A Reliable Turning Process by the Early Use of a Deep Simulation Model at Several Manufacturing Stages

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Abstract: The next future using machine tools will be dominated by highly flexible and interconnected systems, in order to achieve the required productivity, accuracy and reliability. Nowadays, distortion and vibration problems are easily solved for the most common cases by sing models based on equations describing the physical laws dominating the machining process; however additional efforts are needed to overcome the gap between scientific research and the real manufacturing problems. In fact, there is an increasing interest in developing simulation packages based on "deep knowledge and models" that aid the machine designer, the production engineer, or machinists to get the best of their machines. This article proposes a systematic methodology to reduce problems in machining by means of a simulation utility, which recognizes, collects and uses the main variables of the system/process as input data, and generates objective results that help in the proper decision-making. Direct benefits by such an application are found in a) the fixture/clamping optimal design, b) the machine tool configuration, c) the definition of chatter free optimum cutting conditions and the right programming of cutting tool path at the Computer Aided Manufacturing (CAM) stage. The information and knowledge-based approach showed successful results in several local manufacturing companies.

Keywords: simulation software; manufacturing systems; process integration; machining optimization; Industry 4.0; knowledge-based manufacturing

1. Introduction

The modern evolution of the manufacturing systems was initiated with the so-called Computer-Integrated Manufacturing (CIM) in the 1980s, as the way to automate, optimize and integrate all the manufacturing processes. During this decade Llorente *et al.* [1] and Burgos *et al.* [2] CIM grew up towards robotics implementation, development of artificial intelligence (AI) and flexible manufacturing systems (FMS) in order to reduce the work-in-process (WIP), manufacturing systems breakdowns, manual work and costs, adapting system configuration to the rapid changing in products and batch sizes. Simultaneously, a new concept called Total Quality Management (TQM) was undertaken to consider the effects of all the agents involved during the product life cycle in order to improve product features to meet or even exceed customer expectations.

Progressively, the CIM concept aided by the TQM, just-in time (JIT) or more recently with lean manufacturing principles faded a little in fashion, to return with force in the last 2011 and 2013 EMO exhibition fairs. The most successful companies started to implement new concurrent and multi-disciplinary strategies (outsourcing, full-service supply, offshore manufacturing, and joint ventures) closely connected with the client requisites. Then, open architecture manufacturing and

agile manufacturing [3] appeared as emerging trends in automation and control devices. In the past, proprietary designs allowed developers to create controls with unique characteristics and to embed them into proprietary architecture, making them more difficult for competitors to copy. This protection method worked well when the control technology lasted for 4-5 years. Now that the lifecycle is much shorter (6-8 months), proprietary control developers require longer times to incorporate new technology into a proprietary design than the own technology's expected life. To stay competitive in both cost and technology, Computer Numerical Control (CNC) manufacturers are now forced to find better ways of updating controls to sudden technology changes other than launching huge development projects each time a technology change is needed. Open architecture provided and provides that capability.

On the other hand, an emerging trend for the last 20 years is the Digital Manufacturing approach (DM), defined as an integrated approach that allows the simulation, 3D visualization and analysis making use of collaborative tools [4,5]. Digital manufacturing evolved from computer-integrated manufacturing (CIM), enlightening the need of greater collaboration between product design and process planning. The 3D simulation tools open the implementation of virtually model machines, robots, workcells, assemblies, but also factory buildings, production lines and workflow, all factors involved in the complex production environment. Nonetheless, many of the long-term benefits of Product Lifecycle Management (PLM) cannot be achieved without an integrated digital production strategy [6]. The process chain coordination allows manufacturing companies to achieve their short time-to-market requirements, production volume targets and cost savings. Today digital manufacturing is based on to the integration of Computer Aided Design (CAD) / Computer Aided Manufacturing (CAM) applications on PLM tools. Thus, CAM allows that "virtual cutting tools" to be driven over digitally rendered part surfaces, producing a code to be used by CNC controllers to drive "real tools" into the workpiece. Currently virtual simulation tools came to build virtual models of the i) machine tool, ii) workpiece and iii) cutting tool, as well as to simulate the machine movements and the consequent material removal, allowing a rapid checking of interferences, excessive tool engagement and collisions. The risk of a hit caused by a wrong machining operation is a continuous nightmare for any machine programmer, for workers and for the managing director. The concept virtual manufacturing (VM) makes reference to reproduce a virtual complete model of machine, processes and auxiliary devices [7]. This allows visualizing the feasibility of a process without using any real test. If evaluation is positive, the operations are then translated into the real world. Following the thread started from the digital and virtual manufacturing ideas, the virtual machine tool (VMT) concept appears as a multi-approach software where users can interact to evaluate different machine tool architectures.

For instance, complex operations may require hours of preparation for machine setup, during which the machine tool is unproductive, or the use of the machine to form the operators is another example of productivity decrease. Many companies tries to make exhaustive use 7/24 of their production facilities, therefore to have a virtual machine is a good way to eliminate void times. However when machines are switched on it is important to do so with a 100% confidence that there will be no any collision, interference or excessive tool engagement [8]. Instead of the traditional checking of CNC programs step by step in the real machine previous to launch a part program, the VMT verify them in ordinary PCs [9]. VMT is built from a toolkit of software components, a 3D model of the machine tool with machining simulation software and a machine/human interface (MHI) [10]. The organizational logic of the virtual system is divided in two functional axes. One characterizes the machine tool structure under certain conditions (loads, temperature, etc.), while the other is related to the motion of the machine elements and associated errors. The programmed motions, possible errors, deformations induced by process force and heating from several sources lead to a relative motion between the tool and workpiece, which caused the target part surface, and so that it has to accomplish drawing requirements. A high-end VMT must predict the cutting forces, temperature variables and the outcome characteristic of machined parts. During post-processing, the VMT module graphically simulates and verifies the programs. To date, process

models included in VMT are very simple, with no use of deep process basic laws; this lack will be an opportunity for the present approach.

The internet-based manufacturing is improving the communication between manufacturers, clients and suppliers [11], and it has a key role for shortening the time-to-market [12]. The information integration is now being called Industry 4.0 approach. Hence, Industry 4.0 is a project in the high-tech strategy of the German government, which promotes the computerization of traditional industries such as manufacturing. The goal is the intelligent factory (Smart Factory), which is characterized by adaptability, resource efficiency and ergonomics as well as the integration of customers and business partners in business and value processes. Technological basis are cyber-physical systems and the Internet of Things. It is expected that future wireless plant-floor networks will remotely control manipulators and robots as well as CNC machines.

On the other hand, remote-monitoring is already offered by some big machine tool builders. For instance, the machine e-Tower of Mazak® offers a virtual assistant for setup and maintenance support in-office or off-site aiming for management functions, work scheduling, mobile alerts, etc. Also the Web Monitor of Mori Seiki® connects any machine tool to a web-based platform. In both cases users can log in the control to access this information remotely from any internet-connected device and see an up-to-date status of their machine operation.

The world presented here describes a new utility for the prediction, assessment and surveillance of machining processes in manufacturing plants. The modular software includes the ability to predict key magnitudes in machine processes from models involving the static and dynamic behavior of the machine/part system. It also works with experimentally acquired signal data, for an a priori or in-process decision making. Due to this plural conception, the software can be used at different manufacturing stages, either at the process definition steps (clamping design for a component, selection of machine tool architecture), or machine programmer, or even in-situ by the machine operator. Therefore, it could be an essential "intelligent utility" for structuring the process stages. Previously Section 2 overviews the recent advances related to software integration in manufacturing activities, Section 3 presents the development of the software in C-Sharp programming language (C#) [13]. Section 4 defines the basics from the underlying mechanical concepts and finally Section 5 shows two successful applications to real industrial problems. The approach solves the usual gap between current commercial VMT utilities and the academic machining process models.

2. Models in Machining Processes

All the aforementioned state of the art facts bring up the necessity for simulation packages that represent the production system performance. Although most common machining problems were solved in literature, it appears that the available solutions are more frequently used at the academic or scientific community than really adopted by industrial sectors. To overcome this gap, and in common words to be able to achieve the objective stated as "put models to work!!", intense efforts were carried out in recent years [14]. The solutions may be classified depending on whether the optimal cutting parameters are chosen before (predictive) or during cutting (in-process, so in a reactive way).

On the one hand, predictive or offline methods [15-17] forecast the chatter-free conditions. They are applied before cutting but need experimental information from the system dynamics and cutting parameters. Cutpro® developed by Prof. Y. Altintas, is a well-known simulation software for chip removal processes that solves the process stability equation in the frequency domain [18]. Recently, this laboratory has released new more complex software, MACHpro®, to integrate the compliance of a given system into a CAM module aiming for tool path optimization (both trajectory and cutting parameters) from a dynamic point of view.

On the other hand, in-process methods monitor a machining significant magnitude, which is real-time analysed for a rapid changing in the machine spindle speed. The onset of chatter is identified by comparison with a threshold value. As main drawback of this approach, chatter/vibration marks are just imprinted on the workpiece before any cutting parameters modification is commanded. For instance, Accord Mill® records the sound signal during cutting, which is then noise filtered and post-processed before being transformed into the frequency domain. The optimum spindle speed is calculated from the measured vibration frequency, the natural frequency of the system, the initial spindle speed and the end-mill number of teeth. Similarly, Harmonizer®, created by Prof. J. Tlusty, is able to determinate the chatter frequency just measuring the Acoustic Emissions (AE); in 2 or 3 iterations the program is able to find a spindle speed where cut would be stable [19]. However when the machining depth of cut is too high or in finishing operations where the vibration modes notably vary (in magnitude and direction along time) this solution has a difficult convergence. So, the system is useful for 1 degree of freedom (DOF) systems and for rough to medium operations. Normally, such types of software allow introducing information from real cutting tests to feedback and tune the predictive analysis. For instance, the MetalMAX® package offers a complete modal characterization module (TXF), prediction software (MilSim) and the Harmonizer module to obtain the recommended new spindle speed.

However, all this models run stand-alone, with no integration with other decision and control stages of the manufacturing system. This is a drawback solved by the present approach, where efforts push the use of models instead of their precision, in which is where scholars usually lose themselves.

3. Software Used for the Integrated Approach

The increasing demands on part tolerances by the end users have forced to collaborative process planning by all the staff of any industrial company. From the CAM stage till the finished product, the need of software integration over the different production steps is a key issue to maintain the market share. For this reason authors developed an innovative software, named Dynpro®, which integrates some of the models developed during the last years concerning to static and dynamic behaviour (section 4) of the turning, boring and milling processes. The developing tool Visual Studio was selected for the implementation of the program code, due to its multi-step nature. Additionally, MATLAB was used to create other different modules in which numerical calculations are required.

Regarding to the installation requirements, Dynpro® only uses 50MB of space memory. The program may run on platforms Windows Vista, Windows 7 and 8. The user should install the Matlab Compiler Runtime program to get access to the Matlab functions as well.

3.1. User Interfaces

This section develops how the utility addresses diverse machining problems, from the input data asked to the user to the final graphs that will help him/her in the decision making. Figure 1 shows a typical interface. Thus, on the up side of the screen (A), the toolbar menu presents the access to the program options such as Simulation, Tools, or Help, as well as different shortcuts for fast actions. On the low side (B), the user must fill in the input data to get access to the next tabs. As seen, the system operator only is asked for data in a technical language and focused on the machining operation, solving the drawback of a lot of machining simulation software above mentioned in which a lot of previous knowledge about the fundamentals and basis of the equation dominating the process is needed; in general this was a common drawback that had, and still has, set back 20 years the spread of approaches as that presented here. The main interface use codes, pictures and options related to machining that are used by all machining users.

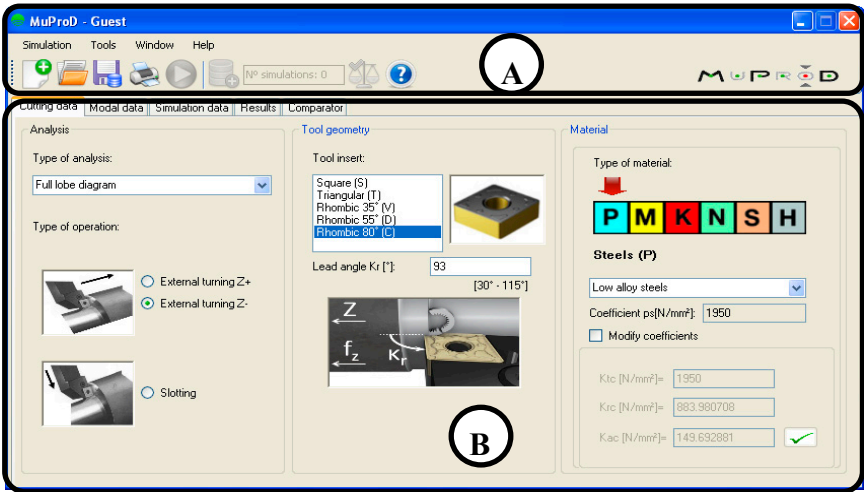



Figure 1. Example of interface appearance.

The software is divided into different modules: simulation in static conditions (Simulation of static behaviour), simulation in dynamic conditions (Simulation of dynamic behaviour), signal measurement and recording and post-processing. As shown in Figure 2, the program focuses on most common chip removal processes, namely, turning, milling and boring.

The static behaviour module calculates cutting forces, roughness, power consumption or torque in vibration free state. These can be valuable to predict the static deformation errors. The simulation of dynamic behaviour module obtains the stability lobes graph of systems with complex dynamics. Both modules can be useful for the optimization of machine tool or for the design of complex cutting tools (i.e., serrated-edge tools or variable pitch end-mills).

The third block accounts for a more in-situ approach to the machining process with the ability either to record cutting signals or to post-process and manipulate them to obtain cutting forces, specific cutting energies, etc. It is also possible to judge the quality of the machining process by comparing the peaks of the frequency spectrum with respect to the natural frequencies of multiples of them.

The integration of the mathematical models into the software was made through the creation of a Dynamic-Link Library (DLL), made using Matlab toolbox.

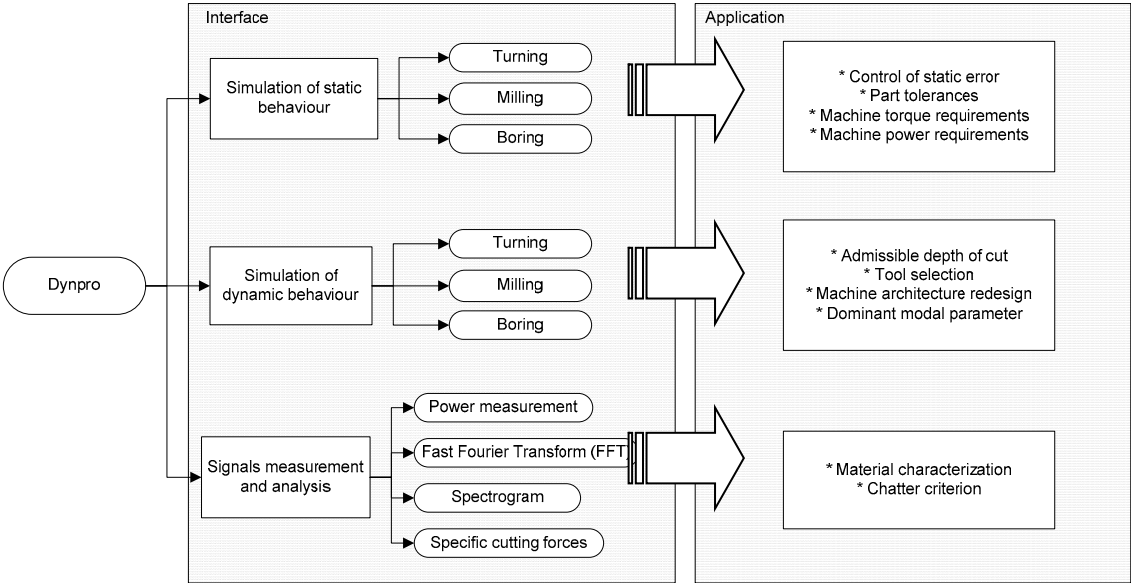



Figure 2. Functions and applications of the approach.

3.2. Simulation Under Static Mechanical Conditions

The toolbox "Simulation of static behaviour" is based on the mechanistic cutting force model developed in Section 4.1, which assumes a proportionality law between forces and the removed chip section. From this relation, the software predicts the three Cartesian force components along machine or process axes for a wide combination of operations, tool geometries, part materials and cutting parameters (Figure 3). The module is completed with additional tabs for the calculation of the roughness, power and torque consumption in stable conditions.

User must introduce the machine tool, tool or piece stiffness values, usually in the weakest points in the machine workspace. Doing that, the module may help in estimating possible deformations during cutting, making possible to prevent them by varying the cutting conditions (tool geometry, cutting parameters). Different machining conditions can be easily simulated to select the best choice. In addition, a fast tab for the roughness calculation can be run to predict estimated roughness. Considering together these two features a balanced decision can be held between productivity, dimensional accuracy and surface roughness.

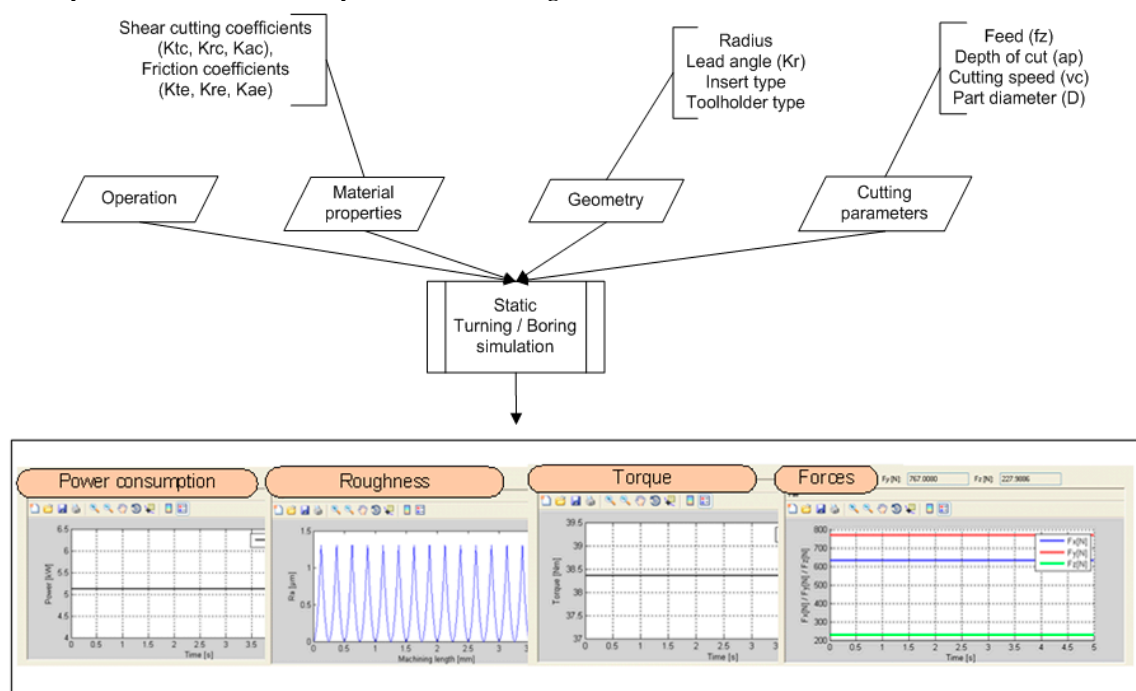



Figure 3. Model dataflow in static conditions.

3.3. Simulation of the System with Dynamical Behavior

Chatter problems are a typical constraint for achieving a high productivity, appearing soon or later in most of the machining operations. Chatter vibrations cause surface marks that lead to part rejection, tool breakages or even severe damages in machine tool spindles. With Dynpro®, the user would be able to predict those dynamic problems by obtaining the so-called "stability lobes". These graphs give the frontier between stable and unstable cutting conditions (plotting Spindle speed S vs. Depth of cut a_p) in the working range once the dynamic features, tool geometry and material properties are fed into the model. In section 4.2, the basics from the numerical method implemented in Dynpro® will be presented. Both turning/boring [20] and milling models [21] have similar code structure.

In the Simulation of dynamic behavior module, the user must introduce the process kinematics, tool geometry and material properties in the first tab. Then, the modal parameters of the machine and tool couple are load or asked to the user as well.   Dynamic parameters are obtained by impact tests using an instrumented hammer and a vibration analyzer, through the calculation of the dynamic response function (FRF). Accordingly, Dynpro® includes an innovative toolbox to filter

and fit the frequency response function (FRF) archives to modal parameters, easily recognized and used by the program. These are then directly set by keyboard in the Modal parameters tab. Otherwise, a *.txt archive with equivalent information can be loaded. Once modal parameters are loaded, a final tab with the simulation parameters must be filled. The output data are the stability lobes but, depending on the selected type of analysis, other graphs are also available such as Maximum allowable depth of cut vs.   Lead angle or Maximum allowable depth vs. Type of process.

3.4. Signals Measurement and Analysis

The third module in the approach allows the user to record and analyze some parameters of the machining operation. Signals measurements are usually linked with the use of costly additional equipment (Kistler® dynamometer, Artis®, vibration analyzers, DAQs, etc.), any of them common in a usual workshop. Dynpro® software has a power toolbox for in-process power measurements that makes this task easier. A low-cost device is implemented for measuring the power directly from the machine servodrives, using Ethernet connection. After that, user can post-process these time signals, for example, to obtain estimations of the specific cutting energy. Once the threshold value for the power consumption in stable cutting is defined, this feature can be used either to predict tool breakages or to keep wear under control [22].

Also a signal analysis utility is integrated in this module. In this case, a recorded time signal is visualized, filtered or post-processed (FFT, spectrograms, etc.) to obtain direct information of the system performance during cutting and to help the machine user in the decision-making for keeping manufacturing system in the best running status.

3.5. Resources

The distribution of the different functions and tasks into independent modules, referred here as resources, makes easier both the computational times and the programming. In this section, an overview of these resources and their functionality is summarized.

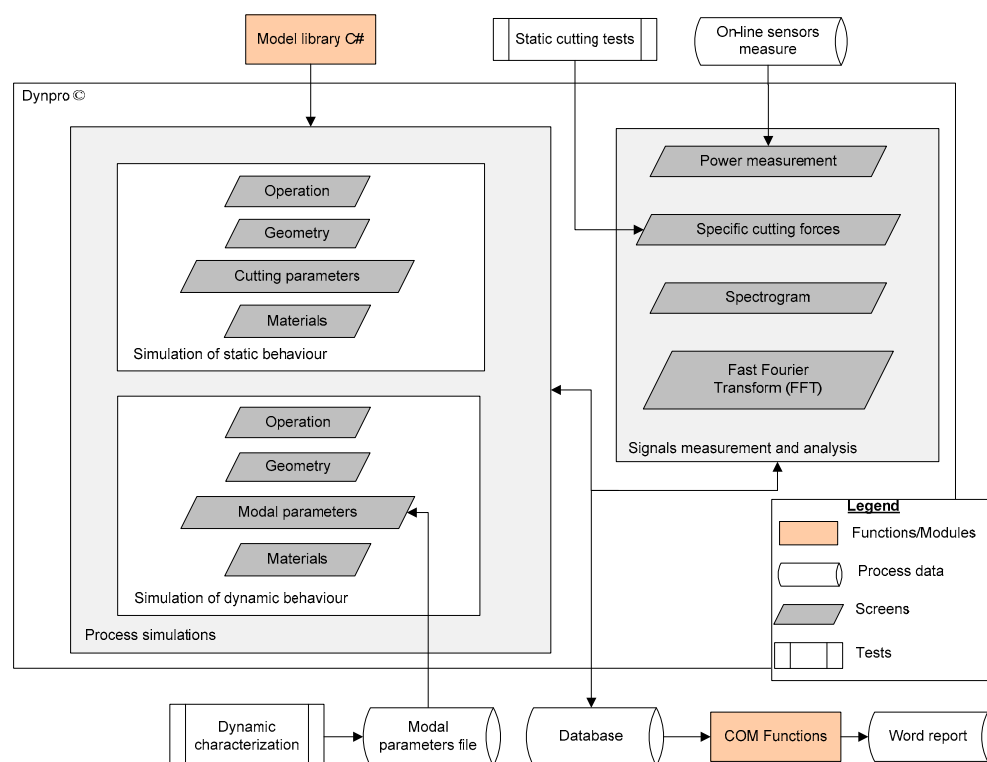



Figure 4. Approach workflow.

Thus, Figure 4 depicts the work flux showing the dependency among the software modules (Simulation of static behavior, simulation of dynamic behavior and signals measurement and

analysis) and the resources. These have been classified in three groups: Functions/modules, Tests and Process data.

The first group refers to the various programming functions packages (libraries) used by the modules. Libraries are then sub-classified into the ones predefined by the programming interface (or COM Functions) and the ones created exclusively for the project (i.e., Model C# library). The test group works with the experimental information brought to the software from the user-defined experiments (machine tool dynamic measurements, machining noise, etc.). Finally, the process data group describes and identifies the selected format and specifications for the data management and storage.

3.6. Functions and modules

On one hand, the function or module packages arise from the need of grouping and arranging each of the functions to its own model. Dynamic-Link Libraries (DLL's) were developed for an easy programming in C#. On the other hand, Matlab® offers an integrated development environment with a custom programming language, which is the most appropriate for developing these libraries. Using this programming design, a black box utility isolates the analytical expressions of the model from the Dynpro® interface.

Other Microsoft® Windows functions were used to generate the report of simulations. These functions, which belong to the Visual Studio development kit, allow creating a Word document from the simulation data obtained by Dynpro®.

3.7. Tests

For a more realistic approach to the machining process and operations, a module to introduce real data from user-defined experiments was designed. This module interacts and uses real (experimental) data and then, may serve them to other different modules as input data.

For instance, in the module for simulation of dynamic behaviours, the program requires some input variables (section 3.1) such as the modal parameters. Dynpro® offers a toolbox for obtaining and fitting the modal parameters (peak-picking) once the frequency response function (FRF) has been obtained (by impact hammers or shakers).

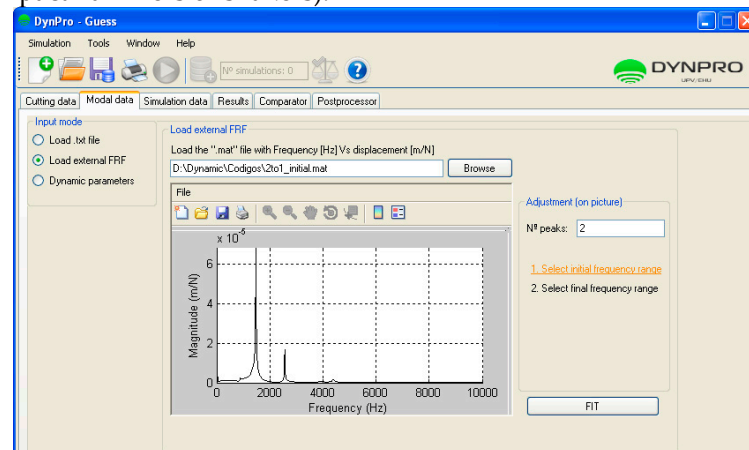



Figure 5. Frequency Response Function (FRF) analysis.

Additionally, the software may be used to help the characterization of raw materials considering machinability. Moreover, machinability can be expressed in function of the so-called *cutting coefficients*. These can be taken either from the material database of Dynpro® or, if the user has undertaken experimental tests for material characterization, they may also be edited (and loaded) by keyboard.

3.8. Process data

The program data distribution allows Dynpro® to reduce waiting times and unnecessary data loads, by implementing a database to save all simulations. The features of a commercial well-known

database fit in well with the required amount of data to be saved. Its content is divided into four tables (users, materials, tools and simulations). Database access is performed using predefined functions of the Visual Studio (Object Linking and Embedding for Databases (OLEDB). The available capabilities are implemented by using COM objects – the OLEDB supplier links functionality of one technology to the selected COM interface. It marks a clear boundary between i) the code that calls a method and ii) the code that implements the method; in computer science terms, the caller is decoupled from the implementation. The program uses the following classes to access the database: OleDbCommand, OleDbConnection, OleDbDataAdapter and OleDbCommandBuilder.

The modal parameters file is the result of the dynamic characterization. Those data has to be encapsulated in a text file following some specifications. The approach record it directly, or additionally Dynpro® allows user to create an easy-to-use parameter file just introducing the machining system dynamic behaviour specifying the frequency, stiffness and damping of each mode.

4. Inside the Software: The Deep Model

More effort must be made to consider available process knowledge in order to improve component properties (accuracy of shape and dimensions, surface finish and subsurface layer properties) and process parameters have to be based on product-related production requirements. To satisfy these requisites modelling is the key to optimize the machining processes realistically. Some of the information that the day-to-day metal cutting practitioners find valuable are the prediction of tool life (wear), prediction of the accuracy of the part being machined, prediction of the surface finish and integrity, and prediction of the mechanical loads on the tool/workpiece/fixtures. Machining processes/operations models are framed into different categories:

- Analytical models, out of use currently.
- Mechanistic models based on the concept of *specific force*. They are precise enough and executed in milliseconds, and suitable for being used in real production.
- Finite Element Models to represent chip deformation, but too slow to be use in daily production. FEM is a tool for other types of analysis, for example fixturing design.
- AI-based models based on neural/Bayesian networks or on fuzzy logic. Without a model based on the chip removal mechanism, they are useless.

In this section, the authors resume the basic concepts related to the static and dynamic modelling used in the present approach. These are a combination of the theory of mechanistic models [23], numerical models [16,20] or frequency domain techniques [24].

4.1. Cutting Force Prediction

In each machining case, the machine tool, the cutting tool and the workpiece is a very complex structural system, with a complicated dynamic behaviour where vibrations can arise if machining forces are not under control. For this reason, predicted forces before cutting is a first-order input when workers program toolpaths at the CAM stage.

In every machining process [25] cutting force can be obtained from the projections of a total force F in the three machine tool Cartesian directions X_{MT}, Y_{MT}, Z_{MT} or in the local tool axis (using in this case the indices: c, cutting force; t, tangential force and r radial force). The mechanistic approach assumes that force components are composed of two summation terms, one responsible of the shearing mechanism related to the chip formation mechanism and depending on the chip section ($a_p \cdot f$ or $b \cdot h$) and other related to the friction of chip sliding onto the tool rake face that is proportional to the engaged edge length (or chip width b). Generally, the cutting forces can be expressed as:

$$F_{rct} = K_{rct,c} \cdot bh + K_{rct,e} \cdot b \qquad (1)$$

where $K_{rct,c}$ and $K_{rct,e}$ are the cutting and friction *specific coefficients* respectively, which depend on the chip section ($b.h$) and chip width (b). With slight differences, similar relationships are found for other processes such as boring or milling. Once these coefficients are defined the mechanistic model

predicts the static cutting forces based on Equation 1. In other words, Dynpro® makes use of the cutting coefficients (obtained either from a material database or from user-defined `previous experiments) to calculate the cutting forces. It also predicts the cutting forces in finishing operations including the effects of any particular tool geometry (with nose radius r_ϵ and cutting edge angle κ_r).

From the cutting force calculation, other parameters such as torque and power consumption are estimated. Those are important magnitudes for tailor-made machines subjected to strict part specifications and power requirements. Moreover, knowing the cutting forces for any tool geometry can be used during tool design by tool makers to guarantee tool functionality in terms of mechanical tool stresses and tool life.

4.2. Chatter Avoidance

Chatter vibrations occur due to dynamic interactions between the tool and the workpiece. Chatter is caused by a regenerative effect in the chip section between successive cuts, responsible for this dynamic instability. Depending on the feedback system gain, chip width b and spindle speed S, the system may be stable or unstable. To avoid regenerative chatter, predictive maps or stability lobes have been used for years. From these, optimal combination of spindle speed and depth of cut can be defined to meet at once productivity and security.

The approach integrated in Dynpro® to study stability combines the collocation method [26] which is a numerical method with the dynamics of the machine tool in modal coordinates. The multi-mode approach takes into account the orientation of the machine tool modes. This modal vector is referenced to the machine-tool axes, denoted X_{MT}-Y_{MT}-Z_{MT}. Thus in turning, X_{MT} defines the radial direction, Y_{MT} the cutting speed direction and Z_{MT} the feed (or axial) direction, in a common straight turning operation (Figure 6a). One frequency mode is defined by two angles: β_y, the angle between the modal vector i_m and the X_{MT}-Z_{MT} plane and β_{xz}, the angle between its projection over the X_{MT}-Z_{MT} plane with respect to X_{MT}. In milling (Figure 6b), the machine tool axes are different from the tool local axis. Here, Z_{MT} is defined by the rotational motion of the tool (or axial) and α_f is the angle between the feed direction (X_T) and X_{MT}. Now, the modal orientation is defined through the angles β_z, between i_m and its projection in X_{MT}-Y_{MT} and β_{xz}, between the projection of i_m and X_T. α_x is the sum of angles α_f and β_{xy}.

(**a**)   (**b**)

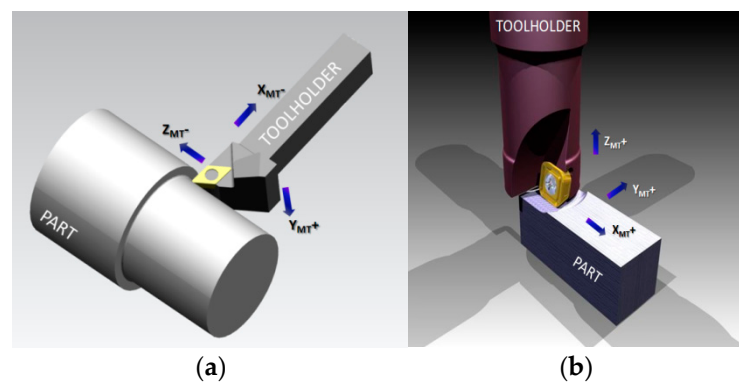



Figure 6. Orientation of a modal vector: (**a**) Turning operation; (**b**) Milling operation.

From this approach, the dynamic equation for n modes results as:

$$
\begin{Bmatrix} \ddot{\delta}_1(t) \\ \ddot{\delta}_2(t) \\ \vdots \\ \ddot{\delta}_n(t) \end{Bmatrix} + [C] \cdot \begin{Bmatrix} \dot{\delta}_1(t) \\ \dot{\delta}_2(t) \\ \vdots \\ \dot{\delta}_n(t) \end{Bmatrix} + [K] \cdot \begin{Bmatrix} \delta_1(t) \\ \delta_2(t) \\ \vdots \\ \delta_n(t) \end{Bmatrix} = \begin{Bmatrix} g_1 \\ g_2 \\ \vdots \\ g_n \end{Bmatrix}
$$

(2)

where *[M]=[I]* and *[C]* and *[K]* are the damping and stiffness matrices defined as:

$$[C] = \begin{bmatrix} 2\xi_1\omega_1 & 0 & \cdots & 0 \\ 0 & 2\xi_2\omega_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 2\xi_n\omega_n \end{bmatrix}; \quad [K] = \begin{bmatrix} \omega_1^2 & 0 & \cdots & 0 \\ 0 & \omega_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \omega_n^2 \end{bmatrix},$$

(3)

and the right *term {g}* represents the delay term responsible for the regenerative effect. Starting from the equation motion, a numerical method (named Chebyshev collocation method) is used to approximate the solution to the stability problem.

Using this approach, the model easily recognizes the influence of modes acting with different orientations. As for the simulation of the static behaviour module, the positioning and tool geometry can also be considered.

5. Application to Real Case Studies

In this section, the models are put to work in two case studies. The first one is related to the module that predicts the machine behaviour in static regime while the second one has been selected to verify the capabilities of the dynamic module. This module should predict reliable stability boundaries to ensure stable but productive machining.

5.1. Case Study 1: Design of Clamping Systems

The following case study was conducted in the main factory of a windmill gearboxes manufacturer, where gears, shafts, casings and planet-carriers. Normally, the latter type of workpiece involves turning, boring and slotting operations, performed in large vertical turning lathes. These parts ask for tailor-made clamping systems to avoid static deflections and vibrations during machining. A good clamping design should allow a reliable machining, keeping the workpiece into the specified tight tolerances. This requires a proper clamping of the part limiting the movement of the weakest part features, such as flanges or slender wings. In this case, the holistic approach was and is still being applied to avoid excessive deflection of the component during machining.

First, the machine tool-part assembly stiffness was experimentally analysed to obtain the forces-displacement relations. Stiffness calculation must be corrected discounting the own compliance of the measurement devices. Then, for the couple tool-workpiece, the cutting forces are obtained from a set of cutting conditions, tool geometry and workpiece material. Finally, a deformation model may be proposed for the machine. This will allow the analysis of the part-fixture-machine assembly. Once the cutting forces are known, the static deflections may be predicted and controlled.

For the full system stiffness determination a series of experiments were performed. Stiffness is determined as the ratio between the force applied at any point and the deformation of the mechanical system measured at that point as well. The excitation force was applied moving the lathe ram against the part hundredth of millimetre, putting the dynamometer between the tool tip and the upper part of the cylindrical shape workpiece. The applied forces were measured using a strain gauge dynamometer, which flexibility must be taken into account. As shown in Figure 7, the dynamometer was located in order to measure the stiffness of the part (3 in figure) on the 3 spatial directions.

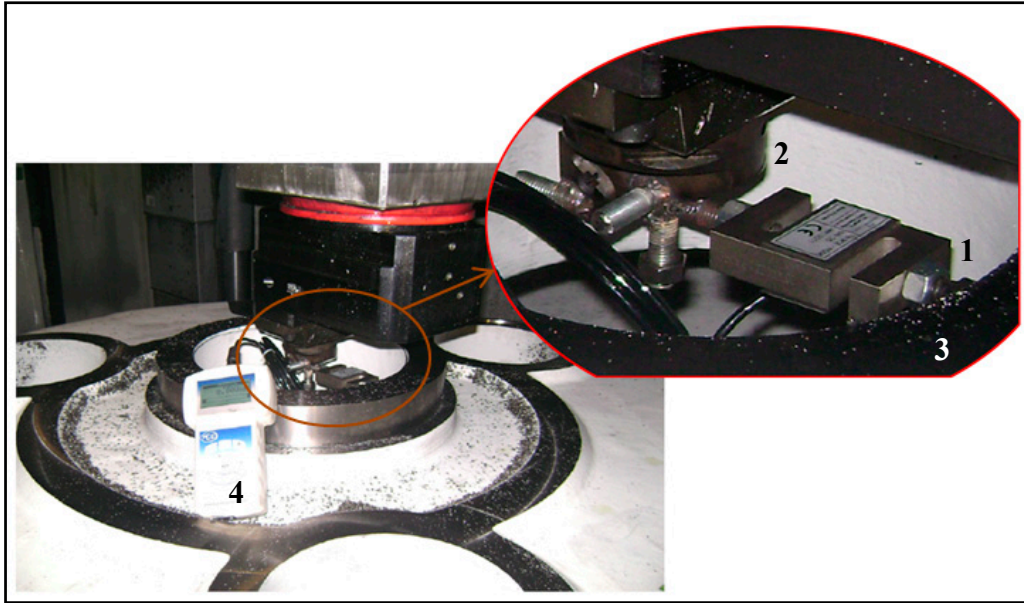



Figure 7. Stiffness measurement between tool tip and a planet carrier. (1) Strain gauge, (2) Adapted design tool, (3) Part, (4) Strain indicator device.

Bearing in mind the machine tool-workpiece assembly, two degrees of freedom will be considered. On one hand, the mechanical behavior of the workpiece, fixture and worktable is modeled as a single element using a rotary spring with a turning radius, so that the forces will produce different moments and deformations depending on the Z coordinate. On the other hand, the contribution to the total deformation from the side of the tool is represented using two different elements. The first one includes the effect of all the elements of the machine except the ram using a rotary spring. As in the modelling of the workpiece/fixture, the rigidity will differ depending on the application point (Z coordinate) of the forces. Then, the ram itself is modeled as a cantilever beam, being the most flexible part of the chain. In sum, the total deflection can be expressed as:

$$\delta_{tot} = \delta_{machine-tool} + \delta_{ram} + \delta_{piece-fixturing} = \frac{FL^2}{K_{mt}} + \frac{FL^3}{K_{ram}} + \frac{F\left(L'-A\right)^2}{K_{pf}} = \frac{F}{K_{tot}} \tag{4}$$

The mechanical analysis of the complete system (part, fixture and worktable) was performed using the finite elements method (FEM) in lineal mode. Then, the best turning radius for the rotary spring model was determined. This turning radius and the theoretical rigidity of the assembly were used to validate the experimental results. Dynpro® was used to predict the cutting forces for different tools, workpiece materials and cutting conditions. Figure 8 shows the three Cartesian cutting forces for two typical turning tools, a rhombic 35º insert (standard VBMT) and a square one 45º (SNMG).

(a)

(**b**)

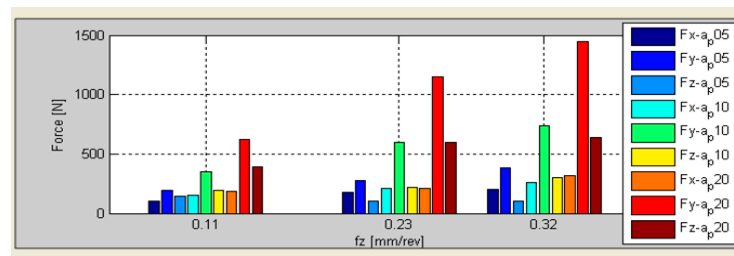
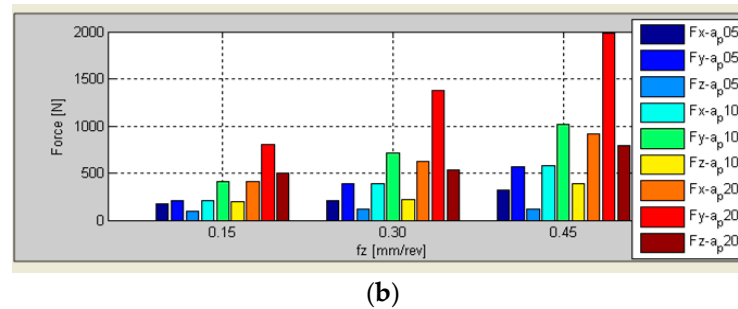



Figure 8. Cutting forces from Dynpro® for two turning inserts: (**a**) Rhombic 35º (VBMT); (**b**) Square 45º (SNMG).

Taking the estimated cutting forces and the experimental stiffness as input for the developed software, it was possible to predict the tool tip maximum static deformations and the worst positions in which they were maximum.

Hence, Figure 9 shows the deformation of the part-fixture-table assembly under radial forces for two different clamping of the same part, using FEM. Therefore after the virtual testing of proposed designs, it is possible to define the best clamping system.

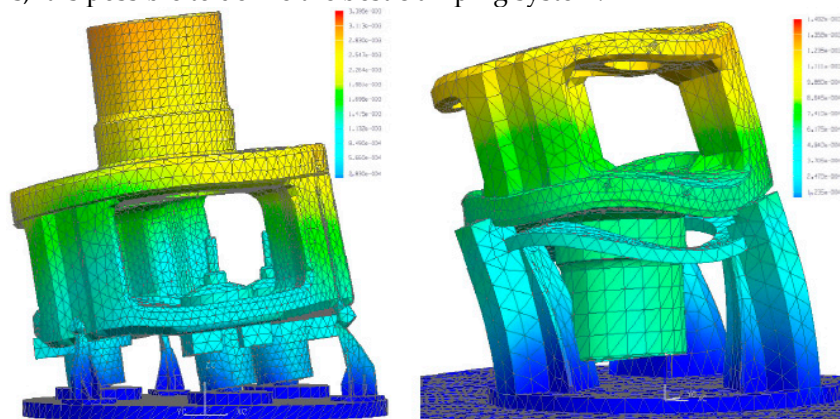



Figure 9. FEM model results for two fixture configurations.

In this company, the estimation of cutting forces is used in a daily basis for the best selection of cutting parameters for all machining operations applied on large diameter parts made in high-strength iron casting. Therefore, for a null of models in production, the company is trending to an exhaustive use of them for making decisions about how to apply machining and getting optimal process outcome. An all the cases are recorded in the software database.

5.2. Case Study 2: Chatter Free Turning of Large Crankshafts for Naval Industry

In this case, Dynpro® was and is mainly used to predict chatter-free zones in the turning of large crankshafts, getting the stability lobes that can be used for evaluating the best dynamic behaviour among different virtual architectures. The selected machine for model validation was a large horizontal lathe. As seen in Figure 10, the dynamic study of the process was performed following different levels. Firstly, the modal data from the machine tool cutting system was obtained by FEM and hammer impact tests. Secondly, the Simulation of dynamic behavior module simulated the stability limits for an operation typically performed in this machine.

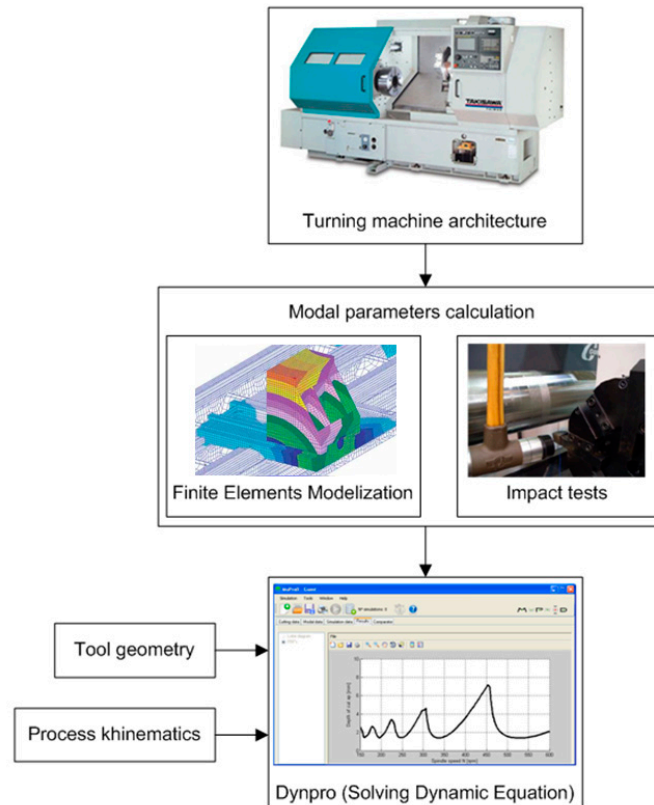



Figure 10. Experimental procedure for improved dynamic performance.

To solve the chatter equation, the specific cutting energy is needed. Because of geometrical interferences a dynamometer was not possible to be adapted in situ. However a power sensor was put to work during the characterization tests.

(**a**)   (**b**)

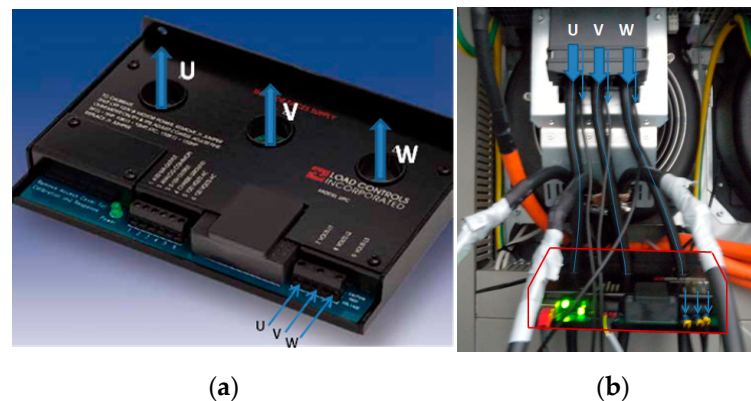



Figure 11. (**a**) Power sensor UPC-E; (**b**) Sensor installation on the plate motor.

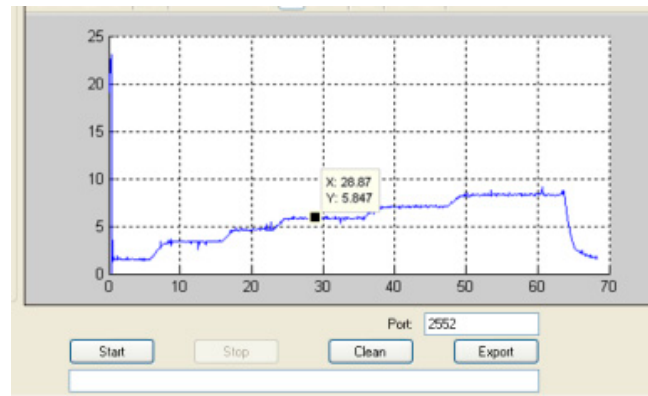
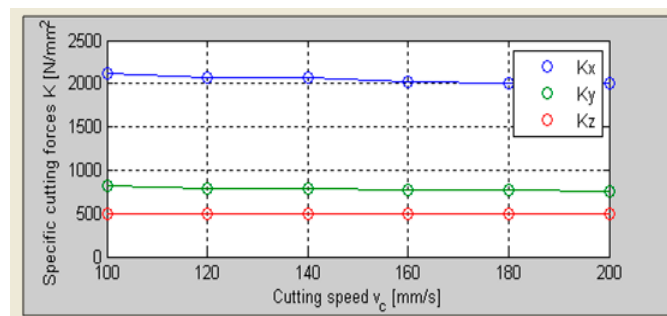
This device takes instantaneous and direct readings from the spindle drive, which are recorded and filtered with Dynpro®. With the power values, the specific cutting coefficients in Cartesian and tool coordinates were obtained for a rhombic carbide insert (CNMG19) and AISI 1045 steel, resulting Kt=2079 MPa, Kr=775MPa and Ka=533MPa. It must be noted that this tool is prone to vibration in axial direction (Z) when performing   straight turning operation due to its lead angle (positioned at κ_r =95º).

(a)

(b)

Figure 12. (**a**) Power measurements; (**b**) Specific cutting coefficients in Cartesian directions.

The modal parameters were obtained by hammer impacts and FEM modelling of the machine (Table 1). First, a mode-to-mode plot was simulated to identify the most limiting modes. Among them, it was noted that *mode 1* of the workpiece and *mode 7* from the tool were the most restrictive, both with high tendency to vibrate in Z direction. Figure 12 presents the boundary curve corresponding to those modes acting simultaneously (full plot) against the experimental points from chatter tests. Stable and chatter cases (respectively with o and x marks) are derived from the signals recorded during cutting by two accelerometers and a microphone.

Table 1. Lathe/workpiece modal parameters.

Element	Mode #	f_n [Hz]	u_x [1/√kg]	u_y [1/√kg]	u_z [1/√kg]	ξ
				Modal parameters		
Workpiece	1	30	0.0067	-0.1508	0.2770	0.020
	1	178	0.55	1.078	0.814	0.020
	2	1338	2.40	0	4.88	0.030
	3	1736.3	4.45	3.71	9.75	0.020
Tool/Machine	4	2220.1	1.15	3.18	6.27	0.023
	5	2509.6	6.20	13.85	7.87	0.0175
	6	2600	4.15	24.22	3.9	0.015
	7	3026.5	8.23	31.06	23.97	0.0155

(**a**)   (**b**)

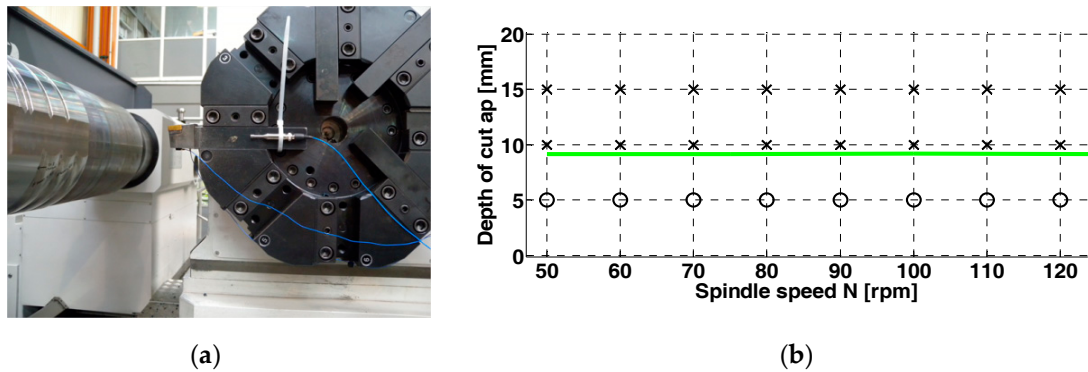



Figure 13. (**a**) Sound acceleration recording; (**b**) Stability lobes versus experimental points.

The cutting signals were then post-processed with the software to identify the sources of vibration. Dynpro® allows for converting the signals to FFT spectrum (magnitude vs. frequency) or to spectrogram (frequency vs. time). It was observed that the machine exhibited high frequency vibration (near 3026 Hz). This was confirmed also by the wave length of the surface marks. Figures 14a and 14b show the frequency signals with respect to time, the frequency spectra (FFT) and the final surface finish for two cases, stable and chatter. First one leads to a distributed FFT signal in the frequency range with low amplitude peaks while the second one presents a dominant peak near the natural frequency and a phase lag periodic peak pattern with respect to the cutting frequency of the cutting and its multiples (circles in red of Figure 14b).

(**a**)   (**b**)

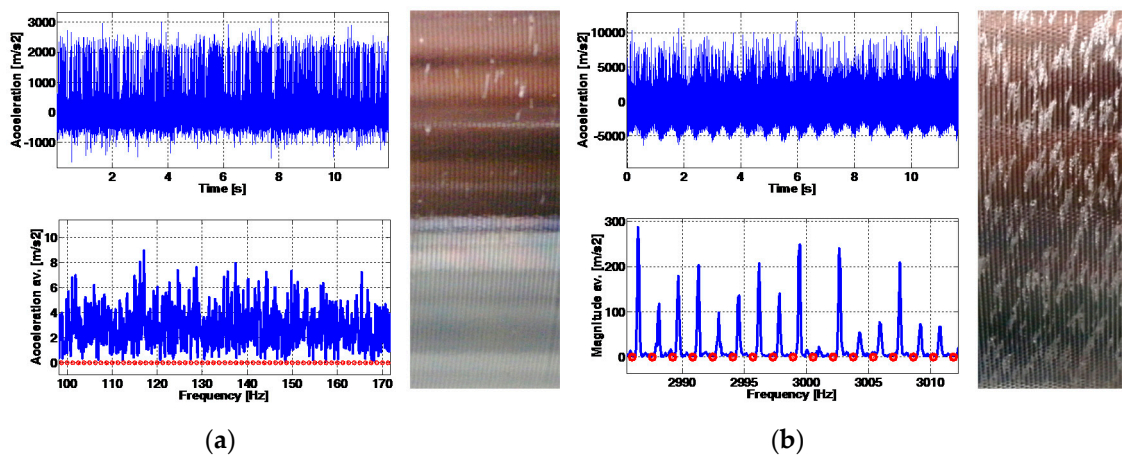



Figure 14. Frequency spectrum of the signal and surface finish: (**a**) Stable case a_P=5 mm/ N= 80rpm; (**b**) Unstable case: a_P=10 mm/N= 100 rpm.

Company machine designer are using the above approach in the daily design of machine variations, increasing the number of cases and simulations in the database, and can reduce a 87% of cases of vibrations on roughing and semi-finishing turning operations. Finishing operations are not addressed because vibrations never appear at very low depth of cut values.

6. Conclusions

Industrial enterprises demand integrated information systems that can comprise the whole production process of any new product. In the case of companies dedicated to the machining of high-added value parts, or to the manufacturing of the machine-tool, this demand is even higher, in view of the increasing customer expectations on the part quality and the competitiveness of this business. Considering that many of the usual   machining problems   were been solved by the state of art but not currently applied in the daily production, it is crucial to have a reliable utility that can provide the greatest number of solutions in an easy and nimble way, being of invaluable help to the enterprise people in the decision-making process.

This work presents a utility approach emerged from the university-research sphere, for closing the lack of process decision and assistance support in machining companies. The latter are engaged in the day-to-day business, thinking in short than in the long term. The utility includes different models that were developed during the last ten years to the present. Besides, this simulation utility incorporates not only predictive applications, but also the possibility to interact with the process so as to prepare and work with real cutting signals. In this way, it means an on-line/off-line dual application. By the time being, it is capable of recording power signals, working with force and noise signals, or else adjusting response functions in frequency (FRF). With all this, this assistant tool involves different company departments for working in a cooperatively way. Thus, a) CAM engineers to program the right toolpaths, b) machine designers for defining the machine configuration, c) process technicians for the detection and reduction of the vibrations during machining, d) cutting tool manufacturers for the design of tools, and others. It is also sought to reduce the human factor whenever possible. In order to prove the capabilities of this program, two successful cases have been shown: a machine tool builder and a manufacturer of components for big gearboxes for the windmill sector.

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Author Contributions: G. Urbikain and M. Arsuaga have developed vibrations and deformation models. M. A. Alonso has programmed the software. L. N. López has worked in machine structural behavior definition. All of the authors have carried out the tests and validation.

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