



Ain Shams University  
Faculty of Engineering  
Design and Production Engineering Department

**Simulation approach to evaluate the performance of  
a milling machine based on the accuracy of the  
milling products**

A Thesis Submitted in Partial Fulfilment for the Requirements of  
the Degree of PhD in Mechanical Engineering

**by**

**Amr Ahmed Sayed Shaaban**

Master of Science in Mechanical Engineering

**Supervised by:**

**Prof. Dr. Monir Mohamed Farid Koura**

**Asst. Prof. Mohamed Lotfy Zamzam**

**Cairo-2015**



Ain Shams University  
Faculty of Engineering  
Design and Production Engineering Department

**Simulation approach to evaluate the performance of  
a milling machine based on the accuracy of the  
milling products**

A Thesis Submitted in Partial Fulfilment for the Requirements of  
the Degree of PhD in Mechanical Engineering

**by**

**Amr Ahmed Sayed Shaaban**

Master of Science in Mechanical Engineering

**Supervised by:**

**Prof. Dr. Monir Mohamed Farid Koura**

**Asst. Prof. Mohamed Lotfy Zamzam**

**Cairo-2015**

## **STATEMENT**

This thesis is submitted as partial fulfillment of Ph.D. degree in mechanical engineering, Faculty of Engineering, Ain Shams University.

The author carried out the work included in this thesis, and no part of it has been submitted for a degree or qualification at any other scientific entity

**Signature**

**Amr Ahmed Sayed Shaaban**

## **EXAMINERS COMMITTEE**

The undersigned certify that they have read and recommend to the Faculty of Engineering – Ain Shams University for acceptance a thesis entitled “Simulation approach to evaluate the performance of a milling machine based on the accuracy of the milling products” submitted by Amr Ahmed Sayed Shaaban, in partial fulfillment of requirements for the degree of Doctor of Philosophy in Mechanical Engineering.

**Name**

**Signature**

**Prof. Dr. Azza Fathalla Barakat**

Professor of Production Engineering  
Dean of Faculty of Engineering- Helwan University

**Prof. Dr. Hesham Aly Abdelhamed Sonbol**

Professor and Head  
Design and Production Engineering Department  
Faculty of Engineering-Ain Shams University

**Prof. Dr. Monir Mohamed Farid Koura**

Professor of Production Engineering  
Design and Production Engineering Department  
Faculty of Engineering-Ain Shams University

## ACKNOWLEDGMENT

My very respectful supervisor **Professor Monir Koura**; it is needless to say that I owe you so much for your tireless efforts in guiding and supervising. I thank you deeply for your patience and tolerance. I know that you always look up for the best in everything. You may have not had the best student, but you taught me never to stop trying.

I also want to extend my thanks and gratitude to **Dr. Zamazam**. I was always in need for your helpful advice and to your fatherly feelings towards me.

## **Abstract**

This thesis presents a simulation system which is employed in order to evaluate the static, dynamic, and thermal performance of machine tools. Obtaining such a virtual model could replace many experimental tests that must otherwise be carried out each time the parameters affecting the machine performance are changed. The system is created based on well-defined design considerations, then, it is verified, and applied on some realistic cases. The system evaluates the machine tool performance based on several perspectives namely: static loop stiffness, mode shapes, frequency response function at tool center point, and thermal deformation. Mechanical modeling of mechanical structure and other subsystems of machine tool is achieved, cutting loads are analytically generated, and the heat generation at the hot spots is determined as well. Cutting conditions, cutter and work piece characteristics, category of mechanical structure, supporting webs, position of spindle head are all considered when evaluating the performance of the machine tool in order to provide designers with helpful recommendations in the early design stage. The obtained results from the designed simulation approach provide an evaluation of the behavior of the tool center point in relation to the work piece. Since that behavior will be reflected on the product, these results can be used as criteria for the product accuracy.

The designed evaluation system is proved to give a realistic simulation of the performance of machine tools that concerns the behavior of various machine tool elements and the parameters affecting the machining process.

### **Keywords:**

Machine tools; Static loop stiffness; Natural frequencies; Dynamic performance; Finite element method (FE); Thermal deformation.

## **Thesis summary**

Virtual prototyping is one of the most crucial research points in the field of machine tool design over the last decade. It provides the designers with a realistic simulation of the machine tool behavior without the need for experimental tests that consume cost and time. Obtaining such a realistic model facilitates investigations and modifications during the design stage. Among various modeling techniques, the FEM technique is proved to be a useful mathematical model for simulation.

In this thesis, a virtual system that employs the FEM technique is created to evaluate the static, dynamic, and thermal performance of machine tools. Modeling of the machine tool mechanical structure that includes machine bed and column is carried out together with the modeling of the mechanical and thermal behavior of various machine tool elements such as guide ways, feed drives, spindle unit, and bolted connections. On the other hand, in order to simulate the cutting process and integrate its contribution to the overall machine tool performance, analytical methods are used to obtain the cutting loads generated on both TCP and worktable during single tooth cutting interval. Based on the desired logic and the designed flow chart, the evaluation system is constructed so as to comprise five analysis modules created using FEM solving tool. The prerequisites of each module, the data connection among them, and the generated results from each are all clearly defined.

The system is applied to a case study where it is used to evaluate the static, dynamic, and thermal performance of a 3-axis open milling machine tool. All useful data related to the mechanical structure, various machine subsystems, and the cutting process is clearly defined and entered to the data sink of the evaluation system. The results generated by static analysis give an evaluation of the static performance of the machine tool in terms of

directional and total relative deformation between TCP and worktable and the static loop stiffness in various planes. The dynamic performance of the studied machine tool is evaluated based on the results generated by modal and harmonic analyses such as the fundamental frequency, the range of the first six mode shapes, and the TCP compliance along the exciting frequency range. In the same context, the time-varied deformation on both TCP and worktable in x and y-directions is generated by the transient response module along single tooth interval. Besides, the thermal performance is evaluated in terms of temperature distribution all over the milling machine and the thermal deformation at critical regions such as TCP guide ways and screws. The obtained results from the designed simulation approach provide an evaluation of the behavior of the tool center point in relation to the work piece. Since that behavior will be reflected on the product, these results can be used as criteria for the product accuracy.

The designed evaluation system is then employed to carry out some investigations that help the machine tool designers to achieve the desired performance during the early design stage. These investigations include the comparison of open and closed structures, the effect of supporting webs in columns, and the spindle head position effect, which are all carried out and the results are represented.

The designed system is proved to be capable of giving a total evaluation of the performance of machine tools concerning the major parameters that affect it.



## **Contents**

<b>ABSTRACT</b>	<b>V</b>
<b>THESIS SUMMARY</b>	<b>VI</b>
<b>TABLE OF CONTENT</b>	<b>VIII</b>
<b>LIST OF TABLES</b>	<b>XIII</b>
<b>LIST OF FIGURES</b>	<b>XIV</b>
<b>NOMENCLATURE AND ABBREVIATIONS</b>	<b>XVIII</b>
<b>CHAPTER 1 INTRODUCTION</b>	<b>19</b>
<b>CHAPTER 2 LITERATURE REVIEW</b>	<b>5</b>
<b>2.1 Virtual modeling of machine tools.....</b>	<b>5</b>
2.1.1 Modeling of the mechanical structures and other subsystems	5
2.1.2 Modeling of the cutting process	11
2.1.3 Thermal deformation analysis in machine tools	14
<b>2.2 Problem identification.....</b>	<b>15</b>
<b>2.3 Research objectives.....</b>	<b>16</b>
<b>CHAPTER 3 THE VIRTUAL EVALUATION SYSTEM</b>	<b>17</b>

<b>3.1. Definition of the evaluation aspects.....</b>	<b>17</b>
3.1.1 Static performance of machine tool	17
3.1.2 Dynamic performance of machine tool	17
3.1.2.1. Modal analysis.....	18
3.1.2.2. Frequency response function (FRF) .....	18
3.1.2.3. Dynamic simulation of TCP in time domain.....	19
3.1.3 Thermal performance of machine tool	19
<b>3.2. Modeling of the mechanical structure .....</b>	<b>20</b>
3.2.1. 3D modeling of mechanical structure	20
3.2.2 Contact definition	21
3.2.3 FE model of mechanical structure	21
<b>3.3. Modeling of guide ways .....</b>	<b>22</b>
3.3.1. Modeling of guide way stiffness	22
3.3.2. Modeling of sliding friction heat generation	23
<b>3.4. Modeling of feed drive units.....</b>	<b>24</b>
3.4.1. Modeling of the mechanical behavior of the feed drive	25
3.4.2. Modeling of the thermal behavior of feed drive system	26
3.4.2.1. Heat generation of electric motor.....	26
3.4.2.2. Heat generation of bearings.....	26
3.4.2.3. Friction heat at ball screw/nut .....	27
<b>3.5. Modeling of machine tool spindle.....</b>	<b>27</b>
3.5.1. Modeling of the mechanical behavior of the spindle unit	27
3.5.2. Modeling of the thermal behavior of the spindle unit	28
<b>3.6. Modeling of bolted connections .....</b>	<b>29</b>
<b>3.7. Modeling of spindle head position.....</b>	<b>30</b>
<b>3.8. Modeling of the cutting process .....</b>	<b>31</b>
3.8.1. Modeling of the cutting loads	31

3.8.2. Modeling of cutting heat generation	31
<b>3.9. Construction of the evaluation system</b>	<b>32</b>
<b>3.10. Summary</b>	<b>36</b>

## **CHAPTER 4 VERIFICATION OF VIRTUAL EVALUATION SYSTEM**

**37**

<b>4.1. Case definition</b>	<b>37</b>
<b>4.2. Preprocessing</b>	<b>38</b>
4.2.1. Adjusting spindle head position	39
4.2.2. Cutting loads generation	39
4.2.3. Preprocessing of static and dynamic analyses	40
4.2.4. Preprocessing of thermal analysis	40
4.2.4.1. Sliding friction at Guide ways	40
4.2.4.2. Heat generation at motors	41
4.2.4.3. Heat generation at bearings	41
4.2.4.4. Rolling friction at screws/nuts	41
4.2.4.5. Cutting heat temperature	42
<b>4.3. Static analysis results</b>	<b>42</b>
<b>4.4. Modal analysis results</b>	<b>42</b>
<b>4.5. Harmonic analysis results</b>	<b>43</b>
<b>4.6. TCP deflection during one tooth cycle</b>	<b>43</b>
<b>4.7. Thermal analysis results</b>	<b>50</b>
<b>4.8. Summary</b>	<b>54</b>

## CHAPTER 5 COMPARATIVE INVESTIGATION ON MILLING MACHINE STRUCTURES USING THE VIRTUAL EVALUATION SYSTEM 55

<b>5.1. Open and closed categories .....</b>	<b>55</b>
5.1.1. FE modeling	55
5.1.2. Comparative investigation based on static performance	55
5.1.3. Comparative investigation based on mode shapes	58
5.1.4. Comparative investigation based on FRF at TCP	61
<b>5.2. Effect of supporting webs on open categories.....</b>	<b>63</b>
5.2.1 Effect of supporting webs on static performance	63
5.2.2 Effect of supporting webs on the dynamic characteristic	64
5.2.3 Effect of supporting webs on the dynamic performance	65
<b>5.3. The impact of various types of column webs on its performance .....</b>	<b>67</b>
5.3.1 Static performance of machine tool for various column web types	68
5.3.2 Effect of web type on column's dynamic performance	69
<b>5.4. Improved open categories performance .....</b>	<b>70</b>
5.4.1 Improved static performance	71
5.4.2 Improved dynamic performance	71
<b>5.5. Effect of supporting webs on closed categories performance .</b>	<b>73</b>
5.5.1 Effect of supporting webs on static performance	73
5.5.2 Effect of supporting webs on dynamic characteristic	75
5.5.3 Effect of supporting webs on dynamic performance	76
<b>5.6. Investigation of position dependency in machine tools.....</b>	<b>78</b>
5.6.1 Position dependency of machine tool static performance	78
5.6.2 Position dependency of machine tool mode shapes	79

5.6.3	Position dependency of dynamic compliance	80
<b>5.7.</b>	<b>Summary.....</b>	<b>82</b>
<b>CHAPTER 6 CONCLUSIONS</b>		<b>83</b>
<b>BIBLIOGRAPHY</b>		<b>85</b>

## List of Tables

<b>TABLE 3-1</b> EVALUATION SYTEM ENTRIES AND OBTAINED RESULTS FROM EACH MODULE.....	<b>35</b>
<b>TABLE 4-1</b> INPUT DATA TO EVALUATE THE PERFORMANCE OF THE MILLING MACHINE TOOL. ....	<b>38</b>
<b>TABLE 4-2</b> THE FIRST SIX NATURAL FREQUENCIES OF THE MACHINE TOOL AND THE MAXIMUM DEFORMATION AT EACH MODE SHAPE. ....	<b>44</b>
<b>TABLE 5-1</b> FIRST SIX NATURAL FREQUENCIES FOR BOTH OPEN AND CLOSED CATEGORIES AND THE POSITION OF MAXIMUM DEFORMATION AT EACH MODE SHAPE. ....	<b>59</b>
<b>TABLE 5-2</b> FIRST SIX NATURAL FREQUENCIES FOR FULL WEB OPEN CATEGORY AND THE POSITION OF MAXIMUM DEFORMATION AT EACH MODE SHAPE. ....	<b>65</b>
<b>TABLE 5-3</b> THE FIRST SIX NATURAL FREQUENCIES FOR DIFFERENT TYPES OF COLUMNS: RIB FREE COLUMN, AND FOUR TYPES OF RIBBED COLUMNS. ....	<b>70</b>
<b>TABLE 5-4</b> FIRST SIX NATURAL FREQUENCIES FOR THE ENTIRE MODIFIED STRUCTURE AND FOR THE INCLINED COLUMN INDIVIDUALLY. ....	<b>72</b>
<b>TABLE 5-5</b> FIRST SIX NATURAL FREQUENCIES FOR FULL WEB CLOSED CATEGORY AND THE POSITION OF MAXIMUM DEFORMATION AT EACH MODE SHAPE. ....	<b>75</b>
<b>TABLE 5-6</b> FIRST SIX NATURAL FREQUENCIES FOR OPEN STRUCTURE AT FOUR DIFFERENT POSITIONS OF SPINDLE HEAD. ....	<b>80</b>

## **List of Figures**

<b>FIGURE 3-1</b> MODELING OF MACHINE TOOL GUIDE WAYS USING SPRING ELEMENTS.....	<b>23</b>
<b>FIGURE 3-2</b> A SCHEMATIC CONSTRUCTION OF THE FEED DRIVE SYSTEM. .....	<b>24</b>
<b>FIGURE 3-3</b> LUMPED MASS TO SIMULATE THE MACHINE DRIVES.....	<b>25</b>
<b>FIGURE 3-4</b> SECTIONAL VIEW FOR THE CONSTRUCTION OF THE SPINDLE ASSEMBLY.....	<b>28</b>
<b>FIGURE 3-5</b> BOLTED CONNECTIONS BETWEEN COLUMN/BED AND BED/BASE. ....	<b>29</b>
<b>FIGURE 3-6</b> THE SPINDLE HEAD POSITION AND ITS DEPENDENT VARIABLES.....	<b>31</b>
<b>FIGURE 3-7</b> BLOCK DIAGRAM OF THE VIRTUAL EVALUATION SYSTEM. .....	<b>34</b>
<b>FIGURE 3-8</b> A SAMPLE OF THE INPUT/OUTPUT PANEL OF THE DESIGNED EVALUATION SYSTEM.....	<b>34</b>
<b>FIGURE 3-9</b> THE LOGIC CHART OF THE EVALUATION SYSTEM. ....	<b>35</b>
<b>FIGURE 4-1</b> THE 3D MODEL OF A 3-AXIS OPEN CATEGORY MILLING MACHINE TOOL.....	<b>37</b>
<b>FIGURE 4-2</b> THE FE MODEL OF A 3-AXIS OPEN CATEGORY MILLING MACHINE TOOL.....	<b>38</b>