Modeling of machining operations based on the Virtual Machine Tool concept

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ABSTRACT — _This paper focusses on dynamic modeling of machine tools. Particular attention is given to integration of Computer Numeric Control (CNC) model, and interactions with machining process. In real machining conditions, modern machine tools show close interaction between dynamic behavior of mechanical structure, drives, and CNC. Mechatronic simulations are done thanks to an integrated methodology that combines control and Multibody System (MBS) capabilities in a nonlinear Finite Element solver (FEA). Force interactions between cutting tool and workpiece are also considered. To achieve this end, a specialized cutting force element has been developed. It considers dynamics of the tool tip combined with the tool workpiece engagement to generate cutting forces that are applied on the structural model. The capacity of such digital twin model to simulate complex machining operations is demonstrated considering several applications._

1   Introduction

One of the objectives of the Twin-Control project [1] is to develop a simulation system that integrates different aspects that affect machine tool and machining performance, providing better estimation of machining performance than single featured simulation packages. This holistic simulation model will be linked to the real machines in order to update itself according to their real condition and to perform control actions that will lead to performance improvements.

Accurate simulation of modern high-speed machine tools requires models that represent the flexibility of all components and their interactions [2,3]. A mechatronic model of a machine tool can be defined from combined use of 3D MBS and FEA methods for mechanical aspects, and functional modeling for the CNC. Even though concurrent use of these technologies is quite common in some industrial sectors as automotive, it is quite new in the machine tool industry. The performances of this multi-model approach can be poor due to a lack of integration between the different tools. This paper introduces an integrated methodology that combines MBS capabilities in a nonlinear FEA solver called SAMCEF Mecano [4,5]. The dynamics of the machine is accurately modeled considering FEA models of the components connected together by a set of flexible kinematical joints. Specific models are implemented to deal with drive-trains and motors dynamics. Furthermore, an advanced cutting force model is integrated to capture force interactions between the tool and the workpiece.

2   The Virtual Machine Tool (VMT) concept

Within the scope of the Twin-Control project, the VMT concept was used to model two machines, a high-speed 4 axes box-in-box machine from Comau, and a large 3 spindles five axes machine from Gepro.

2.1 Structural model

To fully model the dynamic behavior of a machine tool in operation, following objectives are set:
- Account for the flexibility of all structural components, connections and feed drive to obtain a model that is able to represent vibrations inside the machine
- Limit the number of degrees of freedom (DOF) to as few as possible to allow for efficient time domain simulation (small time step imposed mainly by the machining simulation module and the controller model)

Usually, a machine is made of several main structural frames, which are modelled using the super-element technique. The modal contains of the super-elements allow considering vibrations up to a given frequency range. Non-structural masses are added to the moving frames to properly account for all moving components.
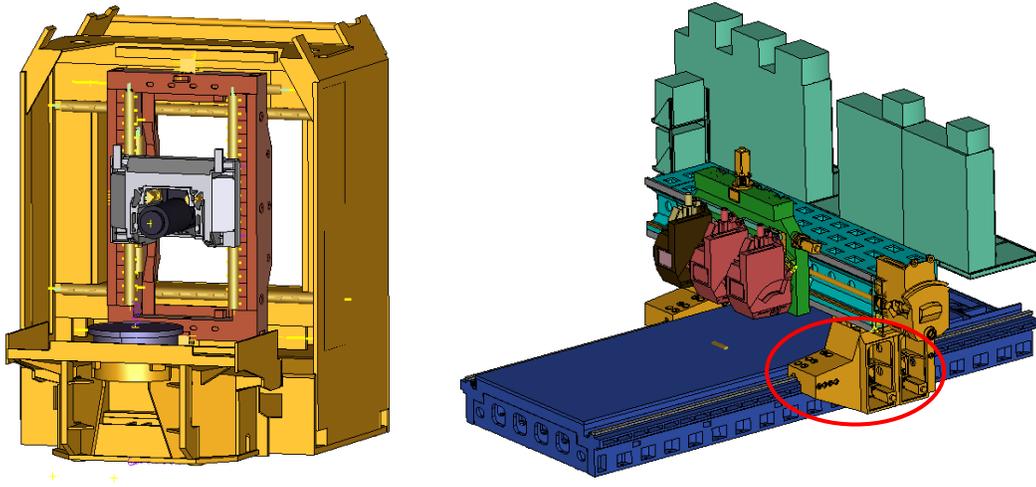
Fig. 1. A) Comau's Urane 25V3 machine B) Gepro's 502 machine

The guiding system for translational motion between 2 frames is based on sliders. Modelling such devices requires a flexible slider element, which constrains a node to move along a deformable trajectory represented by a beam element. As the track is part of the structural frame model, fictive beams are used to connect the slider nodes to the retained node of the super-element, considering its stiffness inside the slider element. The skates are idealized by the sliding node and an associated bushing that characterizes its stiffness and damping.

2.2 Drive train

If the machine is driven by linear motors as in the case of Comau machine, it is modeled by pairs of flexible sliders defined from the frame super-elements retained nodes. As the role of those sliders is to transfer axial forces, and not to contribute to the guiding function, the bushing associated to the sliding node has only axial stiffness. For those sliders we associate the sliding DOF to some additional nodes that can be force-driven by the controller model.

For drive systems including conventional motors, screw, rack-pinions, or other transmission systems, like in the Gepro machine, a library of simplified models is used. An example is given for the drive system of the X-axis of the Gepro's machine (highlighted on Fig. 1), which is made of 4 rack-pinion connections individually driven by a rotational motor and a gearbox.

Fig. 2 shows a schematic view of this model, where blue nodes are structural components, green arrows are kinematical dofs, orange cylinders represents masses and inertia, CNLI are kinematical constraints, K boxes are local stiffness, and red points belongs to the table (slider).
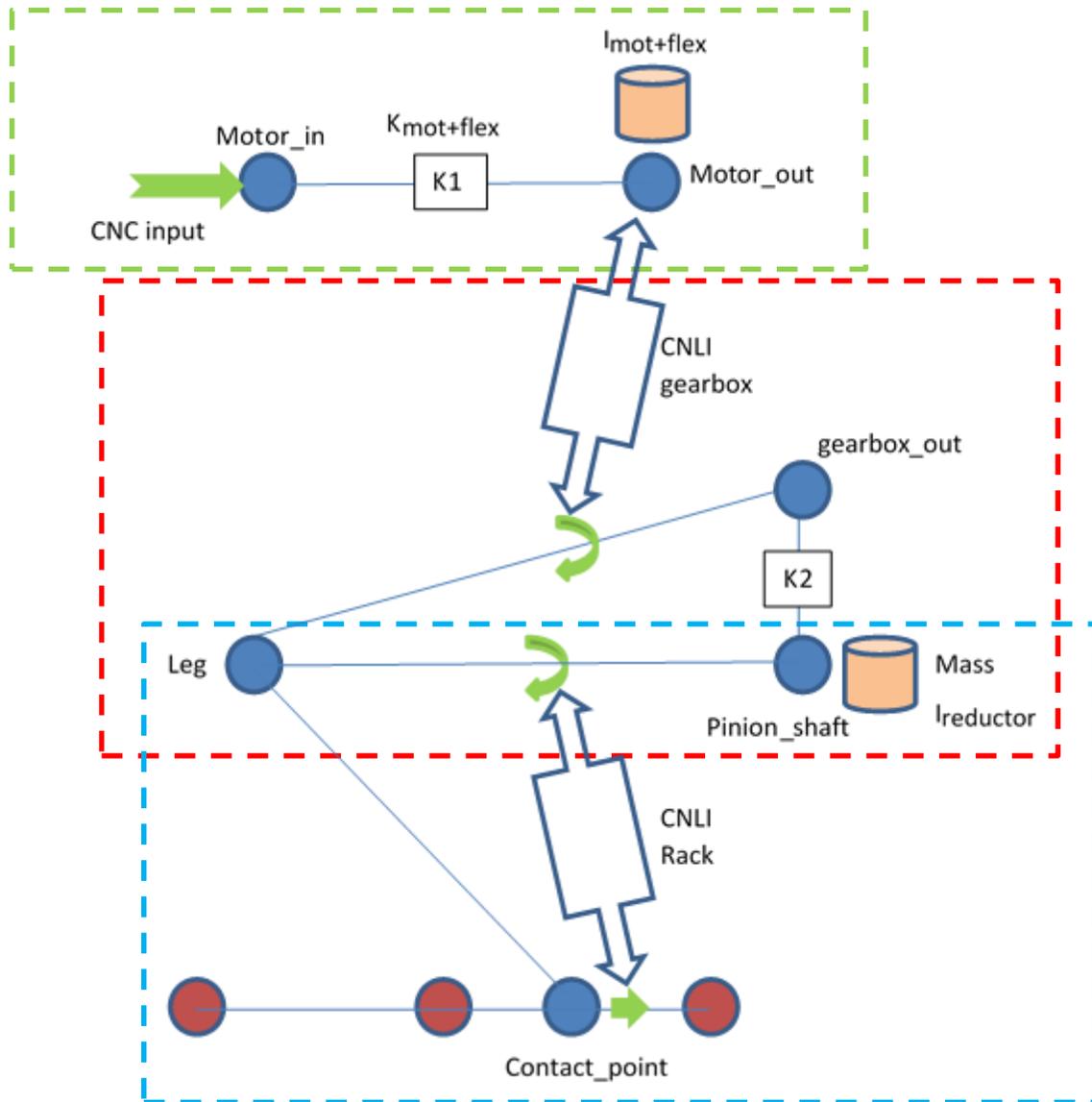
Fig. 2: Schematic view of the feed drive model (X-axis of the Gepro machine)

The green box is the motor model, it is a "scalar model" with only one rotation dof per node; flexible coupling is considered as part of the motor. Torsional stiffness is in K1, while all rotating inertias associated to the motor shaft are in the inertia cylindrical box; motor mass is reported to a structural node of the gearbox model. The red box represents the gearbox. The CNLI constraint account for the reduction factor, it relates the motor shaft dof to the output shaft of the gearbox. The gear box output shaft is modelled by two coincident nodes connected to the "leg" structure by two hinge joint of y-axis. Those two nodes are also linked by the K2 torsional stiffness of the gearbox with respect to the output shaft. The torsional inertia associated to the output shaft of the gearbox is defined in the mass& inertia element associated to node Pinion_shaft, which also include the mass of the whole system. The rotational dof of the upper hinge is driven from the CNLI that imposes the reduction factor, while

lower hinge dof is used to constraint the sliding dof on the rack (red nodes) with the second CNLI. This is done in the blue box that manages the rack pinion interaction. The coefficient of the linear constraint is the primitive radius of the pinion. This model is repeated for each of the four motors associated to this X-axis.

2.3 Control

For each axis, there are one or two rulers measuring the relative motion between two successive frames. The measurements from the two rulers are used as inputs to the controller and to compare against commanded axis motions. Those are represented in the model by sensor elements that associate measurements in the model to some nodal DOF that can be connected to the controller model.

Most of CNCs have similar architecture. Comau machine has a Siemens 840D controller and Gepro machine has a Fagor 8070 controller. The main components of controller model are:
- Position, velocity and current feedback control loops
- Velocity and acceleration feedforward
- Power stage and motor models
- Filters
- Current set-point filters

General architecture of the Fagor 8070 model is shown on Fig. 3
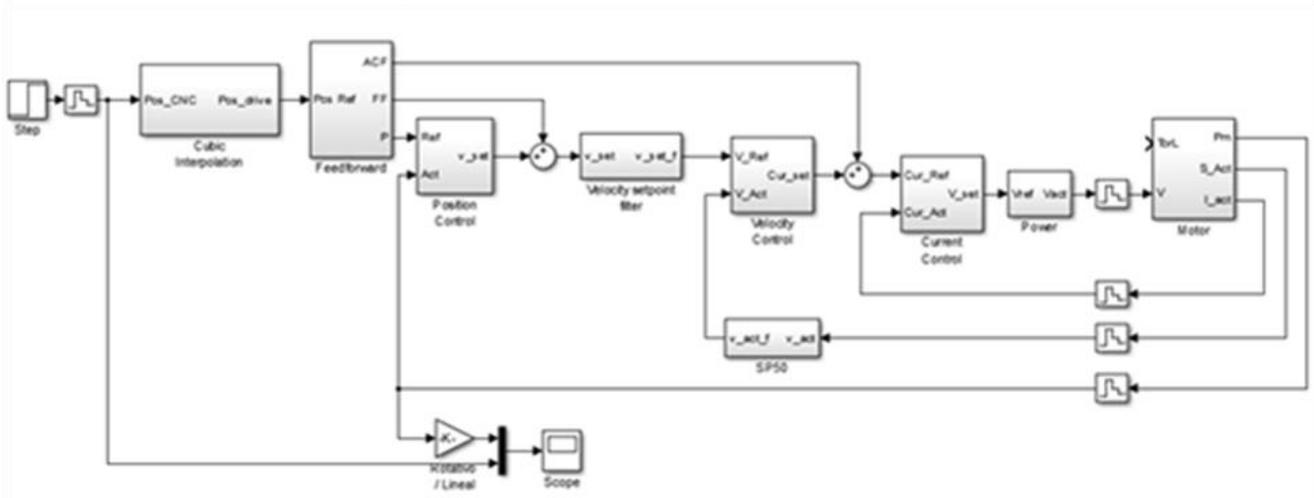
Fig. 3: Simulink model of the Fagor 8070 CNC

This model should be adapted for a transient analysis. A simplified version of the control model was developed [6] by disregarding the effect of current control loop and filters. Proper inputs and outputs are added to connect the mechanical model. Also, specific systems such as the pre-load loop are integrated to adapt to specific machine axes. This adapted Simulink model (see Fig. 4) is translated into a dynamic library and associated to a specific control element of SAMCEF Mecano that is used to manage the coupling between 1D model (Control) and the full flexible 3D model (Machine).
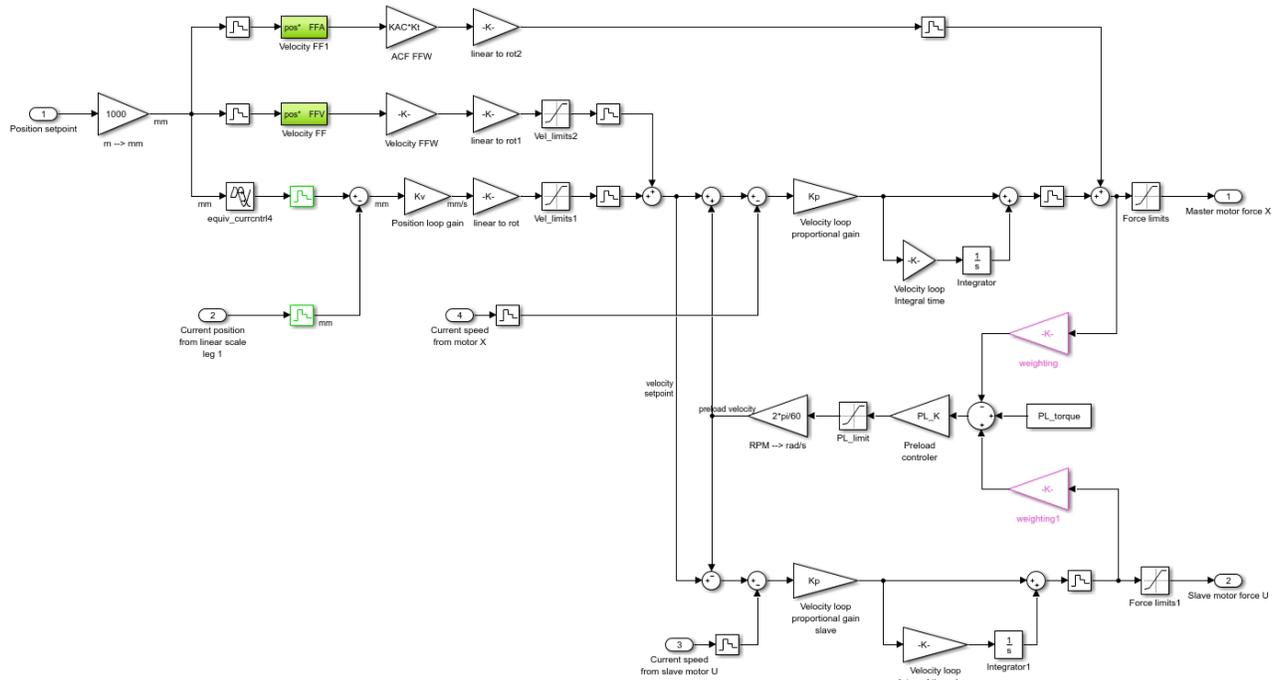
Fig. 4: CNC model for rack drive with 2 motors (X-axis of Gepro 502 machine)

3   Cutting Force Integration

To consider the entire machine system, forces from the cutting process are applied to determine their effect on the machine structure. Derivation of the forces acting between the tool and workpiece is a two-step procedure. First, the geometric and volumetric properties of the removed material are computed based on a tri-Dexel volumetric representation program developed by ModuleWorks [7]. This data is used to determine the region of the tool which is engaged in the workpiece at multiple points along the tool path. This tool-workpiece engagement (TWE), along with the tool velocity and workpiece material data, is used to calculate cutting forces using a discrete cutting force model developed by AMRC [8].

An overview of the process to obtain cutting forces within the Mecano software is illustrated in Fig. 5. Once the tool has moved a predetermined distance along the tool path, the tool position is updated in the TWE software, and updated workpiece geometry and TWE data are returned. Next, the TWE data is applied in the cutting force module to calculate cutting forces in 3 axes for each rotation angle of the tool. Finally, the cutting force module is called at each simulation time-step to obtain the instantaneous cutting forces based on the current TWE and tool rotation angle. Once the tool has again traveled a predetermined distance, the TWE is again updated and the process repeats. Note that this method is described in more detail in [9].
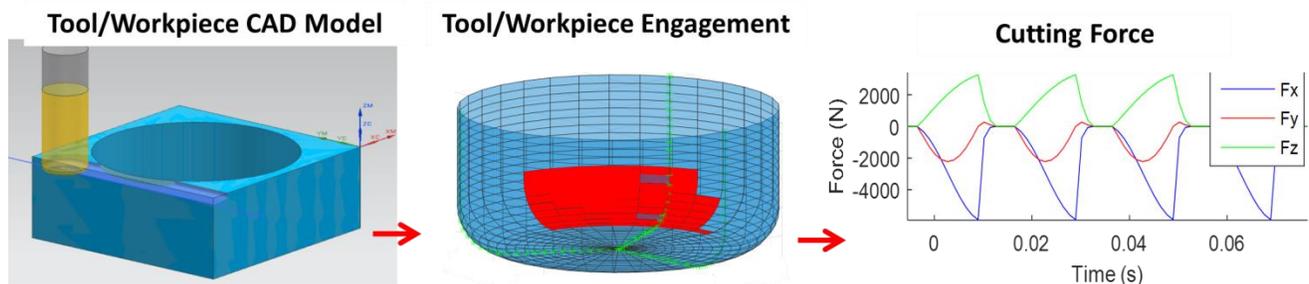
Fig. 5. Process of obtaining cutting forces

5

4 Coupling architecture

The mechanical model of the machine tool is coupled with 3 additional simulation tools (see Fig. 6). The Matlab Simulink model of the CNC is converted to C-code and included in a dynamic library thanks to Matlab Coder capabilities. As the cutting force module is also based on Matlab programming, the same approach of creating a dynamic library from C-code generated by Matlab Coder is selected. Parts of ModuleWorks tool-path simulation tool needed for TWE computation is encapsulated in a dynamic library that can be called from C-code functions

TP: Tool position
TWE: Tool/workpiece engagement
EP: Encoder position
CF: Cuttinf force
MF: Motor force
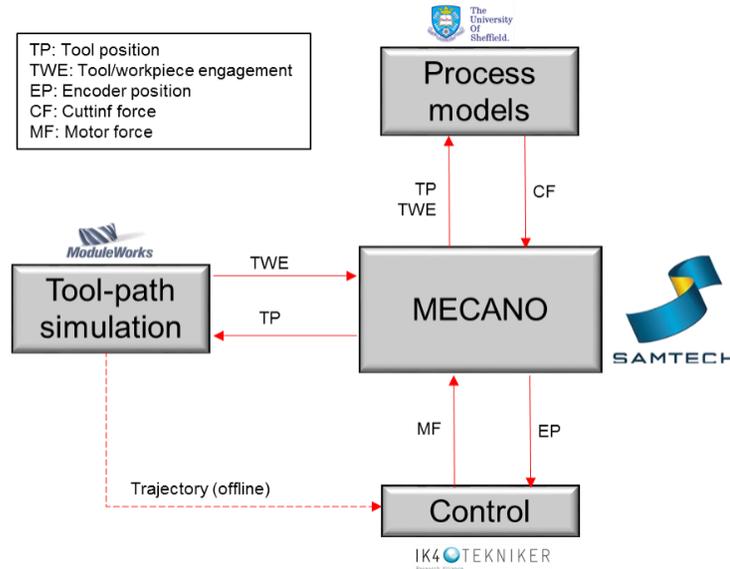
Fig. 6. Coupling scheme

In SAMCEF Mecano, two specific elements have been developed to manage those dynamics library. The DIGI element allows coupling the mechanical model to any Simulink model, and in particular to control system. The implemented staggered method is a fixed time step sampling, where both codes will exchange data (positions, forces …). Both codes manage their own time step, and can compute several instant between two sampling times without updating exchanged data. This weak coupling is usually stable thanks to the small sampling times imposed by the control loops, which imposes passing times to the solver.

The second specialized element named TOOL has been developed to strongly couple the mechatronic model of the machine tool and the machining simulation tool. It considers the relative motion of the tool with respect to the workpiece as input to generate cutting forces. The way the tool is engaged in the workpiece is determined from the position of the tool tip and a CAD representation of the workpiece, it is determined from ModuleWorks CAD/CAM for toolpath generation and simulation. This software also updates the CAD description of the workpiece during the simulation. As explained in [9], the computation of cutting forces is done in a single module that can be called in 3 different ways. Before starting the time integration, the module is initialized. Once the process starts, the TWE is computed for each current individual cut, and the machining module is updated. Finally, the module is called every time that force evaluation is required.

The flowchart of Fig. 7, shows how this elements is integrated to the Mecano time integration scheme. To fulfill equilibrium at each step of the time integration process a Newton-Raphson iterative scheme is used, where cutting forces are updated and the associated iteration matrix is generated at each iteration. As cut definition is obtained from the tool computed kinematics according to a user defined cut length, TWE is updated as soon as the tool has moved about this characteristic length since the previous update. For accurate TWE computation, the cut length

should be chosen significantly bigger than the spatial discretization used in Module Works software. As TWE computation changes the workpiece geometry when a cut is performed, the corresponding DLL can only be called once during the considered cut. This is the reason why TWE is computed outside of the iteration loop. It is updated before starting a time step that reaches the time Tc corresponding to a tool tip displacement that exceed the characteristic user defined length since last update. Next update time is extrapolated from current velocities.
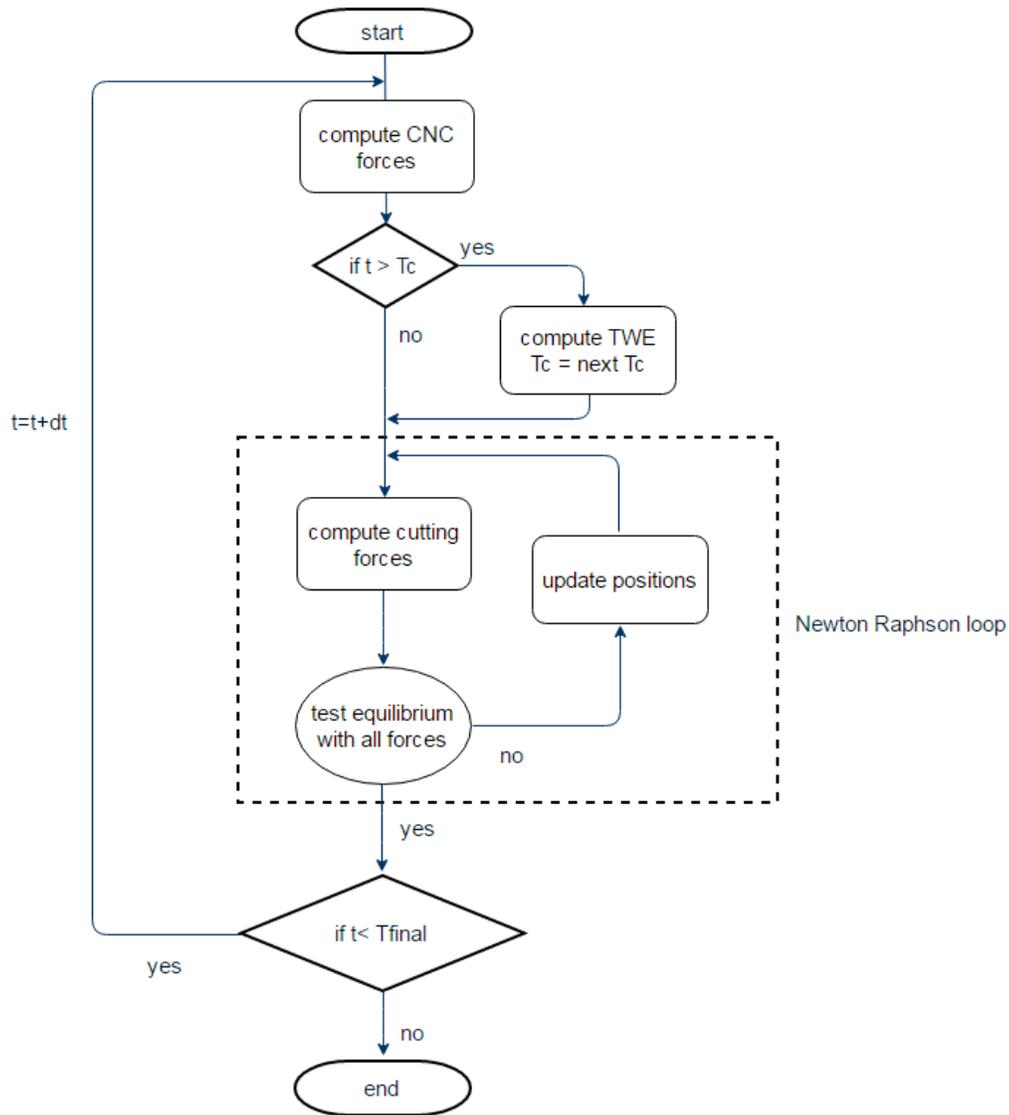
Fig. 7: computational flowchart

5 Validation of the VMT

Models are validated considering two types of tests. First, hammer tests are done in several machine configurations. Obtained frequency response function (FRF) at the spindle's tips in the 3 main directions are checked to verify the modal parameters of the structural model, and to tune the damping level. Secondly, the model driven by its controller is used to impose quick uniaxial motion. Model results are compared with experimental data obtained in real machines from the CNC monitoring. For disclosure reasons, validation tests are only presented for the Comau machine.

5.1.1 Hammer test

The modelling of a hammer test can be performed either in the frequency or the time domain. In the first approach, the flexible MBS model is used to position the machine in the test configuration, and the solver exports its linearized matrices that are used to perform a harmonic response on the frequency range of interest. For this analysis, a unitary force is applied on the hammer impact position, resulting acceleration at the measurement point is monitored to obtain the desired FRF function. Modal damping is introduced to tune the magnitude of the excited modes. For the time domain simulation, the machine is positioned in the desired configuration, and a constant force impact is applied during 1 ms. The one second interval after the impact is simulated and the acceleration signal is stored. The FRF is obtained by dividing the fast Fourier transform (FFT) of the measured acceleration by the FFT of the applied force.
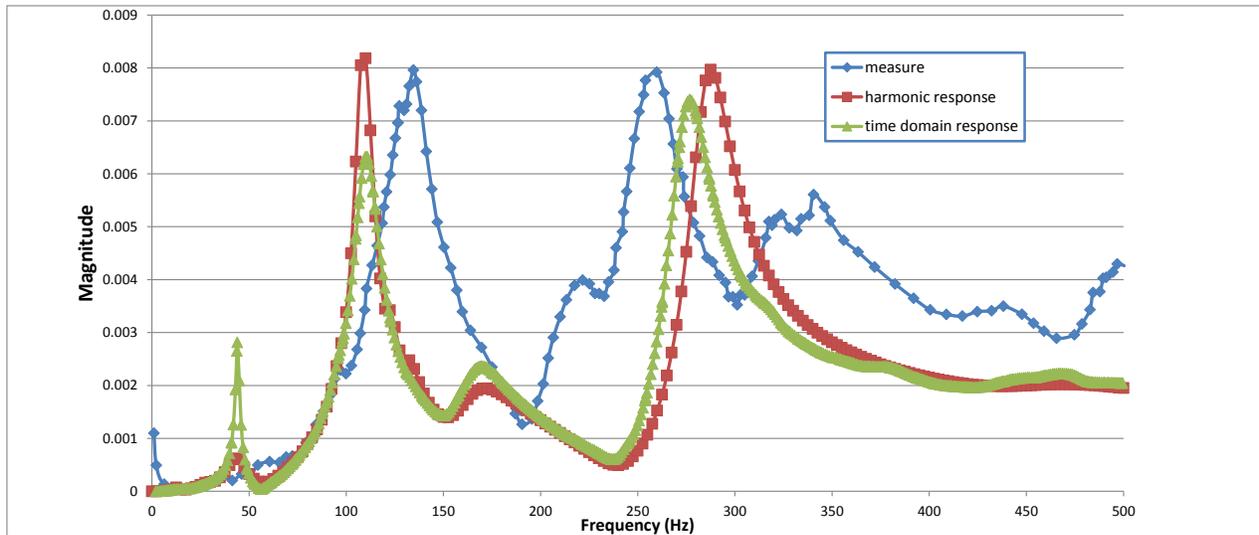
Fig. 8: *FRF (magnitude in X direction) computed by harmonic response, by time domain simulation and measured values*

Both time domain and frequency domain responses show two main peaks close to 110 Hz and 260 Hz that corresponds to the measurement within a 10% error margin. The experimental curve presents "noise" in the frequency range above 300 Hz, this behaviour is approached by the model. For harmonic response, the magnitudes at the resonances are easily tuned from the definition of modal damping. The management of damping in the time domain simulation is less flexible. However, it was possible to approach resonance magnitudes by adjusting structural damping in the super-elements and inside the ground fixations.

5.1.2 Fast 1 axis motion

The purpose of this second type of test is to validate the interaction of the machine and its controller. Using real machine dynamic restrictions (maximum jerk, acceleration and velocity), the quickest 100 mm displacement along the Y-axis is defined, and the corresponding target time function is used as input of CNC model. It also considers the position and velocity along the ruler of the considered axis from the machine model. The controller model is then able to impose forces on the dof of the sliders representing the two linear motors driven by this control loop. CNC model provides also positioning and velocity errors. Fig. 9 and Fig. 10 show the resulting axis simulated motion (position, velocity and positioning error) and motor force.
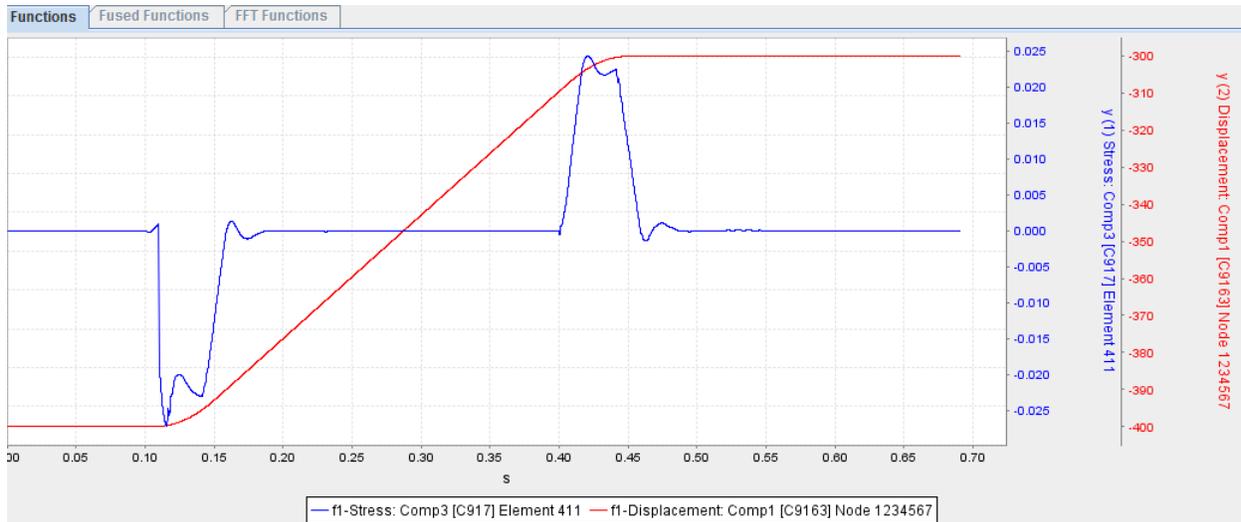
Fig. 9: *Axis position (red) and positioning error (blue)*
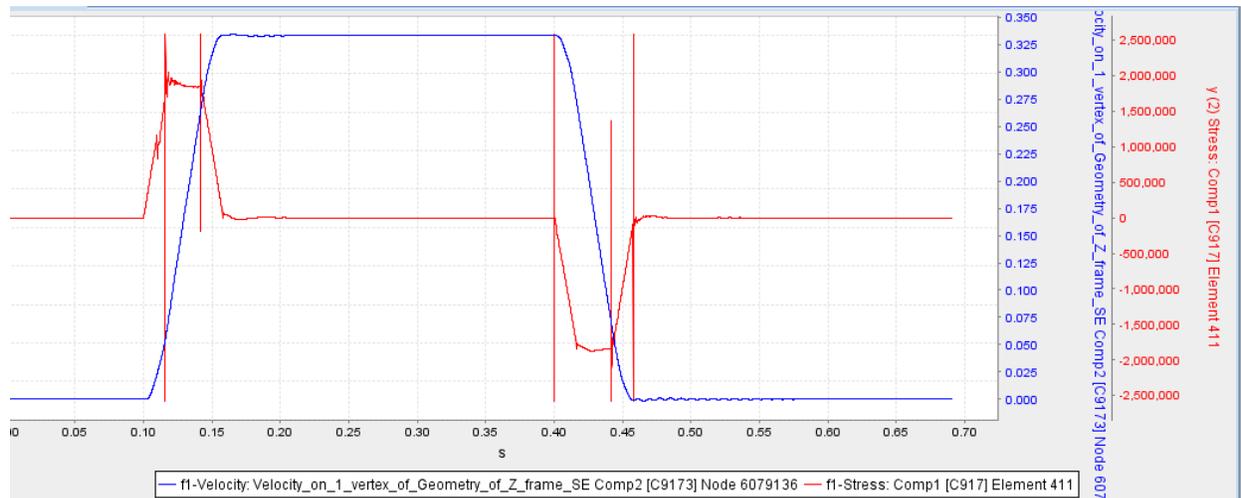
Fig. 10: *Axis velocity (blue) and motor force (red)*

In the simulation, the considered axis is driven by the CNC similarly to the physical machine, the maximal positioning error is limited to about 30 microns during acceleration phases. This is very close to the data recorded by the physical CNC during the manoeuver (Fig. 11). Computed axis velocity is also in close agreement with experimental measures. The simplified CNC model does not include the current loop, current is not available. However, the force applied in the linear motor has the same shape as the current curve of Fig. 10. There are some sign differences between the model and the measurements, those are due to the use of different axes systems in both real machine and model.

The upper graph recorded by the CNC (Fig. 11) presents the requested position and the associated positioning error. The bottom graph presents the velocity and applied current inside the linear motor, which is proportional to the generated force.

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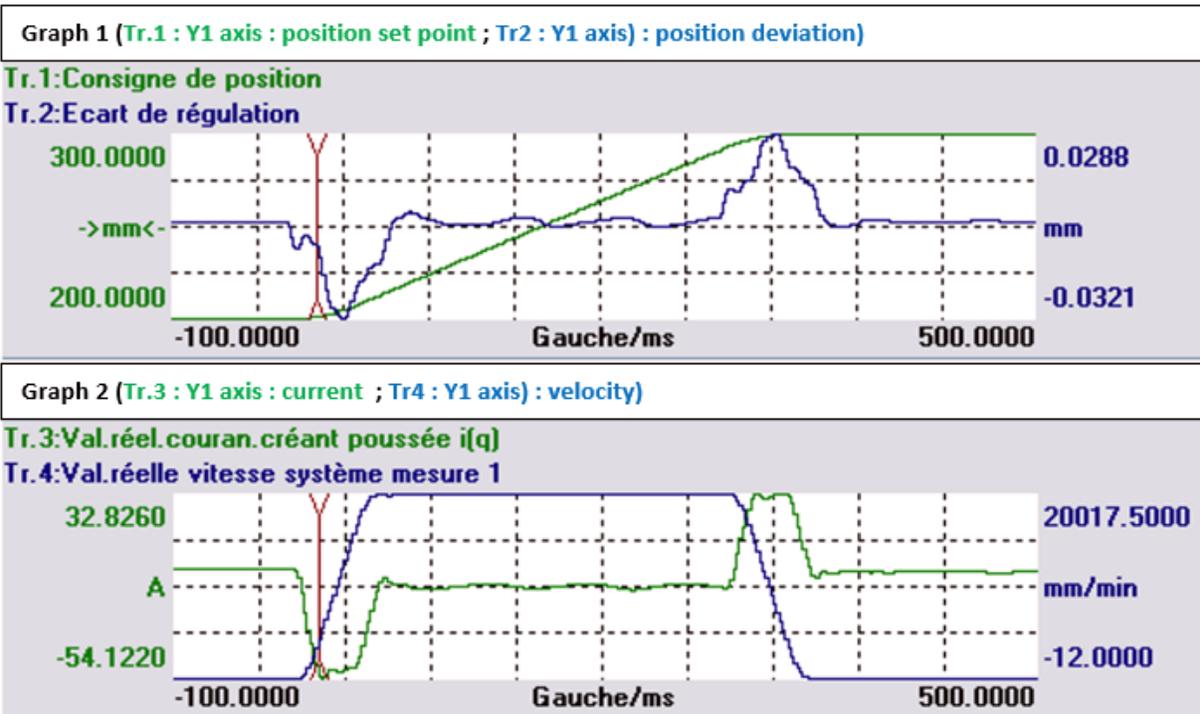
Fig. 11: *Record of the CNC during physical test*

6 Simulation of machining sequences

The VMT concept allow simulating a machining processes, considering the virtual machine tool in its real conditions, accounting for all interactions between mechanical, control and machining models [9]. This capability is illustrated for two machines, the Urane 25V3 high speed box-in-box machine from COMAU, and the Gepro 502 five axes machine.

6.1 Simple machining process with high speed box-in-box machine

The model of the Comau machine is considered. Thanks to the dedicated TOOL element, the interaction between the tool and the workpiece (rigidly attached to the machine plate – see Fig. 12) is defined.

The simulated machining process has the following characteristics:
- Move z-axis (spindle direction) forward to have a axial depth of 4 mm
- Move y-axis (vertical axis) up to simulate one cutting pass (down milling with an end-milling cutter with 50% radial immersion) as shown on the zoom of Fig. 12. The nominal tool y-velocity which is the feed velocity is 1.9 m/min
- The tool's rotational speed is set to 12250 rpm
- The milling tool has a radius of X mm and has 2 flutes. Workpiece is Aluminum 7050-T6.

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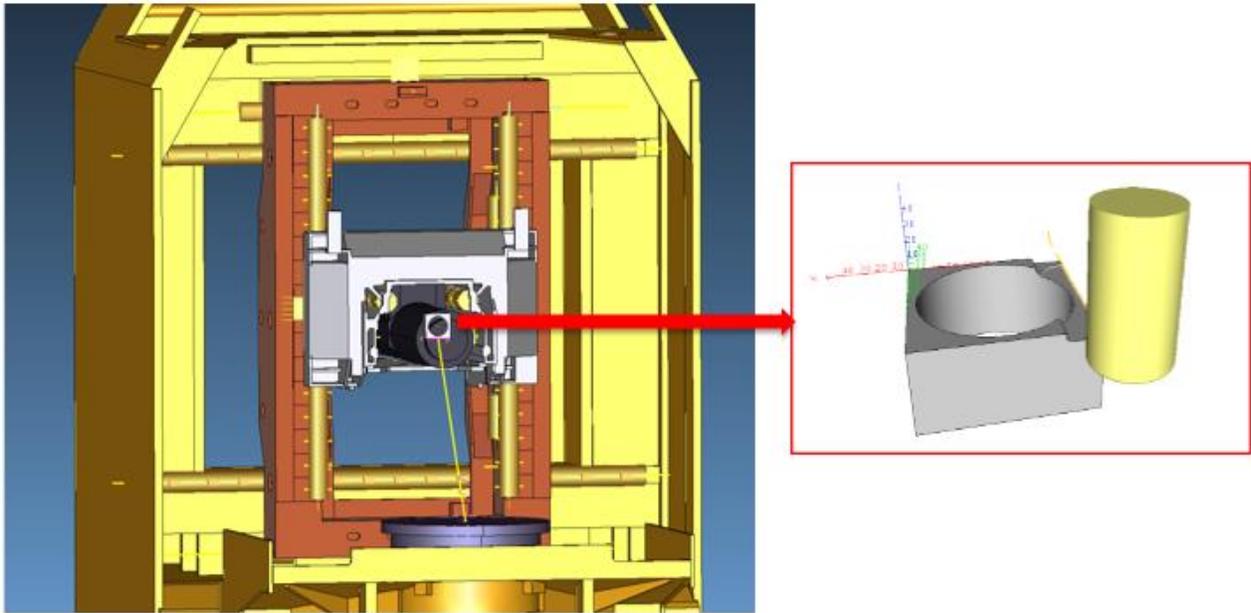
Fig. 12: Workpiece on Comau's machine & toolpath definition

The cutting forces generated by the linear motors to realize the milling process are shown on Fig. 13. One can notice that those forces are mainly reacting to both machining (force magnitude related to the shape of the workpiece) and inertia (significant constant values during acceleration phases) forces. Fig. 14 shows the position of the tool tip along the 3 axis of the machine with 3 different scales corresponding to the min-max range of each axes, the magnitude of X-axis vibration is no more than a few microns, while Y-axis magnitude is 110 mm.
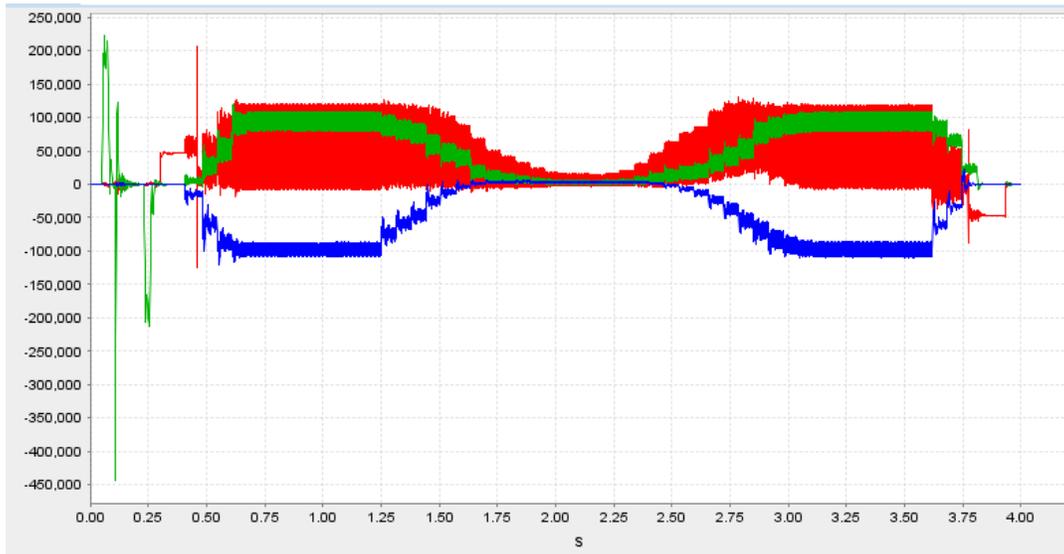
Fig. 13: Force in linear motors (X-axis, Y-axis & Z-axis)

Fig. 14: Tool positions (X-axis, Y-axis & Z-axis)

To highlight the influence of the cutting forces on the machine dynamics, we plotted the positioning error along the moving Y axis in Fig. 15. The (red curve) presented the case with the influence of cutting forces and blue curve represents the case where the cutting forces are not considered. If the influence is considered, the positioning error increases as expected. Fig. 16 shows the same kind of comparison for the tool velocity along Y-axis, vibrations induced by the machining forces are observed.
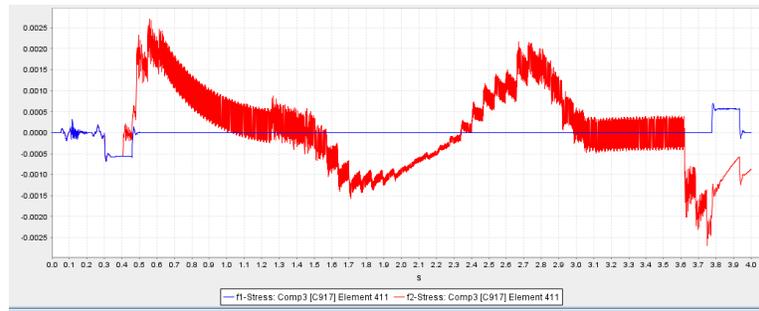
Fig. 15: influence of cutting forces on positioning error
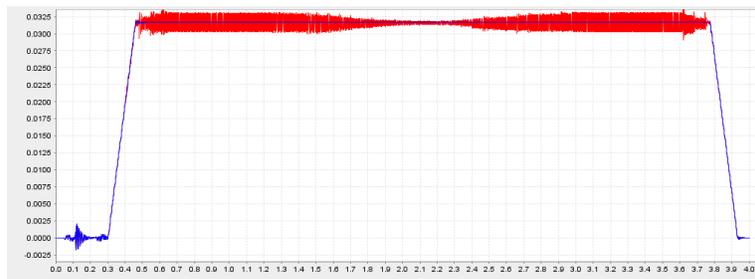
Fig. 16: influence of cutting forces on tool velocity

Finally, sensitivity analyses show the influence of the milling conditions on the cutting forces. Fig. 17 compares the cutting force along the move direction in 3 different cases: nominal (red), faster feed (v=3.8m/min – blue), deeper cut (7mm – green). Shown results are average force computed as post-processing results from the TOOL element.
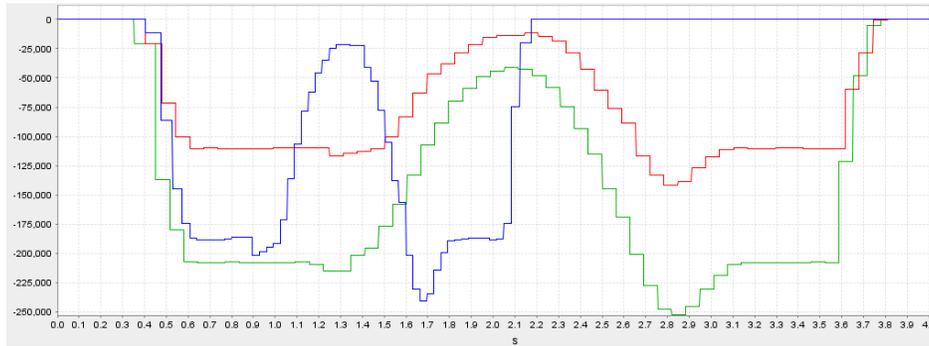
Fig. 17: Influence of machining conditions on cutting forces

6.2   Machining process with tool change with a multi-spindle machine

The Gepro machine is now considered to present another simple machining process. It also considers all interactions between mechanical, control and machining models. Thanks to the dedicated TOOL element, the interaction between the tool and the workpiece attached to the machine table (Fig. 18) is defined. In this simulation, tool changes and multiple spindles are considered. The simulated machining process is the following:

- Spindle 1 (right) is equipped by an end-mill (Diameter 10 mm – 3 flutes – corner radius 2 mm))
- Spindle 2 (center) is equipped by an end-mill (Diameter 12 mm – 3 flutes – corner radius 6 mm))
- Move z-axis down to have a 4 mm cutting depth
- Move x-axis forward to simulate a first cutting pass. The nominal feed velocity which is in X direction is 3 m/min
- Tool spinning velocities are 12250 rpm
- Once first pass is done, tools get out of the workpiece, and the machine gets back in its initial configuration. Tools are exchanged between both spindles, machine is shifted the Y-direction and the operation is repeated.
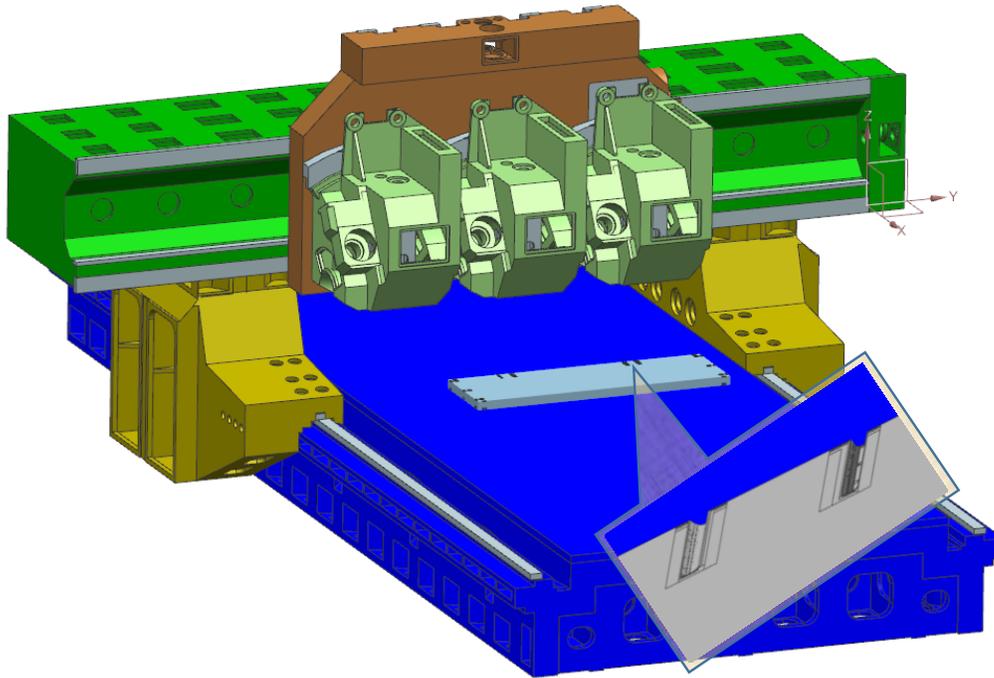
Fig. 18: machining with tool change (Gepro's machine)

During the simulation, the CAD representation of the workpiece is updated at each evaluation of the TWE. At the end of the simulation, this STL file is made available to the user for evaluation of the final workpiece geometry, including the effects of errors in the tool motion. This final workpiece configuration is shown on the machine CAD model, ones can clearly see the effect of the tool change (zoomed area).

6.3   Industrial machining process

In this section, we consider the Gepro's five-axes machine. It is used to manufacture an aluminum workpiece defined as Twin-Control case study, which includes all type of milling operations [10].
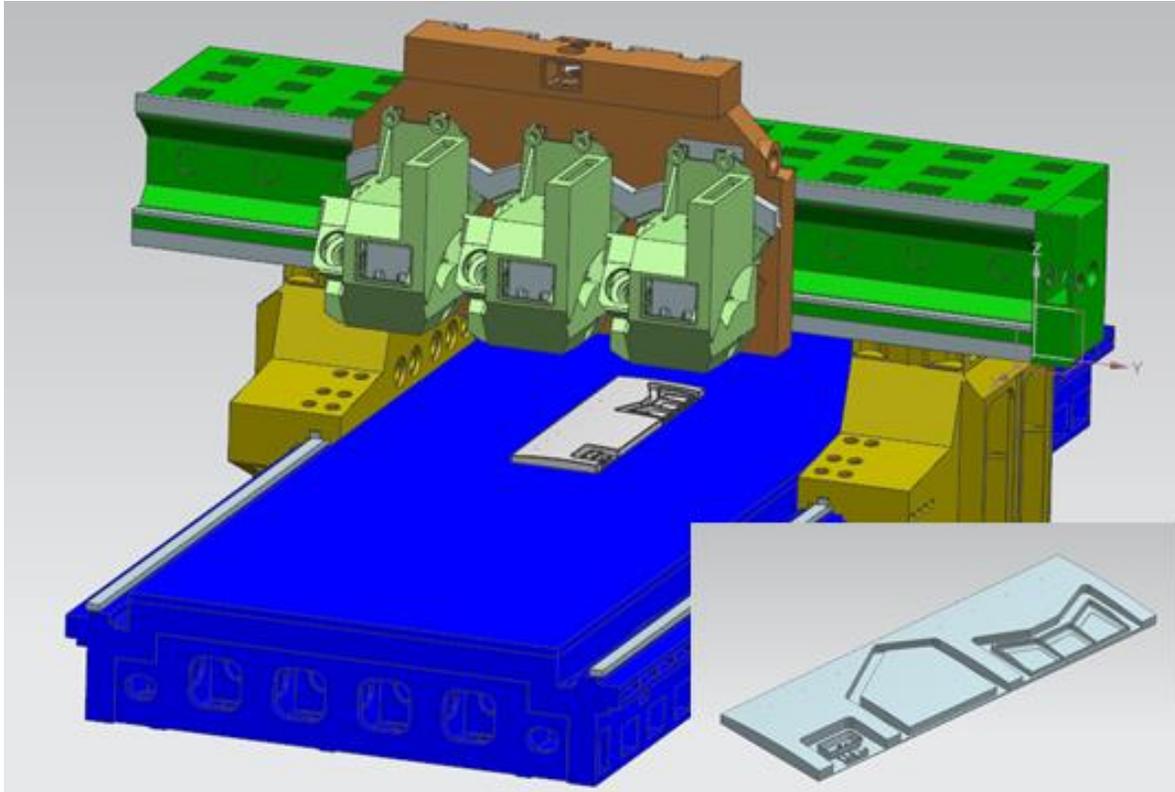
Fig. 19: Machining a complex piece with the Gepro 5 axes machine

Fig. 19 shows how the workpiece is positioned on the machine to realize the milling operations, and the final geometry is shown on the bottom right of the figure. This 3-axes milling operation is realized by the central spindle of the machine, using a 3 fluted end-mill rotating at 15000 rpm. Fig. 20 shows the machined piece. This CAD representation (STL format) is an output of the simulation. It is made available to the user for evaluation of the final workpiece geometry, including the effects of errors in the tool motion. On the zoomed area, one can clearly see the footprint of the tool, and the upper left part of the figure shows the executed tool trajectory.

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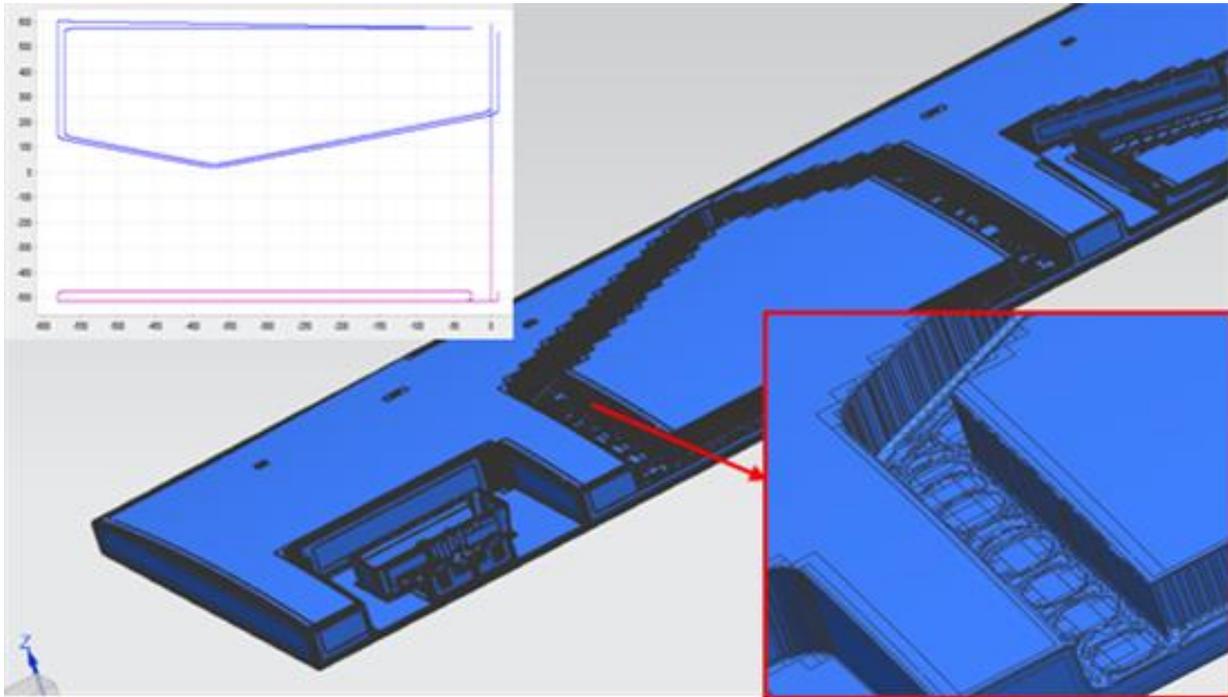
Fig. 20: STL CAD representation of the machined piece

Fig. 21 shows the evolution of the cutting forces at the tool level (large graph) during the machining process, and the associated spindle torque (lower right). Fig. 22 shows tool tip position, where successive zooms highlight mechanical vibration at both a structural natural frequency (22 Hz) of the structure and the cutting frequency (750 Hz).
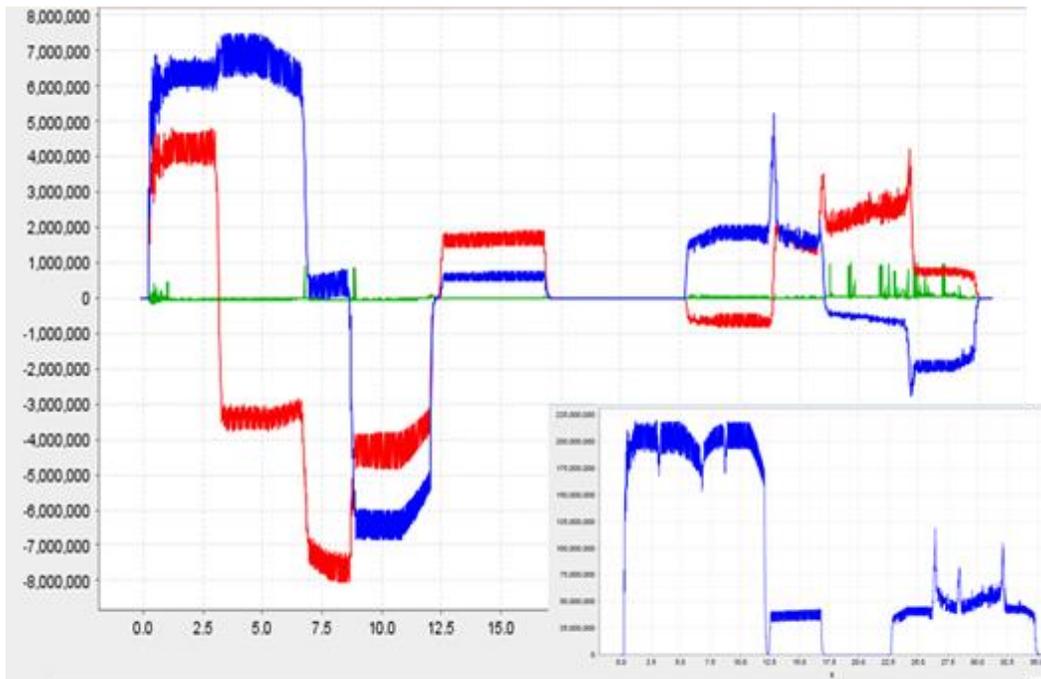
Fig. 21: X, Y and Z motor forces – Spindle torque

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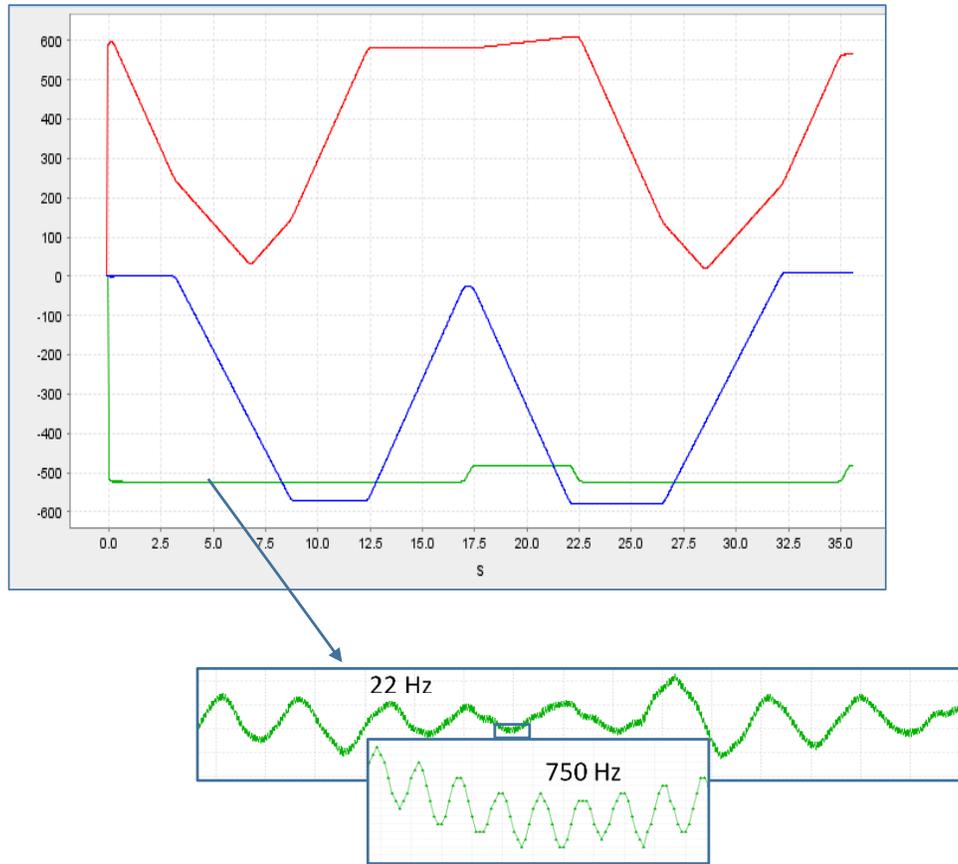
Fig. 22 : Tool tip position (X, Y and Z)

This machining sequence of about 1 minute is simulated in about 2 hours on a normal laptop. Even if far away from real time, this is acceptable for this kind of accurate model (142000 time steps – 4176 dof) used for designing new machine or Process optimization.

7 Conclusions

In this paper, a methodology for virtual prototyping of machine tool is presented.
The proposed technology is used to build mechatronic flexible multibody models of several machines. Those models are validated reproducing test data from the physical machines. This virtual machine tool (VMT) is fully coupled to a cutting force module. This approach provides comprehensive simulations capabilities for virtual machine tool prototyping in working conditions. Several machining tests are presented, which demonstrate the feasibility of such analyses. The resulting Twin-control simulation package is intended for both machine tool builders for design activities and machine tool users to improve their processes. In both cases this virtual model can be used to avoid performing costly physical tests.

Acknowledgements

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