Tolerance analysis in manufacturing using the MMP
Comparison and evaluation of three different approaches

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Abstract
In previous works, the authors have developed the Model of Manufactured Part (MMP) [1], a method for modeling the different geometrical deviation impacts on the part produced (error stack-up) in a multi-stage machining process. They also proposed different solution techniques to identify the worst case for the purpose of tolerance analysis. The first proposed solution technique consists of optimization techniques as Sequential Quadratic Programming (SQP) or Genetic Algorithm (GA) [2]. The second one combines the MMP and the Jacobian-Torsor Model [3] [4] that benefits of the interval arithmetic advantages to solve the worst case searching. The last technique uses Monte Carlo simulation to generate a population of virtually manufactured parts representative of the real produced parts [5]. This paper first reminds the MMP model and the different solution techniques. The different strategies to simulate the deviation parameters of the model are then discussed. For each of the three proposed solution techniques, its convenience and inconvenience is explored in detail. The solution techniques performances are compared from different points of view (i.e. rapidity, convergence to the global minimum, analyzed case …) and some perspectives are presented.

Keywords:
Tolerance analysis, Process plan, Errors stack up, Model of Manufactured Part

1 INTRODUCTION

Today, manufacturing engineers are faced with the problem of selecting the appropriate process plan (machining processes and production equipment) to ensure that design specifications are satisfied. Developing a suitable process plan for release to production is complicated and time-consuming. Currently, trial runs or very simple simulation models (1D tolerance charts for example [6]) are used to check the quality criterion. The trial runs are very costly and, on the other hand, the accuracy of simulation fails to meet today's requirements. These problems can be overstepped by developing accurate models and methodologies for simulating the manufacturing process and predicting geometrical variations in the parts produced. More accurate models will make it possible to evaluate the process plan, determine the tolerance values in terms of manufacturing capabilities during the design phase, and define the manufacturing tolerances to be checked for each setup. In the literature available on this subject, the evaluation of a process plan in terms of functional tolerances is called the tolerance analysis. In this paper the model of manufactured part (MMP) is used for simulating the manufacturing process and then the worst case technique and statistical approach are used for the aim of tolerance analysis.

In this paper we shall focus on tolerance analysis relating to error propagation in a multi-stage machining process. Huang et al [7] propose a state space model to describe part error propagation in successive machining operations. Surface deviation is expressed in terms of deviation from nominal orientation, location and dimensions. The error sources in machining operations are classified as fixture errors, datum errors and machine tool errors. A part's deviation is expressed in terms of the deviation of its surfaces and is stored in a state vector $x(k)$. This vector is then modified by moving from operation k to $k+1$. Zhou et al [8] uses the same state model but the surface deviation compared with the nominal state is expressed using a differential motion vector. However, these two models require specific fixture setups (e.g., an orthogonal 3-2-1 fixture layout). More recently, Loose et al [9] used the same state space model with a differential motion vector but including general fixture layouts. Although a general fixture layout is considered, the error calculation of a fixture is based on its locator deviations (a locator is a punctual connection). Hence, positioning cases with Plane/Plane contact or Cylinder/Cylinder floating contact are not envisaged.

Huang et al [10] propose a simulation-based tolerance stack-up analysis. Manufacturing errors are classified as follows: work holding errors (i.e. fixture errors, datum errors and raw part errors), machine tool errors and cutting tool errors. A surface is modeled using uniformly distributed sample points (point cloud), which is a basic technique applied in CMM type inspections. By putting the part through different machining setups, the coordinates of these points in the local part coordinate system are changed due to manufacturing errors. The Monte Carlo method is used to perform the simulation. The different possible errors are considered in this simulation but Part/Fixture interaction is not studied and it is assumed that part/fixture contact is perfect.

This paper firstly reminds the Model of Manufactured Part (the MMP) [1, 11, 12] ; a method for modeling the different geometrical deviation impacts on the part produced (error stack-up) in a multi-stage machining process. Previously, the same authors presented a generic formulation for tolerance analysis based on searching for the worst case using the MMP. This paper discusses about the different numerical solution technique for performing the worst case based tolerance analysis. Worst case technique then will be compared with statistical tolerance analysis. The statistical approach uses the Monte Carlo Simulation. The convenience and inconvenience of each technique will be then discussed.

2 MMP

[1, 11, 12] propose a method for modeling successive machining processes that takes into account the geometrical and dimensional deviations produced with each machining setup and the influence of these deviations on further setups. In the MMP, the errors generated by a manufacturing process are considered to be the result of two independent phenomena: *Positioning*