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Principle of elastic averaging for rapid precision design

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Abstract

Elastic averaging has worked well throughout history to help create precision machines. With the advent of rapid fabrication processes such as additive manufacturing, abrasive waterjet machining, and laser cutting etc., parts fabricated from these processes can be designed with special elastic features that "average out" the uncertainty in dimension tolerances and manufacturing errors as a collective system at very low cost. This paper presents the principle of elastic averaging and explores simple flexure design to create elastic averaging features within parts for precision alignment and assembly applications. A first-order analytical model and a quick estimation approach is introduced to predict the alignment errors and the repeatability of these parts. Experimental results show that a part with four elastic averaging features was capable of achieving precision assembly with another mating part even after huge errors were purposefully introduced to the mating features. Results also show that the part can achieve sub-micron level repeatability after more than 20 trials of removals and assemblies. Lastly, analytical simulations show that repeatability of the part can be further improved by increasing the number of elastic contacts. All these results suggest that the assemblies of rapid fabricated parts with elastic averaging features can be as precise as those made from conventional machine centers.

Key words: Elastic averaging, over-constrained design, flexure, precision alignment and repeatability

1. Introduction

Rapid fabrication processes such as waterjet, laser cutting, and Additive Manufacturing (AM) etc., are perceived as good technology for producing prototypes rather than producing functional parts for precision applications. In the case of AM technology, it has been widely recognized that 3D printed alloy-based parts have rough surfaces and the poor tolerance that are limited by the size of the powder (100 – 200μm), and the spot size of the lasers (<10μm). Hence, these parts require secondary removal processes (or post-processing) to enhance the surface finish and improve the tolerance. With state-of-the-art AM technology, it is unlikely that 3D printed parts (without post-processing) can be used in precision applications where sub-micron repeatability and accuracy are required. Similarly, neither abrasive waterjet machining nor laser cutting process can reproduce the high dimension tolerances delivered by conventional milling, turning, and grinding fabrication processes.

The principle of elastic averaging has been known and practiced for eons [1, 2, 3, 4, 5, 6, 7] but is often overlooked in the modern world of Computer-Aided Design (CAD) where everything appears exact with perceived perfection. Yet even for precise-machined metal parts, all too often dowel pins are relied upon but the high stiffness of pins pressed into holes requires clearance, and as a result accuracy is compromised. On the other hand, the ubiquitous LEGO™ brick mates have exquisite precision [8] even to bricks made decades ago. Indeed, the same principle has even been applied to MEMs devices [6], wafer [9] and micro-fluidic devices [10] but has yet been applied to rapid fabricated parts, making them applicable for precision applications without post-processing.

This paper presents the use of elastic averaging to design rapid fabricated parts that can be used in precision alignment and assembly applications. By using the underlying physics of elastic bodies motion and force interactions, these parts can be designed with elastic features that can "average out" the uncertainty in dimension tolerances and manufacturing errors as a collective system. The paper is organized with the following sections that present the principle of elastic averaging, a general modeling approach to obtain first-order analytical model to predict the misalignment errors and the repeatability of parts with elastic averaging features, the experimental investigations that were conducted to evaluate the analytical predictions and effectiveness of elastic averaging, and the simulation results on how repeatability can be improved with respect to the number of elastic features.

2. Principle of elastic averaging

Unlike a kinematic coupling that interfaces two rigid-body parts based on exact constraint design [11], elastic averaging requires one of the interfacing parts to have over-constrained rigid features while the other interfacing part made of a network of compliance members equal to the number of those over-constrained rigid features. Think of one of the classic epitomes of elastic averaging: the use of multiple blade flexures to

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