Virtual System to Simulate the Performance of Various Categories of Machine Tools during the Design Stage

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Abstract This paper presents a simulation system designed to evaluate the static and dynamic performance of machine tools. The design considerations of the evaluation system are discussed and the system is then employed in order to compare between various categories of milling machine's structure adapted for end milling operation. The machine performance is identified in terms of static loop stiffness in both x and y directions, mode shapes, and frequency response function (FRF) at tool center point (TCP). The advantage of such a reliable model is that it could replace the many experimental tests that must otherwise be carried out each time the parameters affecting the machine tool performance are changed.

Keywords: machine tools, static performance, natural frequencies, dynamic behavior, finite element method, virtual system


1. Introduction

The experimental approach to study machining process and machine tool performance is expensive and time consuming, especially when a wide range of parameters are included. Hence, virtual prototyping is used instead. The performance of a machine tool depends on parameters related to cutting process, such as: cutting speed, feed rate, radial and axial depth of cut, and end mill and work piece characteristics, and other parameters related to machine structure, such as: structure category, supporting webs, guide ways stiffness, bolted connections, drive's bearing stiffness and spindle head position.

Among various mathematical models used for simulation, finite element method (FEM) is proved to be useful and widely used. Basic ideas of the finite element method were studied at the beginning of the 1940s. Courant (1943) developed finite element method and he used piecewise polynomial interpolation over triangular sub regions to model torsion problems [1]. Clough (1960) was the first to use the term “finite element” [2]. Zienkiewicz and Cheung (1967) wrote the first book on finite element theory [3]. Also other theory books were written by Cook, et al. (1989) [4], Mohr (1992) [5] and Chandrupatla and Belegundu (2002) [6]. Researchers usually wrote their own FE codes for specific process until the mid-1990s. A foundation and comprehensive information related to the field of virtual machine tool design were presented by Y. Altintas, et al; titled as "A study on virtual machine tool" [7]. On the other hand, in order to check the process constraints as well as optimal selection of the cutting conditions for high performance milling, E. Budak developed "Analytical models for high performance milling". Milling force, part and tool deflection, form error and stability models have been presented [8]. Furthermore, other study that focuses on applying virtual prototyping to design a machine tool element is entitled "Virtual design of machine tool feed drive system" achieved by R.C. Parpala [9]. "Integrated dynamic modeling, design optimization and analysis on 5-axis ultra-precision micro milling machine" were developed by D. Huo and K. Cheng. In the same context, "Finite element analysis of bolted joints" was developed by I. piscan, N. predincea and N. pop [10]. This paper presents a theoretical model and a simulation analysis of bolted joint deformations. "FEA of high-speed motorized spindle based on ANSYS" was developed by D. Liu, et al [11]. In this paper, the finite element model of the high-speed motorized spindle was derived and presented. Moreover, the paper entitled "Modal analyses of machine tool column using FEM" was concerned in providing designers with useful information about static and dynamic behavior of various categories of machine tool columns [12].

In this paper, a system that employs the concept of virtual prototyping is created to provide designers of machine tools with useful information, and to facilitate improvement decisions in the early design stage. The system is then employed in order to compare between
open and closed structures of milling machine tools during end milling operation.

2. Definition of the Evaluation Aspects

In this section, the machine tool performance evaluation aspects employed in this paper are discussed. The following sections present a detailed discussion of the function of each module, the connection between the modules, the data entry needed for each of them, and the generated results.

2.1. Static Performance of Machine Tool

Static analysis calculates the effects of steady loading conditions on the machine, while damping effects are neglected. Based on that evaluation aspect, the structural loop stiffness which characterizes the machine's overall static performance is calculated.

2.2. Dynamic Performance of a Machine Tool

2.2.1. Modal Analysis

The natural frequencies and mode shapes are obtained by solving the eigen-value problem:

\[ [K][X] = \omega^2[M][X] \]

where \([K]\) is the stiffness matrix, \([X]\) is the displacement matrix that contains all degrees of freedom and consequently depends on number of nodes, \([M]\) is the mass matrix, and \(\omega\) is the angular frequency (rad/s). The problem can be satisfied by either; \([X] = 0\), which is a trivial solution, or, \([K] - \omega^2[M] = 0\), where \([K]\) is the determinant of a given matrix. The eigen values \(\omega^2\) yield the natural frequencies \(\omega\) of the system, while the eigen vectors \([X]\) define the mode shapes. The first frequency is usually called the fundamental frequency.

2.2.2. Frequency Response Function

Harmonic analysis is performed to quantitatively determine the steady-state response of the machine towards sinusoidal loads. Although the cutting forces are varying with time over each tooth interval in a complex manner that is not actually sinusoidal, the cutting forces are repeated for each tooth with a certain frequency that depends on cutting speed. As a result, harmonic analyses are helpful to verify whether or not the design will successfully overcome resonance and harmful effects of forced vibrations.

3. Modeling of the Mechanical Structure

3.1. 3D Modeling of Mechanical Structure

The mechanical structure of a machine tool center can be considered to have the major contribution of its rigidity. It mainly consists of the column, bed, table, saddle, slider, and spindle head. When the cutting process is established on hard materials, the dynamic characteristics of the mechanical structure of a machine tool center become crucial. The CAD model is created using any of the commercial CAD software and imported to Ansys® which is the analysis tool package used in this work. Lumped masses are used to simulate the effect of the feed drive and spindle housing. The joints at the guide ways are assumed to be rigid, as well as, the joint between screws and their bearing supports. Bolts are simulated with spring beam elements, and they are preloaded with initial tension of 5 KN for each. A fixed support was assigned to the lower surface of the machine base as a boundary condition. Any topology that has no significant effect was removed for simplicity and to minimize computation time.

3.2. FE Model of Mechanical Structure

The FE model of the mechanical substructures are generated from their perspective CAD models using tetrahedron elements. The tetrahedron elements are proved to be more suitable than the bricks elements to simulate machine tool structures. The main characteristic of interest when evaluating a FE model is the mesh size. The fine mesh size leads to converged results, but on the other side, it increases the DOFs which increases the computation cost as well. However, local refinements in mesh size can be specified at critical regions such as TCP and work table using the sphere of influence.

To obtain a mesh independent model with the minimum computation time, constitutive iterations are carried out to properly select mesh characteristics in order to achieve convergence of the results to the exact value within an accepted residual error. The h-method in which the mesh size is refined until convergence is employed in this work. This method is preferred for its ease of execution rather than the P-method in which the degree of polynomial used for the shape function is changed until convergence.

4. Modeling of the Cutting Process

To obtain a realistic integrated simulation system, modeling of the cutting process is integrated with the modeling of machine tool mechanical components discussed in the previous subsections. This integration leads to a realistic representation of the overall performance of the machine tool.

Many works have been carried out on different aspects linked to cutting forces prediction. Recently, researchers used Finite element method to simulate the cutting process and hence, predict the cutting forces and the chip morphology [13]. However, Simulation of cutting process using finite element method is not crucial to this paper. Therefore, analytical method has been used instead. Tlusty and McNeil’s cutting force model was developed for conventional end-milling operations [14].

5. Construction of the Evaluation System

Based on the concepts discussed on the previous subsections, the theory based on which the evaluation system is designed can be represented by the chart shown in Figure 1, while the GUI (graphic user interface) of the evaluation system is illustrated in Figure 2. The system’s GUI consists of three areas. The system inputs and outputs are defined in Area1, the user-defined design points at which the system runs appear in Area2, and finally, Area3 shows the charts that represent relationships between specified parameters. All input data and design points that are defined in Area1 and Area2 are automatically
transferred to carry out the corresponding analyses without any need to log in any of the modules; then the generated results are transferred back to be displayed. The system logic and the interconnections between the modules are represented in Figure 3. The data entry of each module and the results generated from each are represented in Table 1. The data is classified to that related to the machine tool such as: 3D model file, spindle head position, characteristics of spring elements, heat generation at hot spots and bolts pretension, others related to the cutting process such as: static load at TCP, amplitude and exciting frequency of harmonic loads, $T_c$ and data sheet of time varied loads along one tooth interval.

Table 1. The evaluation system entries and obtained results from each module

<table>
<thead>
<tr>
<th>System entries</th>
<th>Obtained results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Spindle head position</td>
</tr>
<tr>
<td>Static</td>
<td>Cutting load at TCP and worktable in x and y-directions</td>
</tr>
<tr>
<td></td>
<td>Bolt's pre-stress</td>
</tr>
<tr>
<td></td>
<td>Static stiffness and damping coefficient of the spring elements</td>
</tr>
<tr>
<td>Modal</td>
<td>Only the 3D model</td>
</tr>
<tr>
<td></td>
<td>Static stiffness and damping coefficient of the spring elements</td>
</tr>
<tr>
<td>Harmonic</td>
<td>Range of exciting frequencies of cutting loads</td>
</tr>
<tr>
<td></td>
<td>Amplitude of harmonic load at TCP and worktable in x and y-directions</td>
</tr>
<tr>
<td>Time-varied</td>
<td>Tabular data contains time-varied cutting loads within the time period at which one tooth is engaged</td>
</tr>
</tbody>
</table>

Figure 1. Flow chart of the virtual evaluation system

Figure 2. A sample of the input/output panel of the designed evaluation system
6. Comparison Investigation on Open and Closed Milling Machine Tool Categories

6.1. Case Definition

The virtual evaluation system is applied on both 3-axis milling machine tools of open and closed categories. The open frame machining center mainly consists of the column, bed, table, saddle, and spindle housing, as well as, three screws to provide the traverse motion in three axes as shown in the CAD model in Figure 4 (a), while the closed frame machining center consists of two columns, bed, table, X-guide, X-slider, Z-slider, and spindle housing as shown in the CAD model in Figure 4(b). Both two categories are within the same volumetric size 1200 mm* 1790 mm* 1920 mm. The material of the machine structural components was assigned as gray cast iron with modulus of elasticity of 89 GPa; density of 7250 kg/m$^3$; and Poisson's ratio of 0.25. On the other hand, the cutting process is carried out on work piece material called Inconel718, with cutting conditions [radial depth of cut (a) = 4 mm, axial depth of cut (b) = 4 mm, feed rate (u) = 100 mm/min, feed per tooth (fz) = 0.0125 mm/tooth, and cutting speed (s) = 2000 rpm], using an end mill of radius (r) = 10 mm, number of teeth (n) = 4, and helix angle (ß) = π/6.
6.2. Preprocessing

6.2.1. Adjusting Spindle Head Position

Before running the system, all data stated in the previous subsection are entered and transferred to each module of the designed system according to its requirements. The spindle head position is adjusted according to the specified depth of cut so the end mill lower surface is 4 mm below the work piece surface.

6.2.2. Cutting Loads Generation

According to the cutting conditions previously stated in the case definition, the cutting load generated using analytical methods is shown in Figure 5. The graph shows the cutting load values with respect to the end mill angle of rotation along one tooth interval.

6.2.3. Preprocessing of Static and Dynamic Analyses

For the static module, the TCP is subjected to static load of 1000 N in X-direction and 500 N in Y-direction. For the harmonic module, sinusoidal loads of 1N amplitude with exciting frequency ranges from 30 to 300 HZ frequency are subjected to the TCP. Finally, cutting load values are transferred in a tabulated form to the transient structure module where they are subjected to the TCP through a specified number of time steps so as to obtain the deformation of the TCP during one tooth interval.

![Figure 5. Cutting forces generated along one tooth interval](image)

![Figure 6. Tooltip deflection at different loads for open and closed structure](image)
6.3. Static Analysis Results

Figure 6 shows the relative total deformation between TCP and worktable at various static loads. It can be noticed that the closed structure gives much better results compared to the open one, and that the larger the load, the greater the deviation between the results of closed and open categories. The supporting columns in the closed category raise the static loop stiffness in YZ plane from 32.5 in the open category to 52.9 N/μm, and in XZ plane from 70.4 in the open category to 294 N/μm, as shown in Figure 7. The closed category shows greater rigidity in YZ plane with enhancement of 62.7 % as the supporting columns greatly decreases the tilting of the spindle head that occurs in the open category due to the X component of the cutting load. However, the main advantage of the closed category appears in the increase of rigidity in XZ plane by 317 %, which gives the structure great rigidity against bending [5].

6.4. Modal Analysis Results

Table 2 shows the first six natural frequencies for each category, and the position of maximum deformation for each mode shape. The first six mode shapes of each closed and open structure are illustrated in Figure 8 (a), and (b).

The results show that the lowest natural frequency in both open and closed categories occurs at the spindle head, and hence, it can be marked as a weak point from the aspect of dynamic behavior. The first natural frequency in the closed category is slightly lower than the open one. It is also noticed that the range of natural frequencies in the open category is wider than that in the open one, i.e.: at 228 HZ, six vibration modes occurred in the closed category, while five occurred in the open one. This indicates higher sensitivity to vibration in the closed category than in the open one. The explanation of such results may be due to the increase occurred in the mass from 4555 kg in the open case to 5436 kg in the closed one, and also due to the overhang effect of the Z-slider that carries the spindle housing in the closed frame. However, in the open category, the spindle housing show the maximum deformation in the first three mode shapes and the fifth mode shape, while that occurs only on the first and third mode shapes in the closed category. That indicates lower probabilities for resonance in the spindle housing in the closed case. Besides, the table and bed shows low deformation in all mode shapes of the closed category except the fifth one, while in the open category they show high deformation in the last three mode shapes especially the forth one. That indicates higher dynamic rigidity for the bed and table in the closed category.

<table>
<thead>
<tr>
<th>Mode shape</th>
<th>Natural frequencies</th>
<th>Position of max deformation</th>
<th>Natural frequencies</th>
<th>Position of max deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>56</td>
<td>Spindle housing</td>
<td>53.7</td>
<td>Spindle housing</td>
</tr>
<tr>
<td>2</td>
<td>63.5</td>
<td>Spindle housing</td>
<td>57.2</td>
<td>Z-slider</td>
</tr>
<tr>
<td>3</td>
<td>129.9</td>
<td>Spindle housing</td>
<td>90.5</td>
<td>Spindle housing</td>
</tr>
<tr>
<td>4</td>
<td>208.15</td>
<td>Table</td>
<td>96.8</td>
<td>X-Guide way</td>
</tr>
<tr>
<td>5</td>
<td>210.47</td>
<td>Spindle housing</td>
<td>199.9</td>
<td>Table</td>
</tr>
<tr>
<td>6</td>
<td>246.76</td>
<td>Column</td>
<td>228</td>
<td>Z-slider</td>
</tr>
</tbody>
</table>

Figure 7. Static loop stiffness in X and Y direction for open and closed categories
Figure 8. First six mode shapes for the (a) Open category, and (b) Closed category
6.5. Harmonic Analysis Results

As shown in Figure 9, for the open category, the maximum dynamic compliance of about 0.12 μm/N in X-direction and 0.05 μm/N in Y-direction occurred at 60 HZ, which corresponds to a dynamic stiffness in XZ and YZ planes of 8 N/μm, and 20 N/μm respectively. For the closed category, the maximum dynamic compliance of about 0.044 μm/N in X-direction and 0.97 μm/N in Y-direction occurred at 60 HZ and 90 HZ respectively, which corresponds to a dynamic stiffness in XZ and YZ planes of 22.7 N/μm, and 1.03 N/μm respectively. By comparing the maximum compliance and the compliance all over the frequency range for both categories, it can be concluded that the closed structure has much better dynamic performance in X-direction up to 220HZ especially at 160HZ at which it gives the least compliance, while the open category shows better performance in the Y-direction from 70 HZ to 190 HZ, especially at 180 HZ at which it shows the least compliance.

7. Conclusion

An integrated modeling and design approach is developed to create a virtual evaluation system capable to evaluate the static and dynamic performance of machine tools during its design stage without the need of prototyping. The modeling of the machine tool mechanical structures together with the modeling of the cutting process are all integrated together to give a comprehensive evaluation of the static and dynamic performance of the
entire machine tool. The system is then applied to a case study at which a comparison investigation based on static and dynamic performance is established by a series of analysis on open and closed milling machine tool categories. The closed category proved to have better dynamic performance than the open one, especially in the x-direction. It also shows better static performance in y-direction. However, better results are expected if the overhang problem is treated.

References