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Analysis, optimization and accuracy assessment of special-purpose portable machines by virtual techniques

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ABSTRACT

This paper proposes a streamlined method to model, analyze and assess the overall performance of small mobile machines that can move along large parts to perform the required machining operations, conventionally called portable machines. The method is based on virtualization techniques and combines a process-force mechanistic model and a reduced machine stiffness model synthesized from virtual and experimental reduced models of subsystems. The model is used to assess and improve the performance of portable machines by examining the time-domain response of the tool center point in representative operations, rather than limiting the study to the frequency domain. A practical application to a particular portable machine is presented and used to conduct the presentation of the work. With the results of the analysis, the accuracy of the use of the portable machines is studied. The procedure also proves to be a useful tool to optimize the machine design to fit particular applications. The method has been experimentally evaluated in a conventional three axis milling machine to ensure the accuracy of the simulations.

1. Introduction: modeling portable machines

Portable machines are small mobile and free machines that can move along large parts to perform in-situ machining operations contributing to the manufacturing and maintenance of large parts. Their advantages and current industrial use have been thoroughly described by Uriarte et al. [1]. Unlike conventional machines, portable machines do not show a high flexibility to adapt to different parts, different chip removal processes and changing machining scenarios [2]. Owing to this, design engineers have difficulties judging whether a particular portable machine design is optimum for a given machining task. As a consequence, the present machine tool industry demands rapid analysis of machine performance and machine-cutting process interactions in the virtual environment [3]. Usually, machine tools based in workshops are analyzed searching for improved dynamic stiffness, related to accurate parts, and maximum stable depths of cut, related to high productivity. All these machine tool features are variable within the work volume of the machine. At the same time, machine mass should be kept low for high speed positioning and high-productivity machining. In this context, assessment and optimization of machine tools needs quick evaluation of different design alternatives in the virtual environment before physical prototyping [3].

Usually, the evaluation of machine tools is performed studying its response in the frequency domain. In the virtual environment, finite element (FE) models are created, which can efficiently represent machine subsystems such as feed drives [4], spindles [5] and so forth. However, an accurate full representation of a machine can be computationally costly and require precious time and resources [6]. Once the model is created, dynamic characteristics (modes, frequency, tool tip frequency response functions etc.) are obtained. Depending on the specific requirements on the machine, further analysis can be focused on stability limits [7], productivity, dynamics [8] etc.

This situation is worse when position dependent characteristics need to be studied, so machine studies are performed in average or "representative" positions. The alternative would be modeling the position dependency using coupled FE and multibody simulation packages. These methods have been proved useful for rigid-flexible body analysis but are still problematic for large flexible machines with bodies subject to relative motion. Certain assumptions and simplifications can give acceptable results but are only of use under certain conditions. Moreover, the increasing modular approach of the design process means that individual

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subsystems have to be modeled and evaluated separately, creating complex situations during the synthesis process due to varying mesh resolutions at the interface, compatibility conditions etc.

Besides this, the most demanding scenario would be having to simulate relevant or typical manufacturing operations in the time domain. For this, an accurate process force model is needed, which must be coupled to the FE-multibody system. Process forces can be predicted with different accuracy levels employing a wide variety of analytical, numerical or mechanistic models. These three approaches show different computational costs and must be connected somehow to the FE-multibody solver. For a large machine, with an amount of nodes leading to more than a million degrees of freedom, this approach is simply unfeasible for its computational cost and complexity [6].

However, portable machines are usually very small in size, with minor structures and working spaces [9] and therefore they can be accurately represented by a mid-sized model with sufficient accuracy. As a consequence, the described approach would not be extremely computationally costly and FE-multibody systems remain a valid tool for complex and complete simulations.

In spite of this, the portable-machine concept is finding difficulties to enter the industrial use. Technicians are not confident about their true potential and how portable machines will eventually behave on site under variable conditions: e.g. portable machines are affected by changing gravity directions depending on their position and orientation in space and with respect to the work piece. The changing gravity direction may affect the machines in different ways.

Some recent works have already started to explore the limits: virtual techniques were used by Olarra [10] to develop methods for direct tool center point position identification with respect to the machined feature. Law eta al. [11,12] proposed a framework to predict the dynamic response of a given mobile machine with parallel kinematics with varying clamping solutions based on model-based substructure analysis and receptance coupling, and limiting the study to the effect at the tool-center-point (TCP) in the frequency domain. And recently, Eguia et al.. performed the analysis of the error budget and the uncertainty of the use of portable machines equipped with triangulation line laser scanner for machine-part inter-referencing [13].

To facilitate the evaluation of portable machines, this paper proposes an integrated virtual method based on the time-domain analysis of a computationally manageable multibody dynamic model of a portable machine. The method responds to the need for a streamlined, fast and sufficiently accurate method to assess the performance of machine tools under different circumstances. A substructural modeling and analysis approach is used for the machine, models which are then reduced to position independent light models. The machine model is then obtained from the synthesis of these reduced models and coupled to a base mechanistic force calculation method for the time domain analysis. This machine representation is used to study and optimize some components limiting machine accuracy and target requirements. In parallel, representative machining operations are represented and their forces calculated with a mechanistic model. These force values are then coupled to the machine model along the machining trajectories. The analysis is performed tracking the TCP displacements along meaningful machining operations. The obtained deflections and TCP vibrations are then employed to feed an error budget model to assess the accuracy of the machine [14], as it is done in non-conventional machine systems [15,16]. Successive improvements in subsystem or component levels are also possible following the diagram depicted in Fig. 1. All this is performed before the actual machine is built, to maximize the impact of the virtual model in the design phase of portable machines.

The effect of this method on the virtual design and optimization of portable machines is shown on a particular machine already presented by the authors [17], leading to breakthrough characteristics in stiffness/weight ratios and part accuracies. To ensure that the conclusions obtained from the model of the portable machine are accurate, the whole virtual method is experimentally validated on a conventional three axis milling machines, which is modeled exactly like the portable machine. On this conventional machine, machining tests are performed to prove that the simulated results are acceptable.

The paper is organized as follows: the target machine and its functional requirements are presented in Section 2; in-depth insight on the virtual machine model is given in Section 3; in Section 4, the machine performance is analyzed in the time domain and optimized to meet the requirements of the application, followed by the experimental evaluation in a conventional machine in Section 5 and conclusions in Section 6.

2. A portable machine for large vacuum vessels

In response to the requirements of its application described in [18], authors developed a new portable milling machine [16], a five-axis, miniature milling machine based on a serial kinematic architecture. This portable machine can perform both mid-duty milling and drilling operations in a five axis configuration. To achieve this, three stacked linear axes are included, which carry a two axis rotary-head holding the spindle, in a compact machine envelope of $1200 \times 1200 \times 1200$ mm. The work volume of the

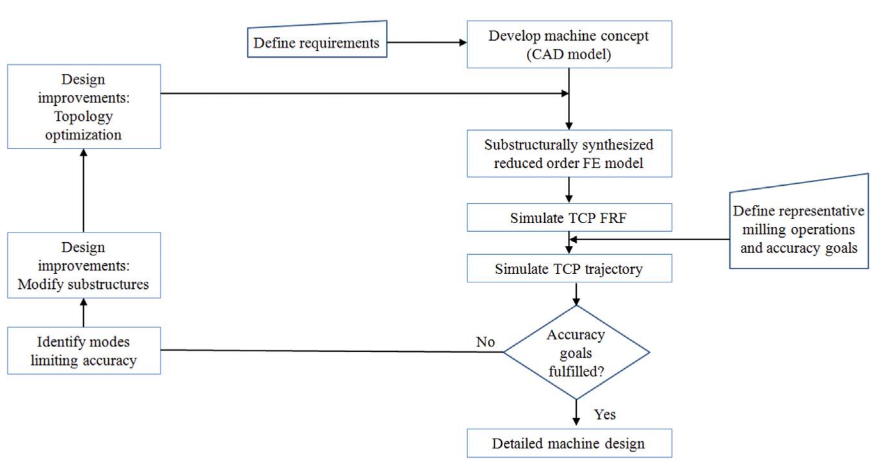

Fig. 1. Concept design of portable machine.