \\ p_{1k} & p_{2k} & \dots & p_{nk} \end{bmatrix} \quad (3)$$

• Step 2. Create the deviated CAD model.

The deviated model of k^{th} product will be created in the CAD software corresponding to the value of each geometrical deviation parameter $\{p_i\}_{(i=1..n)}$.

• Step 3. Simulate the performance of the product.

The deviated model created in step 2 is used to simulate the performance of the product in order to determine the performance of the representative product. The result is appended into the response vector R, as described by equation (4)

$$R = \begin{Bmatrix} r_1 \\ r_2 \\ \vdots \\ r_k \end{Bmatrix} \quad (4)$$

• Step 4. Eliminate the drawn product in the set of M products.

Repeat step 1. In this step, it is necessary to eliminate the product that has been drawn in step 1. The loop is repeated until the number of the drawn products is equal to N products.

Then the relationship between the performance of the product and the parameters of geometrical deviations $\{p_i\}_{(i=1..n)}$ is obtained by using the linear or non-linear model based on the design matrix P and the response vector R.

Then the relationship between the performance of the product and the factors is established by using the linear or non-linear model based on the realised simulations.

3.1 Linear regression model

To reduce the number of factors, key geometrical deviation parameters are defined based on expert knowledge. These key parameters are measured on the product and are functions of the elementary deviation parameters. The value of these factors can be calculated for the m products. Then the number of levels for these factors has to be defined depending on a compromise between the desired precision and the calculation time. The value of each level of each factor is calculated according to its range of variation. The N values of the n parameters are then gathered in a design matrix P, as shown in equation (3).

Two cases are encountered to determine the performance of the N products. In the simple case, the function performance is known and the performance value is obtained by the value of each parameter p_{ij} of each line of the design matrix into the analytical formula. In the complicated case, simulation tools as FEA, CFD, etc., are used to calculate the performance of the product. Thus a set of N deviated models of the product, corresponding to the geometrical parameters p_{ij} of each line of the design matrix, has to be created in the CAD system. Each model is used to simulate the performance of the product in order to determine the performance of the N products that are called response vector R. The response vector R corresponding to the design matrix P can then be filled, as expressed in equation (4).

The relationship between the performance of the product and the selected factors $\{p_1, p_2, p_3, \dots, p_n\}$ is established by the design of experiment method. This relationship can be expressed by equation (5).

$$\text{Performance} = f(p_1, p_2, p_3, \dots, p_n) \quad (5)$$

For example, the linear least square fit model is used to establish the relationship in the case of n factors at 2

levels. From the result of 2^n simulations, the relationship is expressed by the function as shown in equation (6).

$$f = \hat{\beta} \cdot p + \varepsilon \quad (6)$$

Where:

$p = \{p_1, p_2, p_3, \dots, p_n\}^T$ is a vector of the n factors.

$\hat{\beta}$ is a coefficient vector of the model. It is calculated by equation (7).

$$\hat{\beta} = (P^T P)^{-1} P^T R \quad (7)$$

$R = \{r_1, r_2, r_3, \dots, r_N\}^T$ is a response vector including N simulation responses.

ε is a residual vector describing the . It is calculated by equation (8).

$$\varepsilon = E(R) = \frac{1}{N} \sum_{i=1}^N r_i \quad (8)$$

The performance population of the product (for example, a million products) will be generated by replacing the value of the selected factors $\{p_1, p_2, p_3, \dots, p_n\}$ based on the collected data of the Monte-Carlo simulation in equation (5).

4 A CASE STUDY

A geometrical deviation model of a product during its lifecycle has been presented in the above section. Then the Monte-Carlo simulation method is used to estimate the probability distributions of the geometrical deviations of the product. As a result, the relationship between the performance and the product is established by the design of experiment method. Then a population of the product performance is generated by using the collected data in the Monte-Carlo simulation stage. In order to illustrate the method, we propose, in this paper, a simple example of a spring system using three proposed methods

4.1 Spring system

Geometrical deviation and frequency model

The numerical model of the spring system is modelled in CAD software. It is represented in figure 4. The frequency of the spring system is investigated in this case.

The frequency of the spring system is expressed by equation (9).

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad (9)$$

Where:

m is a weight of the load. It depends on the density ρ and the volume V of the load. In other words, the deviation mass of the load depends on the geometrical deviations of the load. For example, the deviations of a cylinder and two plans include their rotation and translation affect on the mass m. It is calculated by equation (10).

$$m = \rho V \quad (10)$$

k is called spring constant or spring stiffness. It is calculated by equation (11).

$$k = \frac{Gd^4}{8nD^3} \quad (11)$$

$$G = \frac{E}{2(1+\nu)} \quad (12)$$

Where:

- E - Young's modulus
- d - Spring wire diameter
- D - Spring outer diameter
- n - Number of active windings
- ν - Poisson ratio

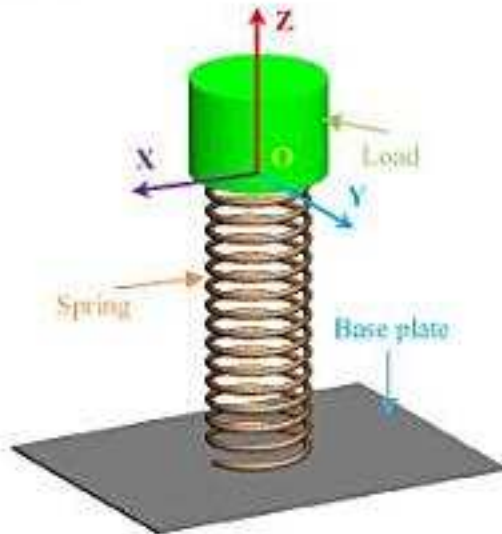


Figure 4: The parts of the spring system.

From the expert knowledge that has been presented above, the frequency of the spring system depends on many parameters, especially the geometrical deviations such as deviations of the cylinder and plan shaping the load, spring wire diameter and spring outer diameter.

The load of the spring system is manufactured by the manufacturing process shown in figure 5.

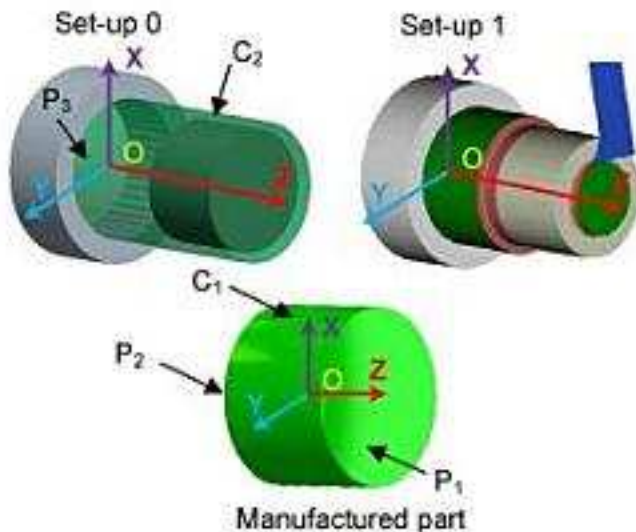


Figure 5: Manufacturing process for the load.

The geometrical deviations of all surfaces of the load are modelled by the manufactured part model (MMP). For example, those of the plan P1 of the load are expressed by following torsor:

$$T_{P^i, P^j} = \begin{pmatrix} -lx_{1,2S1} + rx_{1,2} & -60 lry_{1,2S1} - lx_{1,2S1} \\ + rx_{1,4} - rx_{1,2S1} & + 50 ry_{1,2} - 60 ry_{1,2S1} \\ & + tx_{1,2} + tx_{1,4} - tx_{1,2S1} \\ -lry_{1,2S1} + ry_{1,2} & 60 lrx_{1,2S1} - lly_{1,2S1} \\ + ry_{1,4} - ry_{1,2S1} & - 50 rx_{1,2} + 60 rx_{1,2S1} \\ & + ty_{1,2} + ty_{1,4} - ty_{1,2S1} \\ 0 & 0 \end{pmatrix} \quad (O, XYZ)$$

The Monte-Carlo simulation is used to simulate the geometrical deviations of all surfaces of the spring system. For example, the distributions of the cylinder's deviations of 100000 loads are described in figure 6.

The histogram of the rotational deviation (Rx, Ry) and the distribution of the translational deviation (Tx, Ty) of the cylinder relative to the axis X and Y are shown in figure 6a, 6b and 6c respectively. From this result, the variation of the load mass is calculated by the geometrical deviations of two plans and a cylinder of the load. It is described in figure 6d.

From the expert knowledge presented above, the relationship between the frequency of the spring system and its geometrical deviations is expressed by equation (13).

$$f = \frac{1}{4\pi\sqrt{2}} \sqrt{\frac{G(d+\delta)^4}{n\rho(D+\Delta)^3 \left[-2h\pi R^2 + h\pi(dr+R)^2 + \pi R^2(h+Tz1) + \pi R^2(h+Tz3) \right]}} \quad (13)$$

Where:

Δ, δ - Dimensional deviation of the outer and wire diameter of the spring.

R, h - Radius and height of the cylinder of the load.

$Tz1, Tz3$ - Translational deviation of two plans of the load.

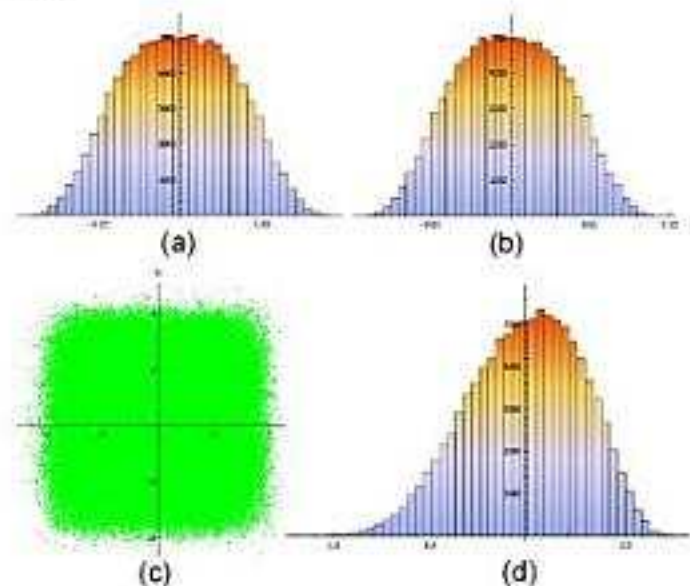


Figure 6: Monte-Carlo simulation results.

The frequency simulation of this system can, in fact, be realised by using equation (13) directly. The histogram of one hundred thousand frequencies is easily shown in figure 7, because the time for calculation is small in this case. The design of experiment method is, however,

preferred to illustrate realisation of the proposed method. We can, in addition, compare the accuracy among them.

Random design

This method is realized by the 4 steps as presented in the above section. Ten spring systems are randomly drawn from ten thousand spring systems. The ten frequencies are calculated by equation (13). Then the linear regression fit model is used to establish the relationship between the frequency and all parameters of geometrical deviations of the spring system. It is expressed by equation (14).

$$f = 4.91592 + 2.53885\delta - 0.1232\Delta - 0.201746dr - 0.0387945 Tz1 - 0.0448108Tz3 \quad (14)$$

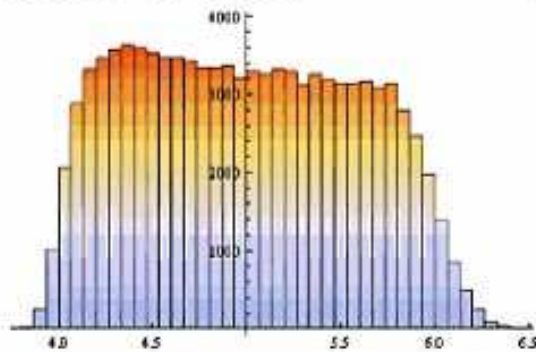


Figure 7: The distribution of frequency.

The population of the frequency is generated by the collected data in the Monte-Carlo simulation stage. The distribution of the frequency is described in figure 8.

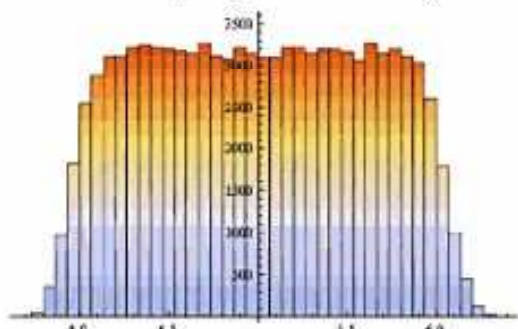


Figure 8: The distribution of frequency by Random method.

Comparison

In order to compare the accuracy of the proposed method, we calculate the error between the frequency of the random design method and real one. The distribution of the error is shown in figure 9. The summary comparison between random design method and exact approximation is shown in table 1.

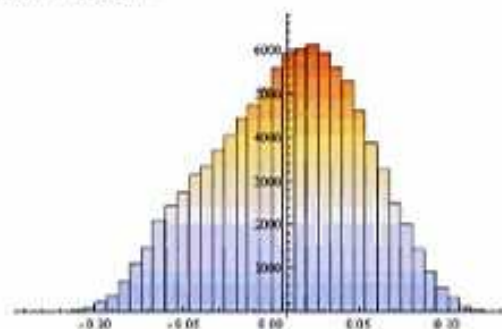


Figure 9: The distribution of frequency error of Random method.

The relationship between the frequency and the geometrical deviation parameters approximated by the random design method is given in equation (14). The relationship approximated by using the regression model with the data of 100,000 frequencies created in the above section is given by equation (15).

$$f = 4.82709 + 0.0226579Tz_1 - 0.184982dr - 0.117445Tz_3 + 2.61698\delta - 0.0989216\Delta \quad (15)$$

In comparison of the impact coefficient of each geometrical deviation parameters, there is not too much difference between the random design approach and the real one. However, it is necessary to realise 100,000 runs if using the real approach. In the complex case, the random design method is obviously better than the real approach in terms of time and cost.

	Exact model	Random design method
Mean of frequency	4.99506	5.0719
Standard deviation of frequency	0.589	0.596
Deviation parameters	All	All
Number of runs	100000	10

Table 1: Summary of the proposed methods.

5 CONCLUSIONS

This paper proposes a new random design of experiment method to establish the relationship between product performance and the geometrical deviations of the product surfaces. This relationship is used to overcome the limitations of the concurrent product modelling technology such as CAD/CAM, CAE, PLM, etc. by integrating the geometrical deviations generated during the production stage of the product lifecycle into performance simulation. The geometrical deviation model already proposed by the authors [1-2] gives an image of the population of produced parts with geometrical deviations. Using this relationship, an image of the population of the product performance is calculated.

In previous papers, two others design of experiment methods have been proposed to establish this relationship: full factorial design [2] and Taguchi design [21]. Random design of experiment, proposed in this paper, is more effective when it is difficult to determine the key factors that have a strong influence on the performance of the product, or when the number of the factors is considerably large.

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