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Various approaches about the factors that influence in errors in a machine tool and the proposed solutions - a theoretical-conceptual review

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Abstract

The competitiveness of the market makes companies look for alternatives in their processes to meet the quality, cost and deadline requirements of an increasingly demanding customer. In this way, many machining companies use machine tools for their versatility, speed and precision. However, during the machining process on a machine tool, errors generated by several factors can occur. These

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factors are divided into: static, dynamic and thermal, and can have a negative impact on the product. For this reason, much research is carried out, looking for alternatives to reduce or eliminate these errors. The present article presents a theoretical-conceptual research on several approaches about the factors that influence machine tool errors as well as the solutions proposed in this context.

Key words: Machine tool, types of errors, theoretical-conceptual review, machine tool error, density analysis

1. INTRODUCTION

The competitive and global market brings with it an increasingly demanding consumer of better quality products, so, for companies to remain competitive, the search for improvements in their manufacturing processes becomes a routine and part of continuous evolution from the company.

In this sense, for Camacho (2015), companies promote a tireless search for efficiency in manufacturing processes, aiming at gains in productivity, competitiveness and performance. In this way, machining companies look for alternatives to improve the performance of their equipment.

Many factors and criteria are used to measure the performance of a company, one of the main ones being its ability to manufacture parts according to its technical specifications, be they in the order of hundredths, thousandths or less. For this, repeatability on a machine is a necessary requirement for the process to be controlled efficiently and still within the necessary deadlines (SCHWENKE et al., 2008).

Currently manufacturing companies, mainly that have the machining process, stand out for meeting the demand with speed and quality. However, in the machining process, errors can occur in the equipment generated by several factors, which has a negative impact on the final product (NASCIMENTO, 2015).

These errors can be caused by several factors, and these factors, according to Brecher and Wissman (2011), influence the precision of the equipment and can be divided into: static, dynamic and thermal. Regarding static and dynamic factors, Xiang and Altintas (2015) say that there are 41 types of geometric errors, divided into movement deviations (geometric error that depends on position) and location (geometric error that does not depend on position).

Errors caused by dynamic factors can cause position deviations in a five-axis machine tool and these errors consequently affect the geometric accuracy of the equipment's surface (UDDIN et al., 2009).

Regarding thermal factors, according to Bryan (1990), these contribute to more than 50% of the errors of a machine tool.

According to Zhang, Gao and Li (2017) errors caused by thermal factors are, in the vast majority of cases, corrected via software.

Studying the influence of dynamic, static and thermal factors and looking for alternatives to minimize or eliminate them is the objective of many researches. For this, the authors propose, in the vast majority of cases, mathematical models to compensate for these errors. Thus, the aim of this study is to present the different approaches on the factors that influence machine tool errors as well as the solutions already proposed in this context.

2. THEORETICAL REFERENTIAL

The machining process on five-axis machine tools is an important process in the manufacture of various products, as it applies to the most diverse market segments, the main characteristic being the flexibility to meet the most diverse types of products and high efficiency. (SHE; CHANG, 2006).

In recent years, MTs have been increasingly used in manufacturing processes for various products, from the most varied sectors such as, for example, aerospace, automotive, consumer products, die and mold manufacturing. However, MT geometric errors are currently explored for several studies. Among the relevant results of these studies, we highlight the proposal of direct and indirect methods to detect and minimize these errors (LASEMI; XUE; GU, 2016).

In addition to the studies already highlighted, for Lee, Lee and Yang (2013) during the machining process in an MT there are many errors, one of the most important being the geometric error of the components and structures of the MT, as they affect the accuracy of positioning throughout the process.

The positioning errors of the tools in an MT are generated by several factors, these factors generate errors which include geometric errors, thermomechanical errors, static loads and dynamic forces. Geometric errors are the ones that most contribute to the volumetric errors of an MT, these errors interfere in parts with imprecise geometry, and can be generated by dimensions of the components of the machines and their configurations, as well as axis misalignment (SCHWENKE et al., 2008).

The geometric errors of an MT can be divided into direct and indirect. Direct errors are measured directly on the machine axes. On the other hand, the indirect ones, which are the location errors, are on different axes and their effect is on the accuracy of the MT positioning (YANG; MAYER; ALTINTAS, 2015).

The position of the tool tip in an MT machining process is determined by the linear and rotary axes of the MT. In addition, there is a non-linear relationship between the coordinates, of the part and the machine, and the positioning or geometry errors of the part are not directly related to the axis coordinate systems (HSU; WANG, 2007).

Other authors, on the other hand, emphasize that the thermal variation of a CNC MT is one of the main causes of problems related to the precision of the equipment. Thermal errors interfere with the deformation and displacement of the MT, which can directly cause quality problems in the machined parts (CHEN; CHANG, 2016).

The thermal variation, or error, of an MT depends on many factors and can also be influenced by the design of the equipment and the thermal characteristics of the MT material. Among all parts of an MT, the spindle is undoubtedly one of the parts of the structure of an MT most affected by heat (BRECHER; WISSMANN, 2011).

Thermal errors can have significantly particular effects on the precision of large machine tools, they can be caused by the thermal deformation of the elements of an MT caused by the heat sources existing in the machine structures (bearings, shafts, motors, friction between surfaces, etc.), as well as the temperature change of the

environments. These errors can represent up to 70% of the total positioning errors of a CNC MT (ABDULSHAHED et al., 2016).
Also, the accuracy of an MT can be affected by two heat sources, internal and external, by varying the temperature of the environment. This variation in ambient temperature can be found on the factory floor, this can cause thermal deformation in the MT structure. These temperature variations at the manufacturing site still show different results during the day and night, and even during season transitions (ZHANG; GAO; YAN, 2017). Likewise, Kim, Jeong and Cho (2004) emphasize that the linear motors used in MTs are efficient to achieve high speeds, however they can be sources of heat generation and this can cause errors in the machines.

Among the many parts of an MT, the spindle is undoubtedly one of the most important and most thermally affected parts. Studying the deformation and displacement of an MT caused by a thermal variation has been the focus of many studies. In this way, the spindle requires a more elaborate study of its thermal characteristics (KONG, 2016).

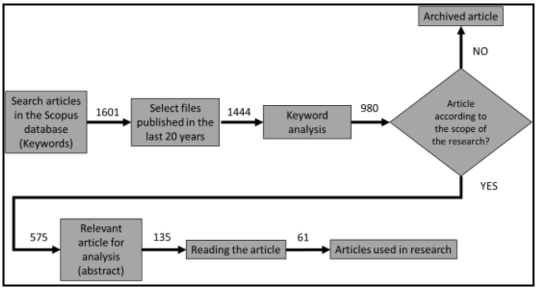
The spindle of an MT is considered to be one of the central components, this element is affected thermally due to its operating characteristics, such as load deformation between the rotating elements, such as bearings and rings. Thus, the spindle has a significant influence on the functioning status of an MT (DONG; ZHOU; LIU, 2017).

3. RESEARCH DEVELOPMENT METHODOLOGY

This article brings a theoretical-conceptual study, which according to Miguel (2007), addresses conceptual modeling, in addition to discussions about the literature and a theoretical contribution on the topic.

Figure 1 shows the flowchart used for literature review based on the model proposed by Carvalho, Fleury and Lopes (2013).

Figure 1: Flowchart of literature review

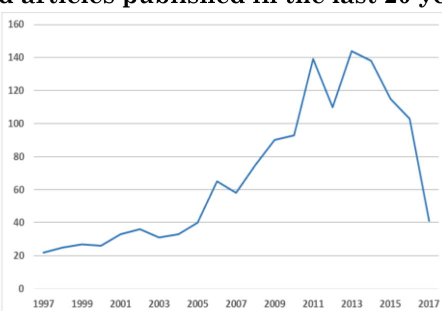


Source: Authors

The search was done with articles that contained the words machine tools AND errors compensation (machine tool and error compensation) in the Scopus database and resulted in 1,601 articles.

As a result of the aforementioned research, articles published in the last ten years were considered for the continuity of the work, a period that presents a significant increase in publications, figure 2.

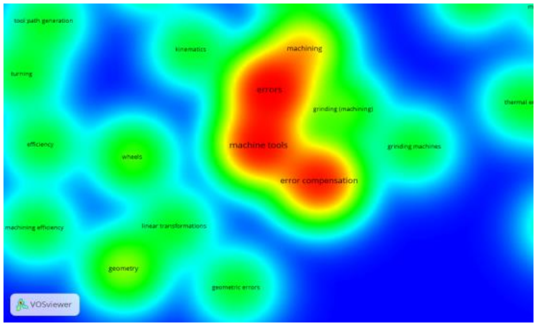
Figure 2: Selected articles published in the last 20 years.



Source: Authors

From this preliminary sample, an analysis was made of the co-occurrence of the keywords presented in figure 3, where the density analysis made using the VOSviewer software, shows that the machine tool and error compensation themes are researched simultaneously (DIODATO, 1994) .

Figure 3: Analysis of keyword density (machine tool and error compensation).



Source: Authors

4. RESULTS AND DISCUSSIONS

To make the present study better understood, two nomenclatures for the types of errors will be presented. They will be thermal errors and geometric errors, the latter includes static, volumetric and dynamic errors.

The following are some of the suggested approaches to compensate for geometric errors in MTs and the results obtained.

For Lei and Hsu (2003), 80% of geometric errors are associated with rotary axes and the remaining 20% are on linear axes. Also according to the authors, the vector of the model proposed for the improvement of an MT in real time contributed significantly to the accuracy of the equipment.

Schwenke et al. (2008) indicate that between 30 to 50% of MTs will have a system for compensating for geometric errors, and that this post-calibration service can be performed not only by manufacturers but also by outsourced companies.

In other applications Uddin et al. (2008) show in their article that with the application of the DBB telescope device (doble ball bar) it was possible to reduce more than 40% of the geometric errors in the circularity of a machined part.

For Alessandro, Gianni and Antonio (2014) it was possible to reduce approximately 80% of the geometric errors on the MT turntable with the application of their model. Also according to the authors, with an analytical modeling, geometric errors can be identified and corrected.

Givi and Mayer (2014) present a correction of geometric errors between 65 to 99% with the application of compensation with the modified G code. The authors studied the geometric error mainly in the depth of the machining of the parts.

According to Ezedine et al. (2015) present a proposal of multiple criteria with the application of DOE (Design of Experiment) for the correction of geometric errors in machine tools for small volumes (compact extra-small - XSS). According to the authors, little research and solutions apply to this type of equipment.

For geometric errors, according to He et al. (2016) a correction of 61.29% was possible in the machining of surfaces through the Self-adaptive Mathematical Expression Model (SMEM). Also according to the authors, this method proved to be effective and can be used to correct errors as well as preventively.

Xiang and Altintas (2016) proposed in their article a model for compensating for geometric errors. The proposed model for the 41 errors found in the equipment showed results of up to 80% correction in one of the axes.

Liu et al. (2016) show a 65% improvement over geometric errors on a surface in ultra-precision machining through the theory based on an MBS (multi-body system) system and the coordination of formatting and shape precision algorithms.

Subsequently, some approaches are presented for the compensation of thermal errors and their results.

Brecher and Wissmann (2011) present in their article a compensation model for thermal deformations in the spindle of an MT. According to the authors, the model showed a 69% reduction in deviation in the Y direction and 82% in the Z direction.

According to Horejs, Mares and Novotny (2012) with the application of the thermal transfer function (TTF) model proposed in their article, it was possible to reduce thermal errors by 75%, in real time, in an MT.

For Shi et al. (2015) with the thermal error compensation model based on Fuzzy logic and linear regression presented in his article, it was possible to achieve deformations of a maximum of 1.5 µm in the ballscrew of an MT.

The compensation of thermal errors can be applied in MTs with computerized numerical commands (CNC) or in measuring machines with the same system. In this sense, Ying, Jia and Xinghua (2016), with the application of the mathematical model to compensate for thermal errors in a measuring machine, based on the double cycle, it was possible to reduce 110 μm to 7 μm.

In their article, Chen and Chang (2016), show an improvement in the accuracy of an MT, more specifically in the cutter, of 33% with the application of a mathematical model based on the multiple regression analysis (MRA).

Dong, Zhou and Liu (2016) propose a model for correcting the thermal errors observed in the spindles of an MT, considering the stress on the bearings of the equipment structure, based on data from the finite element analysis (FEM).

For Kong (2016), simulation through finite element analysis showed that the MT spindle was the most thermally affected region, so the author proposes a change in the spindle's cooling channels. With the application of the solution proposed by the author, the results show a reduction of up to 7% in the spindle temperature, the author also points out that this type of solution is limited because it affects the structure of the equipment.

The compensation model proposed by Abdulshahed et al. (2016) based on the gray neural network with convolution integral, which according to the actors is similar to the artificial neural network model, showed an 85% reduction in thermal errors in an MT. The results are shown in figure 4:

Figure 4: Solutions presented for geometric and thermal errors in an MT.

Error Type	Proposed solution	Author	Year
Geometric	Original model	Lei & Hsu	2003
	Original model (DBB – double ball bar)	Uddin et al.	2008
	Original model	Alessandro, Gianni & Antonio	2014
	Original model (G code)	Givi & Mayer	2014
	Original model (DOE on small machine)	Ezendine et al.	2015
	Original model (SMEM)	He et al.	2016
	Original model	Xiang & Altintas	2016
	Original model (multi-body system – MBS)	Liu et al.	2016
Thermal	Original model	Brecher & Wissmann	2011
	Original model	Horejs & Mares	2012
	Original model (fussy and linear regression)	Shi et al	2015
	Original model (MRA)	Chen & Chang	2016
	Original model (spindle refrigeration)	Kong	2016
	Original model (gray neural network)	Abdulshahed et al.	2016

Source: Authors

5. CONCLUSIONS

This article presented a theoretical-conceptual study on the various factors that influence the errors of a machine tool and the solutions proposed in this context. Altogether, 1,444 articles were found and, using the flowchart for reviewing the literature, 61 articles were selected.

In this way, a discussion and a theoretical contribution on the topic was presented, where the authors and the methodologies used to compensate for each type of error were summarized in the Figure 4.
Additionally, the research carried out allowed other contributions and discussions, not proven in the present article, about the studies aiming at thermal errors in the machine tool spindle, as well as mathematical models to compensate for these errors. It is suggested that this topic be studied in future works.

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