*International Journal of Advanced Information Science and Technology (IJAIST)* *ISSN: 2319:2682*
*Vol.5, No.5, May 2016* DOI:10.15693/ijaist.2016.v5.i5.12-19

# The state of art and a comparative study of the deformable mecanisms in the domain of tolerance

Hafsa Atik
Laboratory of the Productic, Energétic
And sustainable Developement (LPEDD)
higherSchool of Technology ESTF
Fès, Maroc

Driss Amegouz
Laboratory of the Productic, Energétic
And sustainable Developement (LPEDD)
higher School of Technology ESTF
Fès, Maroc

Mouhssine Chahbouni
Laboratory of the Productic, Energétic
And sustainable Developement (LPEDD)
higher School of Technology ESTF
Fès, Maroc

Said Boutahari
Laboratory of the Productic, Energétic
And sustainable Developement (LPEDD)
higher School of Technology ESTF
Fès, Maroc

***Abstract*—The technological choices are naturally oriented towards the use of the flexible parts of which,at least, one of the dimensions is much more smaller than the others, an illustration of this are the profiles and the sheet, however the performance of the flexible part Presentsspecific challenges face the engineers during the geometric identification, the reason is that the flexible part could take in the free state a form substantiallydifferent from their nominal geometry.**

**With the conception development of the mechanic systems, the traditional analysis method, such as the method of 'monte carlo simulation' in which some cases, are not applicable to the flexible assembly due to the possible deformation of the part during the process of assembly.**

**In the process of the fabrication, and more particularly, the phase of the assembly, the assembled usually present a flexibility performance. Many works in the literature have been treated and tried to introduce this variation in the analysis, many researchers have solved this problematic in a different way. However, all of these works are generally arranged and ran through four principals axis.**

**This article aims, first, at presenting a review of the literature as well as presenting the works of thetoleranceof the deformable mechanisms via illustration general in order to reach the second step; wish is a comparative study amongst the research works in the domain of the tolerance of the deformable (flexible) mechanisms.**

***Index terms*—tolerancing,tolerance analysis; deformable mechanisms; method Monte Carlo ; method Coefficients Influence,FASTA.**

## I. GENERAL INTRODUCTION

The use of the assemblies based on the deformable components has become more and common in the industrial sector. The choice of the tolerances at the level of the conception is a very important step in order to realize the assemblies that respond to the functional demands.

Many cases of the assemblies of the flexible components are met in the aeronautic and automobile sectors. A mechanic product is a needed supply and it has to fill up particular functions. In this case, the tolerances of the individual components play a crucial role in the final shape of the assembly because in the flexible assemblies the accumulation of the dimensional variations, may lead to the non-conformist part.

The tolerance analysis is an estimation process of the propagation of the fabrication tolerance and of the arrangement in an assembly. Because of the dimensional and geometric variations in the fabrication and because of the deforms produced at the moment of the assembly, an analysis prior to the tolerances turns out to be essential to estimate the accumulation of the tolerances and ,thus, avoid the failures due to the propagation of tolerances and the non- feasibilityof the assemblies. The most recent process of the fabrication and the present demands in the aeronautic and automobile settinghas obliged industries to maximize their production respecting the principle function of price. Because of the competitiveness, the industries have resorted to the use of the composite materials, which impose limits of the constraints and flexibility of the components.

Because of the shape of the components, the prototyping and the analysis methods of the rigid assemblies, is no longer valid to predict the variations of the components as well as their assemblyto respond to this problematic, many methods have been developed in order to overcome this phenomenon of flexibility. Usually these are based on the analysis approach by the finite element (FEA).the researchers have developed a method named Coefficients Influence [1], the objective of which is to stimulate the assembly variation taking into account the sources of the variation and find out the relationship between the variation of each component and their assembly with the help of a matrix called Sensibility Matrix. Likewise, there are other works, which are interested in a method called FASTA(flexible assemblies of statistical tolerance analysis) [2] [3] that allows statistically prediction of theassembly variations with the use of experimental measures.

Generally, there are several works in the literature of the domain tolerancing non-rigid parts, the last of them are summed upin four principal axes, the first is adaptation modelization, definition of geometric variability, the choice of the boosting of a strategy in order to analyse the tolerancing and finally the simulation assembly. The aim of all the work is summarized in the following diagram (figure1).

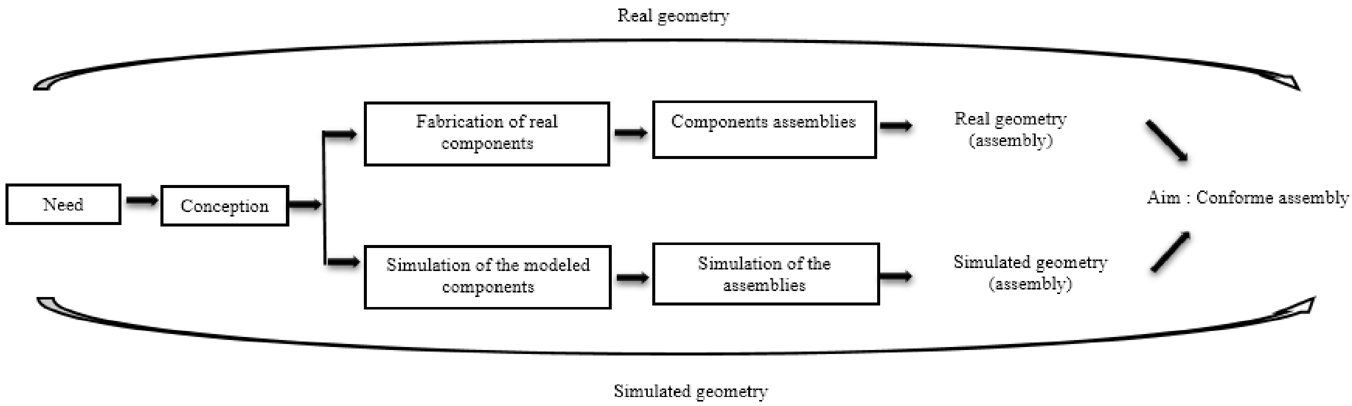


Figure 1. Validation de performance par simulation

## II. LITERATURE REVIEW

The first work on the tolerancing of non-rigid part;has began around with [4] who carried out outan analysis of vibration mode in order to predict the residual deformations and deformations induced by misalignment of holes of the passage of thefixations of the flexible parts. The principal axes around which the research works pivots are:

-Modelization,

-The Definition of geometric variability,

- The choice and the boosting of a strategy to analyze tolerances and,

- The simulating of the assembly.

The following paragraphs explain and site the different works that exists ineach of the axes of the research.

### *A. Modélisations*

Modelization is a delicate issue because of all local appearance phenomena. Moreover, it is the first step in the analysis tolerancing that necessitates a clear definition of the characteristics of variations. At this level of work are carried out to find out the mathematical definitions as well as geometric ones. The most common used model is the finite element model with structure beam elements type [5], then in [6] [7] [8] and in the elaboration a finite element model of the sheets or shells specific to tolerancing. Thereafter in [5] an simplified model interestedin the assembly structure has beensuggested for dimensional control, finally [7] [8] and [9] taking into account unilateral contact interactions between the parts in the areas of recovery.

### *B. Definition of the geometric variability*

The authors interested atthe study of the the effect of the geometric variability on assemblies of non-rigid parts. In fact, the aim of this work was to introduce the dimensional variability of automotive structures by identifying their causes.

We have dissociated two types of defaults: the default of the location of the holes in the passage, and the default of the shape part.

The notion of the skin-model [11] is no more thana presentation where in the geometry is not ideal, the difficulty is then to confirm that the obtained forms [8] [2] [12]are in accepted margin, after this astudy taking into account the variability of rigidity which flow the defaults of the form[6].

Vectors have modeled the geometric variability by characteristic the defects position and orientation of the connection points of the liaison [13] [14]. The nature of the parts of the automotive structural and complexity have pouched them to use finite element models, but without addressing the issues of modeling [15] [16].

### C. *Strategy of the analysis of the flexible assembly and assembly simulation*

The strategy of the analysis is a very variation analysis and a very important step for the industry or in the manufacturing phase or parts, hereof plastic deformation and aspring back that can generates skin model form. Subsequently when these parts are assembled variations in materials strongly influence the final shape of the assembly. This is to predict these variations more analysis strategies have been proposed, we integrated ranked by the work of the authors in two major areas of research strategy: a linear analysis and nonlinear analysis.

- The Linear analysis of the flexible assemblies:

For the analysis of assemblies of the flexible parts, the researchers have suggested in recent years, interesting methods, which it mainly based on the method of finite elements.

The most frequently used strategy in the literature is the Influence Coefficientsmethod that addresses the hypothesis of the global linearization assumption of the problem [1]. This methodology, which has been proposed by Liu and Hu, is based on the concept of Matrix Sensitivity, this method that seek a relationship between deviations of parts and springback of the assembly, thereafter two studies finite elements studies are necessary, the first for the responses of the parts to unit forces the other to the spring back of all.

The method has been developed for the tolerancing of flexible parts, it is to express the interestquantities which we note αj as the sum of the products of each contributor noted that δi and influence coefficients cij determined by assembly simulations. Equation (1) show this approximation by in indexed and matrix notation.

$$\alpha_j = \sum_{i=1}^{N} C_{ij}\,\delta_i \quad (1)$$

The principle of the influence coefficients method is to establish a linear relationship between the gap of the parts and the springback of the assembling, these could explain how a force / displacement on a particular point, could affect the other points. These linear models are subsequently used in a Monte Carlo simulation. This procedure include three steps:

1. Force / displacement response: A unit forcethat is applied in the source of the variation (j = 1 to N) on the sheet. The direction of the force is the same as the variation. The finite element method could be used to figure out the response of the sheet under the force. The deformation to N sources of variation is registered under the columns. If the system is linear, we can say that the system is obtained by the combination of N arbitrary force F_j (j = 1 to N), hence the total displacements of the system will be combinations of the following equation:

$$\{V\} = \sum_{j=1}^{N} \begin{Bmatrix} c_{1j} \\ c_{2j} \\ \vdots \\ \vdots \\ c_{Nj} \end{Bmatrix} F_j$$

$$= \begin{bmatrix} c_{11} & \cdots & c_{1N} \\ \vdots & \ddots & \vdots \\ c_{N1} & \cdots & c_{NN} \end{bmatrix} \begin{Bmatrix} F_1 \\ \vdots \\ F_N \end{Bmatrix} = [C]\{F\} \quad (2)$$

$[C]$Is the matrix of influence coefficients that is symmetrical, according the Theorem Betti.

2 . The matrix could be reversed:

$$\{F\}=[C]^{-1}\{V\}=[K]\{V\} \ (3)$$

$[K]$ The Matrix Stiffness, the equation (3) could be rewritten under the form:

$$\begin{Bmatrix} F_1 \\ F_2 \\ \vdots \\ \vdots \\ F_N \end{Bmatrix} = \sum_{j=1}^{N} \begin{Bmatrix} K_{1j} \\ K_{2j} \\ \vdots \\ \vdots \\ K_{Nj} \end{Bmatrix} V_j \ (4)$$

3. Calculation of the springback: the method FEM is used to calculate the displacements of springback for each node in all directions for assembly. Springback noted in the following vector:

$$\begin{Bmatrix} S_{1j} \\ S_{2j} \\ \vdots \\ S_{Mj} \end{Bmatrix}$$

Or M is the number of nodes, and J (i = 1 to M) the displacements calculated with MEF i-th point due to the variation of the j-th source of variation. The Sij are the sensitivity coefficients. By combining the contributions of all the variation sources, we can write the total springback under the form: $\{U\} = \begin{Bmatrix} U_1 \\ U_2 \\ \vdots \\ \vdots \\ U_M \end{Bmatrix} = \sum_{j=1}^{N} \begin{Bmatrix} S_{1j} \\ S_{2j} \\ \vdots \\ \vdots \\ S_{Mj} \end{Bmatrix} V_j$

$$= \begin{bmatrix} S_{11} & \cdots & S_{1N} \\ \vdots & \ddots & \vdots \\ S_{N1} & \cdots & S_{NN} \end{bmatrix} \begin{Bmatrix} SV_1 \\ : \\ V_N \end{Bmatrix} = [S]\{V\} (5)$$

Or [S] is the Matrix Sensitivity, and {U} the matrix of the total displacement.

In order to enrich the Influence Coefficients Method and to increase the reliability of the simulation results, an algorithm has been proposed in order to forbid the interpenetration of parts during assembly [7] [17]. Thereafter the method is applied subsequently to the whole of the sheet. This unilateral contact problemtic has been treated before by [18] [19] [20] [21] with the integration of a modelpermit to define points of the contact on which we can apply the support conditions. Therefore in order to manage the unilateral contact in the finite element problems, and specifically in the articles mentionedpreviously, Sellem has developed a method which represents two of the most pertinent sources of variability: the position and geometric deflection of the part in the process of the assembly. A method has been suggested by Merkley [8]. Finally an algorithm of the interesting linear contact has been suggested at once in [7] and [22], by combining a search of the linear contact search and a criterion of the equilibrium contact. Their approaches have been integrated in the method of the influence coefficient proposed by Liu and Hu.

Additionally, the work of Alain [9] [10], that are based principally on the development of the method of influence coefficients, but this time with taking into account the variation of rigidity induced by thedefaults of the form and finally the application on a large structure of the aerospace industry.

Another use of the method is to handle a part of the variation of the tool. It calculates a Matrix of Sensitivity that includes the Influences Coefficients of the whole, and present as vectors [23]. Therefore [24] usesthe method for all steps of the assembly process, in order to observe the propagation s of gap. However, [25] suggesting to identify the defaults of the form of natural modes after the analysis of measures and to express tolerances of each mode. In this way, the random shape defaultcould be easily generated. After that [26] suggeststhe use the fields of the deformation obtained thanks to a simulation on a Finite Element Model. [27] and [28] shows the difficulty of generating random defaults and the realist form on the discretize surfaces. The idea includes the binding of the displacements of is to neighbouring nodes by geometric covariance and finally [29] in another work which treats the problematic of linear analysis of flexible assemblies.

The researchers of the Brigham Young University have developed an approach DLM to the flexible assembly process;And developed as well an approach of the statistical analysisof the tolerancing (FASTA) for the flexible assemblies [3]. FASTA is concentrated mainly on the gap on the interface of coupling. Then,by using an analysis finite element approach, the matrix stiffness of the whole describes the conditions of the gap of the equilibrium assembly is calculated finally.By combining the results of the FEA and statistical data input,the final form assembly could be described in terms of mean and covariance. One of the principal limitations of the FASTA method is the hypothesis that the final state of the deformation is independent from the apparatus such the one suggested in Stewart [30]. Besides, FASTA can be applied only for single stationprocess assembly. The thesis of Bihlmaier [31] complements this work suggesting another description method of the geometric variability based on the spectral analysis. From this representation, we uses the analysis method of the tolerancing,called FASTA. In fact there should be a description of the variability of surface defaults under the form of a discrete spectrum in the frequency domain. This concretelymeans that the gap field of the surface is equivalent to a superposition of sinusoids of different amplitudes and wavelengths. The Matrix Covariance, which characterizes the random default, is deducted spectrum, and fields of the original shuffle marginare, thus randomly generated. The FASTA method is compared to a Monte Carlo.

In order to take account the sequences of the whole, the work of [13] has highlighted the propagation of geometric defaults along with the operations assembly. The work of [32] introduces the concept of the cycle "CPRF" (Square Clamp Fasten and Release), to take into account the sequence of the assembly. The CPRF cycle is subsequently used in many works, which are [6] [24].

Finally the famous method used in the analysis of rigid or flexible tolerancing is method monte carlo method, this term refers to any method to calculate a numeric value using random processes, that is to say technical probabilistic as shown in the following figure (Figure 1):

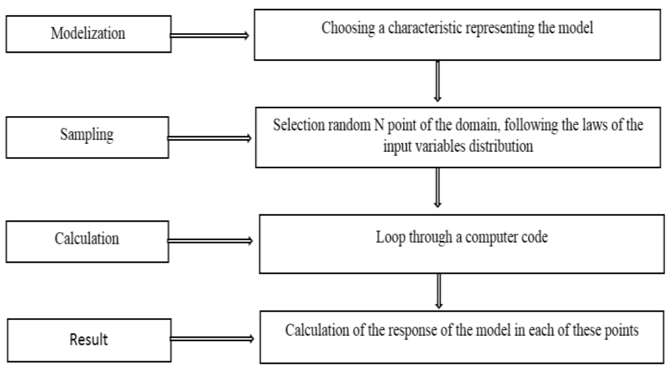


Figure 2. Monte Carlo method

On one hand, the sum cost of a simulation could be very expensive. On the other hand, the analysis of the influence of geometric variations should perform a big number of simulations because the reason of the diversity of possible defaults geometric.

- Non-linear analysis of the flexible assemblies :

The majority of theanalytical work of the tolerancing of the flexible assemblies has been based on the linearization hypothesis of the problem. Therefore,the linear approaches do not yield to exactresults when the big deformation of the parts or the assemblies.

Liao and Xie [33] [34] [35] have displayed how contacts between differing component during the assembly, affect the assembly final form. They have suggested the use of an approach the non-linear finite element to solve the contact problem. We find a party of the non-linear analysis part in the thesis of Alain [10] but he has chosen to make use the Monte Carlo simulation in order to respond to this problematic.

[24] Which treats an assembly case by soldering by points with the help of the successive simulations or the uncertainties of the positioning of the tools compared to the parts are taken into account. [6] Uses PCFR cycle so as to simulate the assembly in two sheets.

## III. COMPARISON

Basing on the previous bibliographicstudy, we have elaborated the Table 1 that represents a comparison of the differentresearch about the field of flexible assembly tolerancing.

Parallel to this research, various contributions have been identified in the area of integration of assistance systems tolerancing (tolerance computer assisted (CAT) or computer aided tolerancing (CAT)) to design tools and computer-aided manufacturing (CAM) and address various problems of tolerancing as the specification and verification.

## IV. CONCLUSION

For the sake of predicting the variation of flexible assembling; many analysis methods of tolerance of deformable mechanisms had been proposed in different article and thesis. The Monte Carlo strategy is the method reference. It is simple to implement but very expensive, this why the method of influence coefficients has been adopted to the models of shape default, and the FASTA method.

This article presents the four-principle axis on which pivot the research work in the domainof the tolerancing of deformable mechanisms: modeling, definition of geometric variability and the analyses approaches of theflexible assemblies and the simulation. Additionally, a comparison among of the different methods used in the research work.

Table 1.the different line of research in the field of tolerancing

*International Journal of Advanced Information Science and Technology (IJAIST)* *ISSN: 2319:2682*
*Vol.5, No.5, May 2016* **DOI:10.15693/ijaist.2016.v5.i5.12-19**

| Research Axis | Solving method | | | Author and year | Principle | Advantage | Disadvantage |
|---|---|---|---|---|---|---|---|
| *Modelization* | _______ | | | (Shiu, 1997)<br>(Franciosa, 2010)<br>(Stricher,2012)<br>(Stricher,2013) | -Modelingintroduced of phenomena local. | - Clarity of characteristics variation.<br>- Mathematics and geometric definitions. | - High cost. |
| *Definition of geometric variability* | _______ | | | (Dantan, 2001)<br>(Zhang, 2012)<br>(Formosa, 2007) | - Study the influence of geometric variability on assemblies. | - Reduce the dimensional variability. | - High cost. |
| *strategy of analysis of the flexible assembly and simulation of the Assembly* | linear analysis | MCI | Single-station Simulation | (Shiu, 1996)<br>(Liu, 1997)<br>(Dahlström, 2007)<br>(Alain 2013) | -Calculus And presentation as vectors the Sensitivity Matrix that contains the Influences Coefficients of the of variations of the assembly.<br>- Relationship between the gaps of parts and springback.<br>- Obtaining of strain fields through simulations. | - Simple implementation.<br>- Application to deformable parts.<br>- Study of linear case.<br>- Calculus time not very important. | - Ignores contact between components. |
| | | | Multi-station Simulation | (Camelio, 2002) | | | |
| | | The method FASTA | | (Stewart, 2004)<br>(Bihlmaier, 1999)<br>(Xie, 2007) | -Average or predicted autospectrum.<br>-Characterization defaults<br>Random with the matrix covariance.<br>-Simule numerically. | - Application to deformable parts.<br>- Study of linear case.<br>- Calculation time not very important. | - The difficulty to include direct statistical analysis Non-linearity in the model.<br>- Takes a lot of time of computing. |
| | | MMC | | (Liu, 1997)<br>(Alain 2013) | - Random sampling distributions.<br>- Simulate numerically. | - Implementation simplicity.<br>- Applied to deformable parts.<br>- Accurate for important N.<br>- Application with any law. | - Number of iterations N important.<br>- Takes a lot of time of computing. |
| | | MEF | | (Liu, 1997) | - Modeling using a finite element model.<br>- Calculation of deformations, forces and constraints. | -Applied to the deformable parts. | - Insufficient for the analysis of flexible assemblies. |
| | Nonlinear Analysis | MEF | | (Liao, 2007)<br>(Xie, 2007) | - Modeling using a finite element model.<br>- Calculation of deformations, forces and constraints. | - Applied to deformable parts.<br>- Study nonlinear case | - Takes a lot of time of computing. |
| *computer aided tolerance (TAO)* | | CATIA tolerancing | | (Germain,2007) | - Specify and verify tolerances. | - Integration of the tool of CFAO CATIA | - Tolerances as annotations in model of CFAO. |

## References

[1] Liu, S. C., and Hu, J. S., 1997, "Variation Simulation for Deformable Sheet Metal Assemblies Using Finite Element Methods," J. Manuf. Sci. Eng.,119,pp. 368–374.

[2] Bihlmaier, B. (1999). Tolerance Analysis of Flexible Assemblies Using Finite Element and Spectral Analysis. Master thesis, Brigham Young University.

[3] Mortensen, A. J., 2002, An Integrated Methodology for Statistical Tolerance Analysis of Flexible Assemblies, MS Thesis, Brigham Young University, Utah.

[4] Gordis, J. H. et Flannelly, W. G. (1994). Analysis of stress due to fastener tolerance in assembled components. AIAA journal, 32(12):2440–2446.

[5] Shiu, B., Ceglarek, D. et Shi, J. (1997). Flexible beam-based modeling of sheet metal assembly for dimensional control. TRANSACTIONS-NORTH AMERICAN MANUFACTURING RESEARCH INSTITUTION OF SME, XXV:49–54.

[6] Franciosa, P., Gerbino, S. et Patalano, S. (2010). Simulation of variational compliant assemblies with shape errors based on morphing mesh approach. The International Journal of Advanced Manufacturing Technology, 53(1-4):47–61.

[7] Dahlström, S.,Lindkvist, L,2007,"Variation Simulation of Sheet Metal Assemblies Using the Method of Influence Coefficients With Contact Modeling " Proceedings 2003 ASME International Mechanical Engineering Congress and Exposition, Washington, D.L., pp. 615–622.june 2007.

[8] Merkley, K. G. (1998). Tolerance analysis of compliant assemblies. Thèse de doctorat, Brigham Young University.

[9] Stricher, A., Champaney, L., Thi ´ ebaut, F., Fricero, B.,and Chevassus, N., 2012. "Tolerance analysis of compliant assemblies using fem simulations and modal description of shape defects". In Proceedings of the ASME 2012 11th Biennial Conference on Engineering Systems Design and Analysis, Nantes, ASME, ed., no. ESDA2012-83002,pp. 307–314.

[10] Stricher .A, "Tolérancement flexible d'assemblages de grandes structures aéronautiques," École normale supérieure de Cachan - ENS Cachan, 2013.

[11] Dantan, J.-Y., Ballu, A. et Mathieu, L. (2001). Expression des spécifications géométriques des produits - Classification des éléments géométriques. In Journée thématique PRIMECA, pages 69–78, Aix-en-Provence, France.

[12] Zhang, M. (2012). Discrete Shape Modeling for Geometrical Product Specifications :Contributions and Applications to Skin Model Simulation. Thèse de doctorat,ENS Cachan.

[13] Ceglarek, D. et Shi, J. (1995). Dimensional variation reduction for automotive body assembly. Manufacturing Review, 8(2):139–154.

[14] Ceglarek, D. et Shi, J. (1996). Fixture Failure Diagnosis for Autobody Assembly Using Pattern Recognition. Journal of Engineering for Industry, 118(1):55.

[15] Ceglarek, D. et Shi, J. (1997). Tolerance analysis for sheet metal assembly using a beam-based model. Journal of Engineering for Industry, (c).Chang, M. et Gossard, D. (1997). Modeling the assembly of compliant, non-ideal parts. Computer-Aided Design, 29(10):701–708.

[16] Formosa, F. et Samper, S. (2007). Modal Expression of form defects,

[17] Dahlström, S., and Camelio, J. A., 2003, "Fixture Design Methodology for Sheet Metal Assembly Using Computer Simulations," Proceedings 2003ASME International Mechanical Engineering Congress and Exposition, Washington, D.C., November 15–21.

[18] Sellem, E. et Gyomard, K. (2000). Outil CATIA pour l'analyse de tolérances des assemblages déformables. Revue internationale de CFAO et d'informatique graphique, 18(1):123–131.

[19] Sellem, E., Rivière, A., 1998, Tolerance Analysis of Deformable Assemblies, Proc. of DETC98, ASME Design Engineering Technical Conference, Atlanta GA.

[20] Sellem, E., Riviére, A., Hillerin, C. A. D., Clement, A., 1999, Validation of the Tolerance Analysis of Compliant Assemblies, ASME Design Engineering Technical Conference, Las Vegas, Nevada, September 12-15.

[21] Sellem, E., Sellakh, R., and Riviére, A., 2001, Testing of Tolerance Analysis Module for Industrial Interest, Proc. of 7th CIRP Int. Seminar on Computer Aided Tolerancing, ENS de Cachan, France, April 24-25

[22] Ungemach, G., Mantwill, F., 2009, Efficient Consideration of Contact in Compliant Assembly Variation Analysis, ASME Journal of Manufacturing Science and Engineering, Vol. 131, pp. 1-9.

[23] Camelio, J. A., Hu, S. J., and Ceglarek, D., 2004. "Impact of fixture design on sheet metal assembly variation".Journal of Manufacturing Systems, 23(3), pp. 182–193.

[24] Camelio, J. A., Hu, S. J., and Ceglarek, D., 2003. "Modeling Variation Propagation of Multi-Station Assembly Systems With Compliant Parts". Journal of Mechanical Design, 125(4), pp. 673–681.

[25] Samper, S., and Formosa, F., 2007. "Form Defects Tolerancing by Natural Modes Analysis". Journal of Computing and Information Science in Engineering, 7(1), p. 44.

[26] Breteau, P., Thiebaut, F., Bourdet, P., and Falgarone, H.,2007. "Assembly simulation of flexible parts through the fitting of linkage devices". In Proc. of the 10 th CIRP Int.Sem. on Computer Aided Tolerancing.

[27] Zhang, M., Anwer, N., and Mathieu, L., 2010. "Discrete Geometry for Product Specification and Verification". In IDMME - Virtual Concept, pp. 2–4.

[28] Zhang, M., Anwer, N., Mathieu, L., and Zhao, H., 2011."A Discrete Geometry Framework for Geometrical Product Specifications". In Interdisciplinary Design: Proceedings of the 21st CIRP Design Conference, no. section 2.

[29] Long, Y., Hu, S. J., 1998, A Unified Model for Variation Simulation of Sheet Metal Assemblies, Geometric Design Tolerancing: Theories, Standards and Applications, Dr. Hoda A. ElMaraghy, Chapman and Hall.

[30] Stewart, L. M., 2004, Variation Simulation of Fixtured Assembly Processes for Compliant Structuresusing Piecewise-Linear Analysis, PHD Dissertation, Brigham Young University, Utah.

[31] Bihlmaier, B. (1999). Tolerance Analysis of Flexible Assemblies Using Finite Element and Spectral Analysis. Master thesis, Brigham Young University.

[32] Chang, M., Gossard, D. C., 1997, Modeling the Assembly of Compliant, non-Ideal Parts, Computer-Aided Design, Vol. 29, p. 701-708.

[33] Xie, K., Wells L., Camelio J. A., Youn, B. D., 2007, Variation Propagation Analysis on Compliant Assemblies Considering Contact Interaction, ASME Journal of Manufacturing Science and Engineering, Vol. 129, pp. 934-942

[34] Liao, X., Wang, G. G., 2007, Non-linear Dimensional Variation Analysis for Sheet Metal Assemblies by Contact Modeling, Finite Elements in Analysis and Design, Vol. 44, pp. 34-44.

[35] Cai, W., Hsieh, C. C., Long,Y., Marin, S. P., Oh, K. P., 2006, Digital Panel Assembly Methodologies and Applications for Compliant Sheet Components, ASME Journal of Manufacturing Science and Engineering, Vol. 128, pp. 270-279.

[36] Germain.f,2007, tolerance statistique tridimensionnel,intégration en CFAO,thése de doctorat, Universuté de savoie, Annecy,Octobre 2007.

**Authors Profile**

**Hafsa Atik :** PhD student in Mechanics Engineering from The University sidi mohamed ben abdelah, of Department of Mechanical and Production Engineering and Industrial Maintenance at the School of Technology, fez,Atik received her Master degree in Mechanics Engineering from The University sidi mohamed ben abdelah, fez, in 2014. Her areas of research include Tolerancing, tolerance analysis, optimization of tolerances in rigid and flexible mechanisms.

**Mouhssine Chahbouni :**received his PhD degree in Mechanics Engineering from The University sidi mohamed ben abdelah, fez, in 2016. Dr. Chahbouni received his Engineering Degree in Industrial Engineering from National School of Applied Sciences of Fez (ENSA - Fez),Maroc, in. Currently, Dr. Chahbouni is a Research professor working as Professor ofmechanic of Department of Mechanical and Production Engineering and Industrial Maintenance at the School of Technology, fez. His areas of research include Tolerancing, tolerance analysis, optimization of tolerances in rigid and flexible mechanisms.

**Driss Amegouz :** received his PhD degree in Mechanics Engineering from The University sidi mohamed ben abdelah, fez, in 2002. Dr. Amegouz received his Diploma Engineer in Production Systemfrom National School of Engineers of Metz ,France, in. Currently, Dr. Amegouz is a Research professor (Grade PES) in the Department of Department of Mechanical and Production Engineering and Industrial Maintenance at the School of Technology, fez. His areas of research include Tolerancing, tolerance analysis, optimization of tolerances in rigid and flexible mechanisms.

**Said Boutahari :**received his PhD degree in Mechanics Engineering from The University sidi mohamed ben abdelah, fez, in 2007. Dr. Boutahari received his Diploma Engineer from the National School of Mineral Industry (ENIM),Maroc, in. Currently, Dr. Boutahari is a Research professor (Grade qualified teacher) in the Department of Department of Mechanical and Production Engineering and Industrial Maintenance at the School of Technology, fez. His areas of research include Tolerancing, tolerance analysis, optimization of tolerances in rigid and flexible mechanisms.