Optimization of Machining Tolerances by the Goal Programming Method under the Six Sigma Constraint

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Abstract - *In this paper, a new approach has been developed for optimizing manufacturing tolerances under the Six Sigma constraints. The principle of this approach is based on the goal programming method. In the first step, an experimental study was presented on the impact of tool wear defects, tool path defects and positioning defects on manufacturing tolerances. In the second step, the goal programming method was used to optimize manufacturing tolerances. A comparative study was presented to validate these results.*

Keywords - *Optimization, Modeling, Manufacturing Tolerances, Errors, Six Sigma*

I. INTRODUCTION

Despite the observed development in machining precision, geometric deviation still a big problems often encounter during machining caused by many errors sources for instance: tool deflection, vibration, wear of cutting tool and thermal errors; many research paper are investigated and published in the field of characterizations of these errors to describe them mathematically by several methods and material, Karoly Szipka et al proposed a new methodology to determine the machine tool errors under quasi-static condition by combination direct measurement modeling to determine axis machine errors and indirect measurement modeling to determine static stiffness variation in the workspace of machine tool [1].Suk-Hwan Suh et al present an error modelization for rotary table of five axis machine tool using HTM Homogeneous Transformation Matrices' and a method for error compensation [2].Tae-Il Seo and Myeong-Woo Cho presented a tool path methodology to compensate tool deflection effect which are determined by two methods, Finite element method (FEM) and cantilever beam model [3]. Moez Smaoui et al determined the amount of cutting tool deflection by means of FEM which is chosen after a comparison was done between two methods, Analytical method (AM) and FEM method with experimental result; the deflection model was given according to the cutting forces in three direction X, Y and Z [4].Wenkui Ma et al presented a new method for compensation of the tool deflection error caused by cutting forces in five-axis ball-end milling of sculptured surface based on mirror image method [5].Rahou Mohamed et al studied machining errors effects and by using Lagrange method and give a modelization of systematic dispersion and random dispersion [6].Rahou Mohamed et al inspected the influence of the systematic dispersion and proposed a model for these errors according to the machined length [7].J. C. Liang et al proposed a method for errors compensation in real time on a turning center, these errors are geometric, thermal and cutting forces induced errors, the models are fitted based on the data obtained by different sensors used [8].A. W. Khan and W. Chen proposed a method for systematic geometric errors compensation in five axis machine tools, the developed technique is based on the table errors, which are modeled by using HTM, then removing the machine errors and reproducing new NC code [9].Y. Zhang et al proposed an geometric errors compensation approach for five axis machine tool with rotary table, the errors measurement was done by double ball bar (DBB) as the measuring instrument is the newest in this paper, which can identified 5 geometric errors [10].J. Wang et al presented a modelization and compensation of thermal errors for nano positioning systems, by using genetic algorithm (GA) a model was given to describe the relationship between temperature and deviation, a system for compensation of these errors is applied [11].Y. X. Li et al based on grey system theory investigated and optimized thermal sensors placement on machine tools to select the most decisive temperature measuring points; for predicting a thermal error model with less variables and more effective [12].H. Zhang et al proposed a sequential step diagonal measurement method to assess volumetric positioning errors, within different thermal constraints to determine the relation between them; the predicted errors by radial basis function neural network are apply for the correction method [13].K. Fan et al presented an error model for compensation the thermal errors in CNC machine, this model describe the geometric errors caused by each axis, geometric errors induced thermally and spindle thermal errors; based on the orthogonal polynomials this model was establish; the total thermal errors are calculated based on this model then transferred to the machine CNC system to rectify the tool position [14].S. M. Wang et al presented an novel approach for error prediction and compensation with non-rigid body condition based on an interpolation scheme that uses three dimensional shape functions to predict tool errors for multi axis machines, the errors predicted are incorporated on a software-compensation program, to correct the cutting trajectory [15].S. M. Wang et al developed an approach for static and quasi static error compensation taking into account the non-rigid machine body condition; where the new error prediction method are based on the element free interpolation method; the predicted errors are used to correct the cutting trajectory by using recursive error compensation software established [16].Ali M. Abdulshahed et al proposed an approach for thermal errors compensation, two thermal errors models are constructed by combination an adaptive neuro fuzzy inference system (ANFIS)with the fuzzy c-means clustering method and ANFIS with grid-partitioning, to build a relationship between thermal errors and temperature [17]. M. Wąsik., and A. Kolka presented an approach for accuracy improvement concerned five axis machining centers; by applying special adjustment procedures and additional workpiece distortion compensations [18].Xaver Thiem et al presented a method for thermal induced motion errors correction in real time by using the thermal and thermo-elastic models [19].R. Ramesh et al discussed in the first review different sources errors which are categorized in three groups 'geometric and kinematic errors, thermal induced errors and cutting force induced errors'; then error compensation methodology is given; after different compensation approach developed for accuracy improving and deleting these errors for geometric / kinematic errors and cutting force induced; in the second paper presented a review of thermal induced errors modelization, estimation and compensation [20]. Hui liu et al studied the thermal errors on CNC machine tool under different conditions, where the thermal error prediction model is established by using the ridge regression algorithm and an compensation of these errors was done by applying this method [21].Kuo Liu et al studied spindle radial thermal drift error (RTDE)for vertical machining center, under various rotating speeds; a novel RTDE modelization method was developed for various thermal postures, and compensation method was presented [22]. Yang li et al presented an review of spindle thermal errors compensation, the spindle thermal errors was examined, various methods for modeling and compensation of thermal errors was presented and discussed, different various approaches of selecting thermal key points was presented also [23].C. Zhang et al studied the thermal errors due to environmental temperature variation, the thermal error transfer function of the machine obtained by using heat transfer mechanism was used to develop a thermal error model [24].Josef Mayr et al presented an review of thermal errors of machine tools and machining center, in particularly turning and milling machines; discussed also measurement of temperatures and displacements of tool center point, thermal errors calculation and diminution [25].Scott W. Doebling presented a review of technique according to different criterion to investigate the destruction in mechanical and structural systems caused by vibration; vibration-based damage identification in general term [26].Jean-Marc Linares et al verified the machine tools compensation accuracy by utilizing racking interferometers with multilateration,the geometrical errors of the same machine tool were measured with the same equipment in different institution with five different strategies [27].Dong dong Kong et al presented a new tool wear assessment technique, based on Gaussian process regression (GPR)model the tool wear predictive value and the confidence interval was determined; the integrated radial basis function based kernel principal component analysis (KPCA_IRBF) is used to improve the status of the confidence interval of the GPR model [28].Pankaj Kumar Sahu presented a review of various models used to determine tool life; these methods were based on the vibration signal, and determine which method is the best [29].M. Binder et al developed a method for tool wear simulation in metal cutting; based on finite element simulation of chip formation, steady state condition and the local thermo-mechanical load spectrum in the tool were determined; by using the tool wear equation, the load spectrum was used to compute local tool wear rate [30]. Jie Gu et al presented a new methodology for global offset error compensation by using measurements of the workpiece; it evaluates the offsets to compensate the machine tool errors [31].H. J. Pahk and S. W. Lee developed a measurement and compensation in real time system for spindle thermal errors and feed axis thermal errors; three different methods are used for modeling thermal errors are multiple linear regression, neural network, and system identification, and compared between them [32].P.-C. Tseng and J.-L. Ho studied thermal errors at a FANUC turning center, and established a relationships models between the temperature and geometric errors based on linear and nonlinear regression analysis, then a comparison is done and an real time compensation method is developed [33].G. Fu et al presented a new automatic modeling of single geometric error component based on F test and error compensation in five axis machine; a polynomial model for geometric errors was given and F test was used to determine the polynomials degree; an geometric error compensation method was developed based on limiting ideal tool positions [34].

II. MANUFACTURING ERRORS DISTRIBUTION

Several experiments show that the distribution of the manufacturing error follows a normal law (Gaussian law) [38], Fig. 1, its expression is as follows:

$$F(x)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right) \tag{1}$$

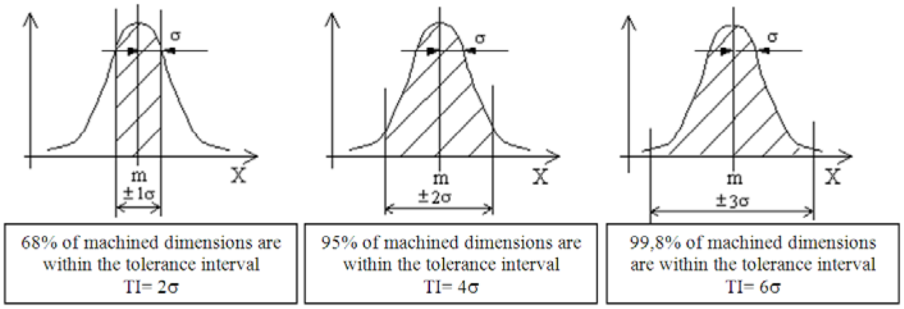

Fig 1: Distribution of Manufacturing Errors

This law is characterized by X (average) and σ (standard deviation).

$$\sigma(x)=\sqrt{\sum_{i=1}^{N}\frac{n_i}{N}(x_i-\bar{x})^2} \tag{2}$$

III.GOAL PROGRAMMING METHOD

Goal Programming (GP) is perhaps the oldest approach within the field of MCDM. GP first appeared in the fifties to obtain “constrained regression” estimates for an executive compensation problem (Charnes, Cooper & Ferguson, 1955) [36]. The overall purpose of GP is the simultaneous satisfaction of several goals relevant to the decision making problem under consideration.

The first step in the formulation of a GP model is the establishment of a set of attributes to be considered in the problem situation. Once the set of attributes is established, it is necessary to determine the target value b, i.e. the achievement level desired for each attribute. Whether this level is to be satisfied exactly, surpassed or be short of it should be indicated. Briefly, the first step in the formulation of a GP model thus consists in establishing the set of goals as a combination of each attribute with its corresponding target.

IV. PROBLEM FORMULATION

The general principle of this study is to apply GP to the manufacturing errors models.

Let suppose that we have n models of manufacturing errors sources,fn $= \{f_1, f_2, \dots, f_n\}$ the sum of these errors must be inferior or equal of the manufacturing tolerance fixed by design office, which allows us to write equation (3) and (4) .

$$X^{\pm IT/2} = X_j - X_i = X + \sum_{k=1}^{n} f_q \tag{3}$$

That’s mean:

$$\sum_{k=1}^{n} f_q \le IT \tag{4}$$

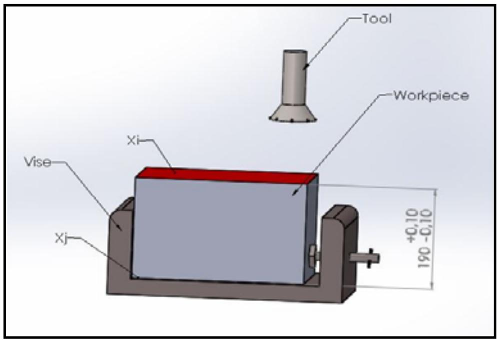

Fig 2: Face Milling Operation

The tolerance value fixed by design office will be divided on these models, taken into account the contribution of every error source percentage on the total error; Now each model have a target level, which is denotedb_q, and an achieved value $f_q(x)$,on its underlying criterion; this lead us to the basic formulation (equation (5)).

$$f_q(x) + \sigma^-{}_q - \sigma^+{}_q = b_q; \quad q = 1, \dots, n. \tag{5}$$

Where δq^- and δq^+ are the negative and positive deviational variable respectively, they represents the level by which the target level is under-achieved or over-achieved respectively, The two deviational variables are compelled to take positive values and both cannot take a non-zero value simultaneously[37].

The next step is to determine the unwanted deviational variable; in this case the positive deviational variables are unwanted, because any positive deviation above the goals level will give us a manufacturing tolerance superior than that fixed by design office so the requirement will not be fulfilled.

Finally, the unwanted deviational variables will be gathered in the form of a fulfilment function, to minimize them. The above considerations allow us to write the algebraic form of the GP (equation. (6)).

$$min\ (w_1 * \delta_1{}^+ + w_2 * \delta_2{}^+ + \dots + w_n * \delta^+{}_n)$$

Subject to

$$f_q(x) + \sigma^-{}_q - \sigma^+{}_q = b_q;$$
$$\sigma^-{}_q, \sigma^+{}_q \geq 0; \tag{6}$$
$$q = 1,2, \dots, n;$$

w Are the preferential weights, which are used to model the relative importance of the minimization of the associated deviational variable to the decision maker [37].

V. APPLICATIONS

For this study we give two examples in order to determine the goals, the first example is dedicated to making a shoulder with a manufacturing tolerance of 0.2 µm (Fig. 3).

By assuming that all the goals have the same importance, which means all the goals have the same weight (w = 1).

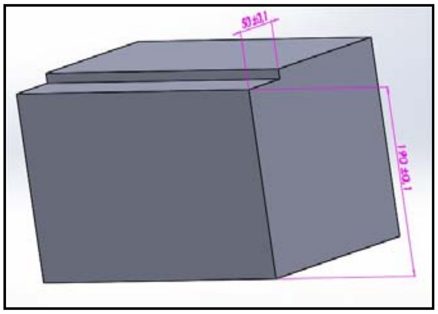

Fig 3: Shoulder milling

The equation given by G. Fu et al 2017 [35], which describe the geometric errors we suppose that's equal to the 50% of manufacturing tolerance (equation (7)).

$$3.440 * 10^{-2} x_1 + 5.977 * 10^{-5} x_1^2 - 1.955 * 10^{-7} x_1^3 + \delta_1^- - \delta_1^+ = 0.1 \qquad (7)$$

The goal here is to find x_1 so that the achieved value must be inferior or equal to the desire value; so $\delta_1^+$is the unwanted deviation away from the target 0.1.
M. Rahouet al 2017[6], determined the amount of systematic dispersion which is equal to 10% of manufacturing tolerance; which lead us to write (equation (8)).

$$2.4 * 10^{-4} + 0.8 * 10^{-5} x_2 + 7.2 * 10^{-4} x_2^2 + \delta_2^- - \delta_2^+ = 0.02 \qquad (8)$$

The goal here is to find x_2 so that the function must be inferior or equal to the goal;$\delta_2^+$is the unwanted deviation away from the target 0.02.
For thermally induced geometric errors we suppose for example that is equal to 40% of manufacturing tolerance; which give us (equation (9)).

$$0.0441\, x_3 - 6.5198 + \delta_3^- - \delta_3^+ = 0.08 \qquad (9)$$

The goal here is to find x3 so that the function must be inferior or equal to the goal;$\delta_3^+$is the unwanted deviation away from the target 0.08;
δ^- : Negative deviational variable;
δ^+ : Positive deviational variable;
$\delta^- * \delta^+ = 0$
$\delta^-, \delta^+ \geq 0$
Our task consists is minimizing the deviations that viol the manufacturing tolerance; so the GP problem formulation is (equation (10)):

$$min\ (w_1 * \delta_1^+ + w_2 * \delta_2^+ + w_3 * \delta_3^+)$$

Subject to:

$$\begin{aligned} &3.440 * 10^{-2} x_1 + 5.977 * 10^{-5} x_1^2 - 1.955 * 10^{-7} x_1^3 + \delta_1^- - \delta_1^+ = 0.1 \\ &2.4 * 10^{-4} + 0.8 * 10^{-5} x_2 + 7.2 * 10^{-4} x_2^2 + \delta_2^- - \delta_2^+ = 0.02 \\ &0.0441\, x_3 - 6.5198 + \delta_3^- - \delta_3^+ = 0.08 \end{aligned} \qquad (10)$$

$$\delta^- * \delta^+ = 0;\ i = 1, 2, 3.$$

For the second example; a piercing operation of diameter Ø40 mm realized (Fig. 4).

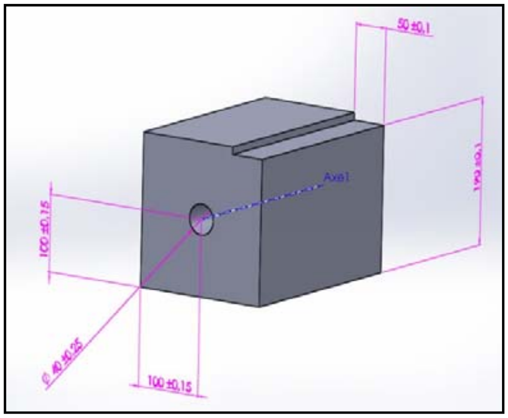

Fig 4: piercing operation

The same steps of the first example are followed; the manufacturing tolerance in this example is 0.3 µm which lead us to write the next GP problem formulation (equation (11)).

$$min\ (w_1 * \delta_1{}^{+} + w_2 * \delta_2{}^{+} + w_3 * \delta_3{}^{+})$$

Subject to:

$$\begin{aligned}
&3.440 * 10^{-2} x_1 + 5.977 * 10^{-5} x_1{}^2 - 1.955 * 10^{-7} x_1{}^3 + \delta_1{}^{-} - \delta_1{}^{+} = 0.15 \\
&2.4 * 10^{-4} + 0.8 * 10^{-5} x_2 + 7.2 * 10^{-4} x_2{}^2 + \delta_2{}^{-} - \delta_2{}^{+} = 0.03 \\
&0.0441\, x_3 - 6.5198 + \delta_3{}^{-} - \delta_3{}^{+} = 0.12
\end{aligned} \qquad (11)$$

$$\delta^{-} * \delta^{+} = 0;\ \ i = 1, 2, 3.$$

VI. RESULT AND DISCUSSION

For the manufacturing tolerance required in the first example, we found that:

$x_1 = 1.193950$
$\delta_1{}^{-} = 0.05884333$
$\delta_1{}^{+} = 0$

$$f_1(x_1) = 0{,}04115667 \leq 0.1 \qquad (12)$$

The positive deviation is null$\delta_1{}^{+} = 0$, mean that the model of geometric error is feasible for this example; we can see that too by replacing x_1 in the model (equation (12)), the achieved value which are the geometric errors are inferior to the target.

$x_2 = 1.232397$
$\delta_2{}^{-} = 0.01865661$
$\delta_2{}^{+} = 0$

$$f_2(x_2) = 0{,}00134339 \leq 0.02 \qquad (13)$$

That's mean the equation of tool wear or systematic dispersions is satisfied because we have a positive deviation $\delta_2{}^{+}$null;we can see that the target is superior than that achieved value (tool wear error)by replacing x_2 in the model (equation (13)).

$x_3 = 1.234568$
$\delta_3{}^{-} = 6.545356$
$\delta_3{}^{+} = 0$

$$f_3(x_3) = 0{,}0800004488 \cong 0.08 \qquad (14)$$

That's mean the equation of thermally induced errors is satisfied because we have a positive deviation δ_3^+null;we can see that the target is equal to the value founded by replacing x_3 in the model (equation (14)) which are the errors induced thermally.
Finally, and for verification of this method, the some of these three errors models must be inferior to the tolerance of manufacturing fixed by design office which is equal to 0.2µm (equation (15)):

$$\sum_{1}^{3} f(x) = 0{,}1225005088 \leq 0.2 \tag{15}$$

For the second example, we found that:
$x_1 = 1.195676$
$\delta_1^- = 0.1087837$
$\delta_1^+ = 0$

$$f_1(x_1) = 0{,}0412163 \leq 0.15 \tag{1}$$

The positive deviation is null$\delta_1^+ = 0$, mean that the model of geometric error is satisfied; we can see that too by replacing x_1 in the model (equation (16)), the achieved value which are the geometric errors are inferior to the target.
$x_2 = 1.232415$
$\delta_2^- = 0.02865657$
$\delta_2^+ = 0$

$$f_2(x_2) = 0{,}09134343 \leq 0.03 \tag{17}$$

That's mean the equation of tool wear or systematic dispersions is satisfied because we have a positive deviation δ_2^+null; we can see that the target is superior than that achieved value (tool wear error) by replacing x_2 in the model (equation (17)).
$x_3 = 1.234568$
$\delta_3^- = 6.585356$
$\delta_3^+ = 0$

$$f_3(x_3) = 0{,}1200004488 \cong 0.12 \tag{18}$$

That's mean the equation of thermally induced errors is satisfied because we have a positive deviation δ_3^+ null; we can see that the target is equal to the value founded by replacing x_3 in the model (equation (18)) which are the errors induced thermally.
Finally, and for verification of this method, the some of these three errors models must be inferior to the tolerance of manufacturing fixed by design office which is equal to 0.3 µm (equation (19)).

$$\sum_{1}^{3} f(x) = 0{,}25255973 \leq 0.3 \tag{19}$$

According to the result of the two examples, we conclude that all the goals have been attaint, and the manufacturing tolerance is satisfied.

This method can be used in the design office, if the models of all the errors are known; the manufacturing tolerance can be fixed so that all the parts will be conforming to the requirement.

VII. CONCLUSION

We have combined several models for manufacturing errors, and by applying goal programming method, an optimization technique for manufacturing tolerances is presented. Two examples have been studied; the results show that all the goals fixed in the application have been fulfilled, and these models can represent all the errors sources considered in this study. We note also that the tolerance value have been minimized about 30% in the first example and 16% in the second example according to the models used in this study. Finally this method can be used to determine the value of tolerance so that all the workpiece will be conform to the requirement, if the models of all the errors are known.

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