MECHATRONIC ANALYSIS OF MACHINE TOOLS

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Abstract: High speed machine tools show close interaction between dynamic behavior of the mechanical structure, drives and numerical control. In order support designers of high performance machines, new analysis tools for an integrated holistic mechatronic optimization have been developed in the European project MECOMAT. Fully parameterized SAMCEF models of the mechanical structure are first optimized using BOSS quattro V4, drivers built in SIMULINK are linked with SAMCEF Mecono and tuned. Subsequently different analyses have been performed to evaluate the performances of the complete mechatronic system.

INTRODUCTION

Today market is asking for fast and accurate machine tools, to reduce machining time and assure the required precision, constructed with stiff but light mechanical structures, and drives with wide bandwidth.

Traditional machine tool design is performed by separated and sequential optimization of the mechanical structure and the control system. Today this approach becomes less and less effective because rigid transmissions and light structures are often used, requiring to consider also the distributed compliance of the structure while evaluating the controlled system performance. Therefore it's essential to study the behavior of the structure with the control system active, using an integrated mechatronic approach that considers the dynamic coupling between them [1].

Many European (and Italian in particular) machine tool manufacturers offer a high number of machine variants, each one customized for the specific needs of a reduced number of customers: each product version is usually obtained starting from existing solutions and modifying some key geometrical dimension or structure size. In this scenario, the whole product range can be usually categorized in a small number of basic “families”, based on the same “machine concept” (i.e. typical applications, axis disposition, transmission typology, etc.) and, sometime, even different families share some common components, following a modular approach to minimize production costs and maximize product quality.

When a new machine has to be developed the “product concept” has first to be defined, requiring the evaluation of several design variants in a short time: a very fast assessment is usually possible only if a specific design experience on similar machine is available, otherwise the time required to estimate the performance of the mechanical structure is usually too long. The MECOMAT project, “MECHATRONIC COMPILER FOR MACHINE TOOL DESIGN” [2], was finalized to develop tools and methodologies to
support machine design, starting from the conceptual phase, by mechatronic synthesis, analysis and optimisation.

The present paper presents the modeling approach developed by ITIA-CNR in the mentioned project, applied to a three axis machining center, proposed as a demonstrator by the COMAU company.

1 ANALYSIS SUPPORT FOR THE “PRELIMINARY DESIGN” PHASE

After the best machine architecture has been selected during the conceptual design phase, in the next step, often called “preliminary design”, the machine is defined more in detail, identifying optimal values for a large set of continuous and discrete parameters, like geometrical dimensions, structure thickness, number of ribs, etc. (see Figure 1). Many constraints and goals, of different nature, have to be taken into account, like stiffness and weight specification, manufacturability, cost, etc. It is important to support this phase with analyses performed by different CAE tools, for example to evaluate the behavior of the mechanical structure. In the industrial practice the first structural models often represent the structure as a set of rigid bodies connected by guideways modeled as lumped compliances. This approach is useful for a first comparison between alternative layouts, but, especially for high speed machines, the approximation done is often too large, because the goal of inertia minimization produce light structures with non negligible distributed compliance.

![Figure 1 A typical machine tool structure, with stiffening ribs](image)

The development of Finite Element models (“FEM”) of the structure is today quite time consuming and, therefore, is relegated to later development phases, when a very limited number of design variants is under evaluation. FEMs are typically used to evaluate purely mechanical aspects, like the static stiffness at the tool or the first natural frequency with locked motors: an indirect estimation of performances like machining capability and motion accuracy is possible only thanks to the large designer experience,
built on similar machines evaluated in the past. This approach is usually very effective but becomes quite risky when especially innovative design solutions, like machine tools adopting linear electrical motors and/or a parallel kinematics concepts: the relationship between purely mechanical analyses and machine performance is less known. Nevertheless it has to be noted that even revolutionary machines can be evaluated by an expert end-user, performing several standard or custom tests, from tracking accuracy along specific trajectories, to part machining and subsequent measurement. Starting from this consideration, the “Virtual prototyping” approach has been developed [1]: the basic idea is to build numerical models that permit to simulate some of the most significant tests performed in practice. To reach this goal it is necessary to build a model able to execute a part program and containing a sufficiently accurate description of all phenomena influencing the quality measure related to the selected tests.

Following mentioned considerations, in the framework of the MECOMAT project a specific modeling approach has been proposed for the “preliminary design” phase, with the following goals:

1. quick, even if approximate, structural analysis of the machine;
2. evaluation of a machine family, defined by a parametric model, enabling sensitivity analysis and optimization, to highlight the most critical regions in the structure, that will require an accurate stiffness and/or mass optimization in the following activity (“detailed design”)
3. preliminary evaluation of the machine in operating conditions by the development of a “virtual prototype”, joining the structural model to a representation of the control system;

The proposed methodology doesn’t pretend to generate “automatically” a detailed design of the mechanical structure: the designer knowledge remains essential, also to correctly evaluate numerous constraints like maintainability, ergonomics, production cost, legislation compliance, etc. The goal here is permit a fast and more accurate analysis of several machine variants.

To evaluate machine accuracy during finishing operations with high acceleration (e.g. a milling machine finishing the sculptured surface of a mould), it is useful to execute mechatronic simulations of motion with no cutting force (avoiding to incur in the complexity of cutting process modeling) as done in industry, using external instruments to measure the tool position (starting from the circular trajectories specified by the ISO 230-4 standard [3]) or performing very light machining operations along specific trajectories and reconstructing the tool position from the workpiece surface profile.

In order to simulate machine motion it is necessary to describe in the model, besides the mechanical structure, also components like motors, sensors, drives and control system. This kind of models can be very complex, because it is necessary to correctly reproduce the characteristics of all components that can limit machine performances. For an effective industrial application of the mechatronic modeling it is therefore required to have at disposal an appropriate library of component models. This library can be built by research centers and large machine tool companies (as it is sometime the case today)
or supplied by the corresponding industrial suppliers of the “physical component” (a very rare case until now). A component for which the collaboration with the corresponding supplier is fundamental is the Numerical Control (“NC”), because it would be extremely complex and unreliable to build a self-made model reproducing the trajectory generation strategy adopted by each specific NC, starting from the part program in ISO format. At the moment some producers of NC are able to supply SWs that reproduce on a standard PC, perhaps with some limitations, the reference position signals calculation (NUM [4], [5] and FIDIA [6]).

2 MACHINE MODELING FOR PRELIMINARY DESIGN

To achieve the previous objectives, models must represent correctly the behavior of the key machine components. Models have been built exploiting the SAMCEF environment [7] but also Matlab-Simulink\(^1\) [8] (and “Real Time Workshop” to generate the corresponding C code) and external code, for specific analysis and components.

2.1 Structural modules

Different approaches were considered, with different accuracy and technical difficulty. In this paper we describe an approach based on SAMCEF fully parametric structural FE models, with shell mesh. A detailed model has to be defined for each structural module considered. Internal ribs distribution and Finite Element automatic meshing are controlled by specific parametric formula.

2.2 Guideways

The model is built with SAMCEF elements and can be used for linear recirculating guideways. The model is able to represent kinematics, compliance and friction of the guideway.

2.3 Kinematics chain

The proposed model built is built with SAMCEF elements and describes an axe transmission based on a recirculating ball screw, with the corresponding bearings and coupling connecting the electrical motor. A specific MECANO element has been developed during the project to represent a screw joint acting along a flexible beam representing the screw.

2.4 Sensors

The control loop is usually based on the actual position measured by a linear optical encoder. The model is built for the mechanical part with SAMCEF elements (and it is assembled, together with the kinematic chain, in the correct location on the machine), representing local resonances and play, if desired. A Simulink model can be added, to reproduce the measuring error and bandwidth limitation.

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\(^1\) Matlab Simulink and Real Time Workshop are trademarks of The MathWorks, Inc.
2.5 Drives and velocity regulators

The drive model is built in Matlab-Simulink. Different models have been developed taking as reference industrial products [10]. In this paper we present a simplified model reproducing the classical structure with concatenated velocity and position loops.

2.6 Numerical Control

The Numerical Control model must be able, as done in reality, to interpret an ISO part program and generate the position references for each machine axis. This operation is differently done by each NC manufacturer and constitutes a strategic industrial know-how. To correctly reproduce the behavior of a specific NC, without diffusing the proprietary algorithm, the NC producer is invited to provide a “black-box” routines (possibly simply extracted from the real NC code in case of PC-based NC), that performs the calculation without revealing confidential information. Also NC installed on real machine tool could provide the same information (saving to a file the requested signals), but this solution would slow down considerably analysis and optimization of several machine variants.

2.7 Structural Model of the machine

Using a SAMCEF fully parameterized FE model for structures, kinematic chains and guideways, we will be able to represent all the structural parameters taken into account during the preliminary design process. The machine used as test case is a three axis milling machine built with box-in-box architecture and a gantry X axis.

![Diagram of Y and Z machine axis with component nomenclature.](image)

Figure 2 –Model of Y and Z machine axis with component nomenclature.

The parameterized model permits to perform structural optimization, imposing objectives and bounds and varying geometrical dimension or other structural parameters like guideway stiffness, ball screw diameter etc. Each component model is described by a large number of parameters, permitting to explore very different design solutions for the machine, belonging to the selected “Machine Family”. The designer can specify the working volume (or the corresponding axis strokes) and performances requirements (as static stiffness).
Figure 3 – Model of the complete machine with component nomenclature.

Figure 4 – SAMCEF mechanical model of the machine with different parameters
2.7.1 Guideway
The proposed model describes linear recirculating guideways, reproducing the kinematics, compliance and friction [11]. The model includes also some structural parts, used to stiffen the machine structure where guideways are located to avoid excessive local deformations. In order to be able to automatically assemble the whole machine model while the guideway location is varied, changing the corresponding parameters, it has been decided to consider the stiffening elements as part of the guideway model: during the assembly process they will be “glued” to the corresponding structural elements (by the .STICK command).

![Figure 5 SAMCEF model of guideway](image)

2.7.2 Ball screw kinematic chain
To build a typical machine tool kinematic chain based on a ball-screw, the following model, based on new SAMCEF element Flexible screw, has been proposed:

![Figure 6 Scheme of ball screw kinematic chain model](image)
The model is able to represent
- Ball screw kinematics, with nut compliance and friction
- Support bearing local compliance
- Motor mass, inertia and screw coupling compliance
- The kinematic chain model includes also the position sensor

2.7.3 Drive

![Simulink model for axis drive](image)

A simplified version of an industrial Drive is proposed, with an inner PI (Proportional and Integral) velocity loop and an outer P position loop. Velocity and acceleration Feed Forward with limited bandwidth derivation are present. This model has been compiled with Real Time Workshop and linked with MECANO and it can be used for non linear time simulations.

2.8 PRELIMINARY DESIGN OPTIMIZATION

With the machine parameterized model it is possible to perform different kinds of analysis. First linear structural analyses were performed during an optimize process driven by BOSS quattro V4, mimicking the process of the mechanical designer to optimize the structural parameters. The optimal solution was then inserted in the complete mechatronic model of the virtual machine.

2.8.1 Structural preliminary design optimization

Structural preliminary design is here optimized evaluating the static stiffness at the tool and normal modes with locked motors. The imposed bounds are minimum value for static stiffness and maximum value for the moving masses. The objective is to maximize the first resonant frequency (locked axes). Figure 8 describes the optimization study definition in BOSS quattro V4.
Figure 8 – BOSS quattro V4 scheme for structural optimization.

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<tr>
<th>Bounds</th>
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<tr>
<td>Static stiffness in X</td>
<td>Kx</td>
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<td>Static stiffness in Y</td>
<td>Ky</td>
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<td>Static stiffness in Z</td>
<td>Ky</td>
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<td>Axe X Mass</td>
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Figure 9. In Figure 10 represents objectives and bounds variations during iterations in an optimization of some geometrical parameters in SLIDE_X and RAM. This is a simple but significant example of what could happen in an engineering department during the design process of a new machine tool.
Figure 9 – Design Parameters variation during an optimization.

Figure 10 – Stiffness bound and frequency objective variation during an optimization.
2.8.2 Super Element Reduction and Drives Tuning

After optimizing the structures, a reduced order linearized model has been generated, adopting the component-mode synthesis approach [9]. The non linear MECANO model is linearized and passed to DYNAM that performs the Super-Element (“SE”) reduction. The following “boundary” or “connection” dofs where selected: motors third nodes and tool translations. The linearized model is imported in Matlab-Simulink environment to perform Drives Tuning, using frequency domain analysis.

Matlab-Simulink is a powerful environment to perform drives tuning. Frequency or time domain analysis are quickly performed using linearized models of the structure, permitting to reproduce some tuning procedures used on real machines.

2.9 COMPLETE MECHATRONIC MODEL OF THE MACHINE

The mechatronic model of the machine is build in the SAMCEF environment. The drives are linked with MECANO and the axis references for time simulations are read from data files generated by a NC emulator provided by NUM.

Once tuned the drives, the model can be used as a Virtual Machine Tool (“VMT”), to perform time simulations, like on real machine tests. We can evaluate the effect of different parameters, relating to sensors, drives, tuning parameters and NC. The VMT on one side is an approximate representation of a real machine, but, on the other side, permits a very deep study of its behavior, that would be possible on a physical prototype only adopting a very complex and costly instrumentation system, able to measure machine motion and deformation during the experiments.
2.9.1 Static Stiffness evaluation with active control

It’s possible to compute deformations due to static forces applied on tool, uniform axis accelerations etc. The mechatronic model permits to reproduce a typical Experimental Static Stiffness Test, evaluating also the effects of linear sensor location and drives tuning on static stiffness at the tool and disturbance rejection.

![Static Response in X direction](image)

*Figure 13 – Time simulation of Static Stiffness test.*

2.9.2 Tool Tip Impact Test

The dynamic compliance at the tool can be evaluated computing the corresponding Frequency Response Function (“FRF”) with active drives. Like in experimental test,
Time simulation are performed imposing a stand-still command to the axis and applying an impact force on tool (see the following figure).

**Figure 14 – Time simulation of impact test.**

Time simulation results are then elaborated in Matlab to obtain the corresponding information in the frequency domain. It is therefore possible to investigate the effect of tuning parameters on the dynamic compliance tool FRF.

**Figure 15 – Comparison between dynamic compliance at the tool with locked motors and active drives.**
2.9.3 Trajectory Execution (without cutting forces)

After having tuned the axis, time simulation can be performed imposing as a reference position on the axis the required trajectory, generated by the NC Emulator. As example the execution of a square angle with 20mm side is shown, using different Acceleration Time values (T_{acc}: it is time that the NC uses to reach the maximum acceleration). The ISO instruction are G1 X20 Y0 Z0; G1 X20 Y20.

Adopting T_{acc} = 5ms and T_{acc} = 50ms, different velocity and acceleration profiles are obtained, as shown in Figure 17. This produces different performance on trajectory execution. The trajectory with T_{acc} = 5ms is faster but less accurate than the trajectory with T_{acc} = 50ms as shown in the following figure.
Figure 18 Trajectory execution. Reference position, compared to the position measured by the linear sensors and to the actual tool position.

3 Conclusions

The paper presented a modeling and analysis methodology developed during the MECOMAT project. The main goals were:

1) Fast model development and analysis, compatible with the short timing of customized product development in the machine tool sector

2) Mechatronic modeling, in a “Virtual Prototyping” prospective, to evaluate innovative design solution for high speed machines, where structure-control interaction is significant

The proposed approach is based on the development of parametric models, describing design solutions belonging to a set of “machine families”. While the development of mechatronic models is today basically possible with the most advanced CAE packages, an efficient industrial application in sectors where, as for machine tools, the analyzed product contains a lot of sophisticated commercial components, will be possible only when an adequate library of numerical models will be commercially available.
4 Acknowledgements

The authors would like to acknowledge the European Commission for sponsoring the MECOMAT project in the ‘Competitive and Sustainable Growth’ Programme (N°: GRD1-2000-25270, 2001-2004) and the valuable work of all project partners (CE.S.I. (I), K.U. LEUVEN R&D (B), LANCASTER UNIVERSITY (UK), BUDAPEST UNIVERSITY (HU), ITIA-CNR (I), CETIM (F), COMAU (I), HOLROYD (UK)).

5 References

[2] MECOMAT project “MECHATRONIC COMPILER FOR MACHINE TOOL DESIGN” (GROWTH N°: GRD1-2000-25270); Final Publishable Report