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Statistical tolerance analysis of bevel gear by tooth contact analysis and Monte Carlo simulation

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Abstract

Tolerancing decisions can profoundly impact the quality and cost of gears. To evaluate the impact of tolerance on gear quality, designers need to simulate the influences of tolerance with respect to the functional requirements. To do so, they use AGMA or ISO tables, or they perform experimentations. The first approach is not very flexible on the other hand the second approach is expensive. We have proposed an approach to analyze the tolerances. This approach includes a vectorial dimensioning and tolerancing model which allows gear conventional tolerancing practice and geometric tolerancing practice, a digital simulation based on Tooth Contact Analysis and Monte Carlo simulation.

Keywords: Tolerance analysis; Gear; Vectorial dimensioning and tolerancing; Tooth contact analysis; Monte Carlo simulation

1. Introduction

As technology increases and performance requirements continually tighten, the cost and required precision of assemblies increase as well. There is a strong need for increased attention to tolerance design to enable high-precision assemblies to be manufactured at lower costs. Indeed, tolerance analysis is a key element in industry for improving product quality.

Designers want tight tolerances to assure product performance; manufacturers prefer loose tolerances to reduce cost. There is a critical need for a quantitative design tool for specifying tolerances. Tolerance analysis brings the engineering design requirements and manufacturing capabilities together in a common model, where the effects of tolerance specifications on both design and manufacturing requirements can be evaluated quantitatively.

The inherent imperfections of manufacturing processes (forging, cutting or grinding) and the gaps involve geometrical variations and a degradation of product quality. These geometrical variations are due to

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- Geometrical deviations of each part.
- Relative displacements between parts according to gaps.
- Structural distortions.

The geometrical deviations of each part must be limited by geometrical specifications (tolerances) to ensure a certain level of product quality, which is defined by the functional requirements. The best way to obtain the optimal geometrical specifications (tolerances) is to simulate the influences of these tolerances with respect to the functional requirements.

Significant amount of literature is related to tolerancing methods. Summaries of state of the art, the most recent developments, and the future trends in tolerancing research can be found in Bjorke [1] and Zhang [2] as well as in a number of survey papers such as Chase and Parkinson [3], Roy et al. [4], Nigam and Turner [5],Voelcker [6], Srinivassan [7], and Ballu et al. [8]. An amount of research has been devoted to the development of tolerance analysis [9–20] and synthesis [21,22]. But, few of this research apply to gear [17–19,23].

In the case of classical mechanism, the influences of parts deviations can be analyzed by different approaches as variational geometry [22,24], Geometrical behavior law [9], clearance space and deviation space [10–15,25], gap space [20], quantifier approach [21], kinematic models [16–19].

In the case of gears, their geometrical deviations impact the transmission error, the tooth contact position, meshing interference, gap [23,26–28]. To ensure a quality level, designers limit these parameters by requirements. To simulate the influences of gears deviations on these requirements, the classical approaches cannot possibly be employed because the tolerance analysis of gears includes a kinematic aspect and a determination of contact position [23]. There are important questions that require need to be looked upon:

- How to modelize the gear geometrical deviations?
- How to modelize the gears tolerances?
- How to analyze the impacts of geometrical deviations on transmission error,... ?
- And how to analyze these tolerances with a simulation tool?

For each question, few answers exist today in the academic works. There is a necessity of developing a complete answer that should: (i) represent standard tolerance practices and (ii) support automated tolerance analysis.

For the first and second questions, two types of tolerancing are used in industry for assigning tolerances: conventional tolerancing and geometric tolerancing. In conventional tolerancing, a tolerance that is applied to a dimension is considered to permit one degree of freedom to the target entity, i.e., displacement only in the direction of the dimension. Geometric tolerancing refers to modern methods that are prescribed in the ISO [44] standard and the ANSI/ASME Y14.5 [45] standard. Here the allowed variation is defined with a tolerance-zone in which the target entity is permitted several degrees of freedom for displacement. Geometric tolerancing is being used increasingly by aerospace and other industries to assure form and function of mechanical parts. A geometrical tolerance controls the form and orientation (flatness, roundness, perpendicularity, etc.) and location (position, concentricity, etc.) of surfaces. We propose a vectorial dimensioning and tolerancing model which includes conventional tolerancing practice and geometric tolerancing practice (Section 2).

For the third question, theory of gearing looks like a pretty difficult subject. It involves a lot of geometry and complex relative motions. Some books like Theory of Gearing by Litvin [27] are now classical. This theory has been widely employed. Moreover, Tooth Contact Analysis allows to simulate the contact of gear tooth surfaces, and it permits to investigate the influence of geometrical deviations on kinematic errors. The principle idea of TCA is based on simulation of tangency of tooth surfaces being in mesh [27,29–32]. We adopt this approach (Section 3).

For the fourth question, tolerance analysis can be statistical. For statistical tolerance analysis, the possible values for an individual deviation of a component part are described by their frequency distribution. By permitting a small fraction of assemblies to not assemble or function as required, an increase in tolerances for individual dimensions may be obtained, and in turn, manufacturing costs may be reduced significantly. Statistical tolerance analysis computes the probability that the product can be assembled and will function under given individual tolerance [5,22]. To do it, we use the Monte Carlo simulation (Section 4).