CutPro

CutPro.exe User Manual

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1 INTRODUCTION

CutPro is an analytical and time-domain machining process simulation and Spindle design software package, developed for off-line process optimization. It can be used as a learning tool, as well as an optimization tool for process planners and machine tool builders to increase production and stability performance of the spindle respectively. Furthermore, CutPro assists you in the tool and spindle design processes for optimum productivity in a controlled environment.

1.1 INSTALLING CUTPRO

Minimum System Requirements:

- Windows 98, Me, NT 4.0, 2000 or XP
- Pentium III 450 MHz processor
- 128 MB RAM
- 120 MB free hard drive space
- SVGA at 800x600, 256 Colors

Recommended System Requirements:

- Windows Me, NT 4.0, 2000 or XP
- Pentium III – 800 MHz or faster
- 128 MB RAM or more
- 200 MB or more free hard drive space
- SVGA at 1024 x 768, True Color

⚠ **In order to use the FULL version of CutPro, you must have a CutPro hardlock (security key) and a valid password for each module you wish to use. You will be prompted to enter these passwords the first time you run CutPro. To obtain your passwords, please contact MAL Inc.**

1.1.1 INSTALLATION INSTRUCTIONS

- Insert the CD labelled **CutPro** into your CD-ROM drive.
- From the Start menu, select Run.
- Type D:\SETUP (or substitute the appropriate letter of your CD-ROM drive for **D**). You can directly run the installation from CD by clicking CutPro.exe.
- Follow the instructions on the screen.

1.1.2 OLDER VERSION OF CUTPRO ALREADY INSTALLED

Before installing **CutPro**, you should uninstall any older versions already installed on your computer and remove the software key from the computer. Any simulation files (e.g., *.mil, *.dat) you created will not be removed.

Follow the steps to remove the existing CutPro in your computer:

- Under the Start menu, select Settings > Control Panel.
- Double-click on the icon labeled Add/Remove Programs.
- Select CutPro from the list and press Add/Remove. This will remove the software from the system.

1.2 CUTPRO MODULES

1.2.1 MILLING

The milling module is highly accurate and the most comprehensive simulation software for optimum planning and trouble shooting of milling processes. The milling module has two sub modules with the following features:

1.2.1.1 2 ½ AXIS MILLING MODULE

The 2½ Axis Milling Module has the following features:

- Simulates regular endmills, variable pitch cutters, ball endmills, indexable cutters, serrated cutters and endmills with any user-defined geometry.
- Has built-in properties of a variety of materials such as Waspeloy, Inconel, Aluminum and Titanium alloys, Steel, standard Sandvik, and Kienzle materials.
- Accepts dynamic parameters of the machine tool and workpiece manually by you or in a variety of formats (i.e. frf, uff, HP sdf, cmp files) created in CutPro or other commercial modal analysis software packages.
- Makes the following predictions and analysis:
  - Simulates **cutting forces in three directions** and surface error under rigid tool/workpiece clamping conditions.
  - Simulates **chatter vibration**, **dynamic milling forces**, tool and workpiece vibrations in the feed and normal directions (x and y), **surface finish roughness**, spindle power, spindle bending moment,

chip thickness and **process stability under flexible tool / workpiece conditions**.

  - **Stability Lobes**: Most accurate predictions of chatter free axial and radial depth of cut and spindle speeds
  - 2D (spindle speed – axial depth of cut) and 3D (spindle speed – axial depth of cut – width of cut) Chatter stability diagrams
  - Simulates time-domain stability lobes
  - Design and analysis of **inserted** / indexable cutters
  - Design and analysis of **variable geometry helical endmills**
  - Design of **variable pitch cutters** tuned to a specific material and spindle for chatter suppression
  - Design and analysis of serrated cutters
  - Automated **identification of cutting constants** from milling tests
  - **User specified material data entry**
  - Simulates stability lobes and forces for a batch of **conditions with multiple immersions**
- Animates cutting processes in discrete domain with vibrations of tool and workpiece.

1.2.1.2 PLUNG MILLING MODULE

The Plunge Milling Module has the following features:

- Simulates plunge milling, plunge milling with a pilot hole, and side plunge milling cutting conditions.
- Analysis of Symmetric and asymmetric tool types with user defined inserts.
- Makes the following predictions and analysis:
  - **Cutting forces in three directions** and surface error under rigid tool / workpiece clamping conditions.
  - **Chatter vibration**, **dynamic milling forces**, tool and workpiece vibrations, **surface finish roughness**, spindle power, spindle bending moment, chip thickness and **process stability under flexible tool/workpiece conditions**.
  - Fast analytical stability lobes prediction, solved in the frequency domain.

1.2.2 TURNING MODULE

The Turning module is simulation software for optimum planning and troubleshooting of turning processes.

1.2.3 BORING MODULE

The Boring module is simulation software for optimum planning and troubleshooting of boring processes. The Boring module has two sub-modules with the following features:

1.2.3.1 SINGLE INSERT

The Single Insert module is designed for quick analysis of single insert boring tools. The Single Insert Sub-Module has the following features:

- Built-in properties of a variety of materials such as Waspeloy, Inconel, Aluminum and Titanium alloys, and Steels
- Accepts dynamic parameters of the machine tool and workpiece manually by you or in a variety of formats (i.e. frf, uff, HP, sdf, cmp files) created in CutPro or other commercial modal analysis software packages
- User specific material data entry
- Makes the following predictions and analysis:
  - Predicts static cutting forces, spindle power and torque, and radial deflection of the boring bar
  - Stability Lobes: Analytical prediction of chatter free radial depth of cuts and spindle speeds

1.2.3.2 MULTI- INSERTS

The Multi- Inserts Sub-Module has the same features as the Single Insert Sub-Module with the following additional features:

- Design of symmetric and asymmetric tools with user defined insert geometry
- Makes the following predictions and analysis:
  - Simulates the cutting forces in three dimensions, with spindle power and torque prediction when the tool and workpiece can be assumed to be rigid or for dynamic tool and workpiece condtions
  - Fast analytical Stability Lobes prediction solved in the frequency domain

1.2.4 MODAL ANALYSIS

The **Modal Analysis** module determines the dynamic characteristics and mode shapes of a machine tool system from frequency response functions (FRF) that are measured at various geometric locations on a system using transfer function measurement software, **MalTF**, an impact hammer, and an accelerometer.

The **Modal Analysis** module has the following features:

- Predicts natural frequency, damping ratio and stiffness of each mode from FRF measurements at the tool tip.
- Receptance coupling of defined end mill with the measured spindle/tool holder. Receptance coupling tool allows you to obtain the assembly response from the responses of the substructures (i.e. spindle and tool) by combining two transfer functions together.
- Flexible tool analysis allows you to predict the transfer function on a slender tool tip where accurate measurement cannot be performed due to multiple hits.
- Predicts and displays mode shapes (1D-2D) and modal parameters from FRF measurements are made along the structure axis, i.e. spindle, thin webs, machine tool column and fixture.
- Accepts FRF measurement files in **MalTF**, ASCII, HP SDF, UFF file formats.
- Easy to use for non-vibration experts.

1.2.5 MALTF

MalTF is a versatile transfer function measurement program, which has been tested for the National Instruments DAQCard-6062E, DAQCard-Al-16E-4 (PCMCIA cards used in notebook computers) and the PCI-MIO-16E-4 (a PCI card used in desktop computers).

The transfer function measurement is performed with impact hammer tests. The results from these tests can be displayed in different formats and saved to disk to be imported into modal analysis software. After performing a series of impact hammer tests the resulting transfer function will be displayed on screen. Various display options can be changed during and after the impact hammer tests to alter the way in which the information is displayed on the screen. The transfer function itself can be viewed in magnitude-phase mode, or alternately in its real and imaginary components. The linear part(s) of the transfer function can be viewed in time domain, or as a frequency spectrum. In addition, the transfer function can be saved in binary format and opened with the all measurement settings at a later time.

MalTF is extremely fast and very easy to use and has the following features:

- Allows measurement in multiple directions.
- Allows the use of different output sources (i.e. accelerometer, displacement sensor, shaker and force sensor) and displaying the results in any format of a/F, X/F or F/F.
- Has an expert system that automatically investigates the quality of the measurement and leads you with the next step to take until all of the measurements meet certain quality requirements. This reduces the inexperienced-user's faults in the measurements and provides consistency in the measurement quality.
- Displays the Input and Output signals in the time domain, the Magnitude & Phase and Real & Imaginary frequency response functions, the Power Spectrum, and the Coherence of the measurements.
- Saves the measurement data in a standard format (frf) that can be directly used in the process simulation modules in CutPro or other software packages.

1.2.6 MALDAQ

MalDAQ is a highly versatile PC-based data acquisition and analysis software. **MalDAQ** can be used to measure cutting forces, vibrations, acoustics, and sensor signals. The program was developed and tested for the National Instruments DAQCard-6062E, DAQCard-Al-16E-4 (PCMCIA cards used in notebook computers) and the PCI-MIO-16E-4 (a PCI card used in desktop computers). The software is also compatible with many analog data acquisition devices that are available from National Instruments.

MalDAQ has the following features:

- Max. 500 kHz sampling frequency
- Up to 8 channel data acquisition
- Logging and streaming data to disk until the disk gets full

- Monitoring real-time data
- Displaying data in time or frequency domain
- Loading and analyzing any range of saved data
- Digital filtering options

1.2.7 SPINDLEPRO

SpindlePro is a specially designed program for the design and analysis of spindle systems. It has two sub-modules:

1.2.7.1 EXPERT SPINDLE DESIGN SYSTEM (ESDS)

This module is used for the initial design of spindles. **ESDS** is based on the efficient utilization of past design experience, the laws of machine design, dynamics and metal cutting mechanics. The expert system leads to automatic generation of spindle configuration which includes drive shaft, motor type and size, transmission mechanism between the motor and shaft, bearing types and tool holder style. The bearing locations are optimized under the constraints of chatter vibration free cutting conditions.

ESDS has the following features:

- According to the cutting conditions such as tool geometry, work-piece material, cutting speeds, depth of cut, etc., the required torque, power and maximum motor speed are automatically predicted
- Automatic **selection of spindle and transmission type**
- Allows **selection of lubrication**
- **Optimizes bearing locations**

1.2.7.2 SPINDLE ANALYSIS MODULE (SpindlePro)

This module is a finite element software that is used for performance analysis and optimization of the spindles. It allows analyzing the static and dynamic response of machine tool spindles. The rotating effects from both spindle shaft and bearings are considered in the model. Timoshenko beam theory is used in the FE model, which includes axial, bending and torsional behavior of the spindle system. The nonlinear bearing model is used to include effects due to preloads and spindle speeds.

SpindlePro has the following features:

- Deflection at any location of the spindle, reaction forces and moments at bearing and housing supports can be predicted under any static forces.
- Damped and Undamped Modal Analysis. The natural frequencies and mode shapes are sorted according to axial, torsional and bending. You can assign modal damping ratios for each mode from your own experience and the database.
- **Fast and user friendly interface** to build the spindle model.
- Performs **Frequency Response Function (FRF) analysis**.
- Includes **rotating effect on bearings and natural frequencies**.
- Predicts **bearing forces under cutting loads**.
- Displays **history of displacement, velocity and acceleration under dynamic forces**.
- **User friendly post-processor**.

1.2.8 VIRTUALCNC

Virtual CNC is a powerful module which provides a comprehensive simulation environment for CNC design engineers and users simulate a wide range of performance-related properties of Cartesian-Configuration CNC machine tools before the actual machining process. This way expensive and time-consuming trial and error cuts can be reduced. It accepts standard APT-CL files, processes them exactly like a real CNC. You can define trajectory generation style, amplifier settings, position (encoder), velocity (tacho generator) and acceleration feedback sensors and their resolutions, and axis control laws. The **Virtual CNC** system predicts the actual positions delivered by the CNC, and plots the reference and predicted actual paths, the tolerance violation points along the tool path, cycle time by accurately calculating the feed fluctuations caused by acceleration/deceleration and control law, motor current and position-displacement and acceleration of each drive. **Virtual CNC** allows testing of different control laws, friction fields, motors, sensors, ball screws and trajectory generation algorithms. It runs in stand alone and MATLAB environments. It also provides time and frequency domain response of individual drives, as well as testing of the CNC on ISO standard test work-pieces such as diamond and circle. **Virtual CNC** can be used by manufacturing shop engineers as well as by the CNC designers and professors who teach position control of motion devices.

Virtual CNC offers the following features:

- Step by step CNC Model Generation
- Detailed CNC Performance Simulation
- CNC Advanced Controller Design/Analysis Tools

1.3 OVERVIEW OF CUTPRO

1.3.1 STARTING CUTPRO

- From the Start menu, click Programs.
- Select CutPro and click on CutPro from the drop-down menu.

1.3.2 THE MAIN WINDOW

When you first open CutPro, the main window appears. This window consists of a toolbar, as well as a series of menus. The ***Properties Window*** is automatically displayed.

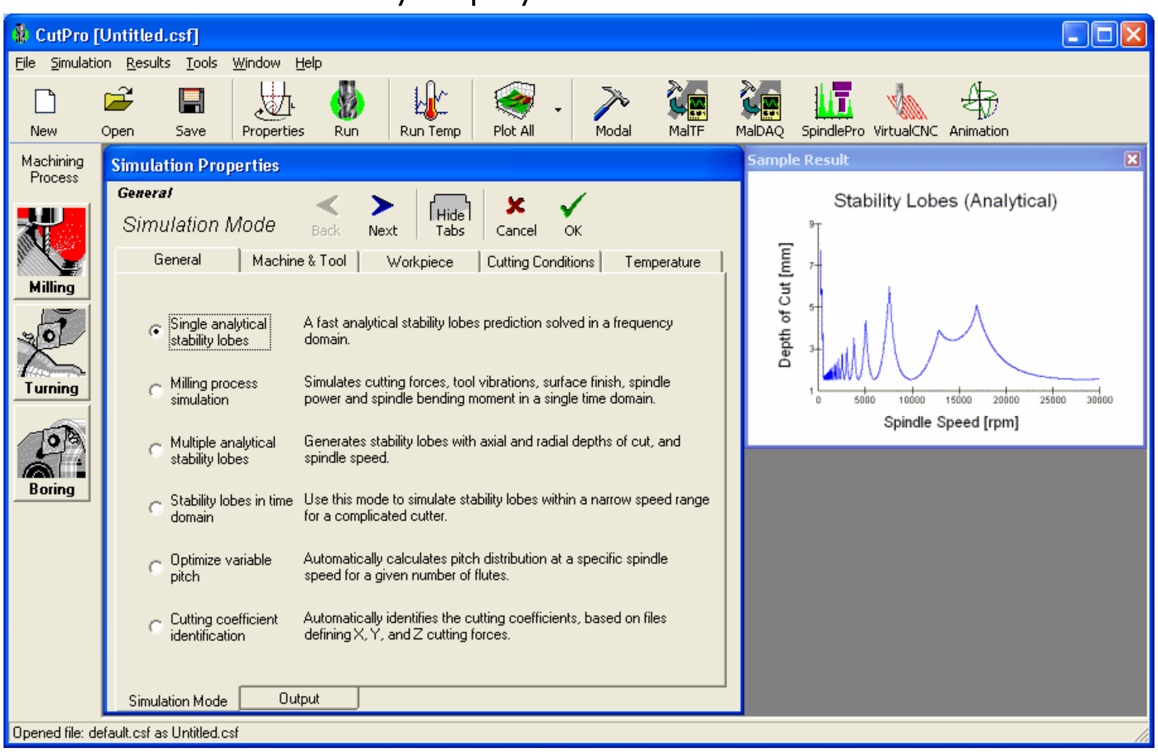
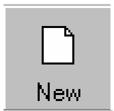
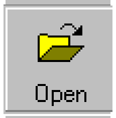
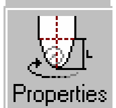
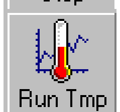
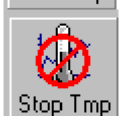
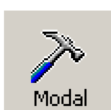
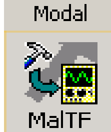
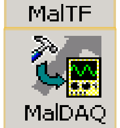
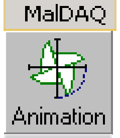
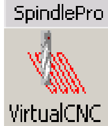


Figure 1.3-1: Simulation Properties window is displayed for the 2½ Axis Milling Module by default when CutPro is started.

1.3.3 MAIN WINDOW TOOLBAR BUTTONS

Table 1.3-1: List of buttons on the CutPro Toolbar

	*New*	*Create a new simulation*
	*Open*	*Open an existing simulation*
	*Save*	*Save the current simulation*
	*Properties*	*View / edit the parameters defining the current simulation*
	*Start*	*Start the simulation*
	*Stop*	*Stop the simulation*
	*Start*	*Start the temperature simulation*
	*Stop*	*Stop the temperature simulation*
	*Plot*	*Plot all of the simulation results; or, click the drop-down arrow to plot a single result*
	*Modal Analysis*	*Load the Modal Analysis tool*
	*MalTF*	*Load the MalTF transfer function measurement tool*
	*MalDAQ*	*Load the MalDAQ data acquisition tool*
	*Milling Animation*	*Load the Milling Animation tool*
	*SpindlePro*	*Load the SpindlePro tool*
	*VirtualCNC*	*Load the VirtualCNC tool*

1.3.4 MAIN WINDOW MENU COMMANDS

1.3.4.1 FILE

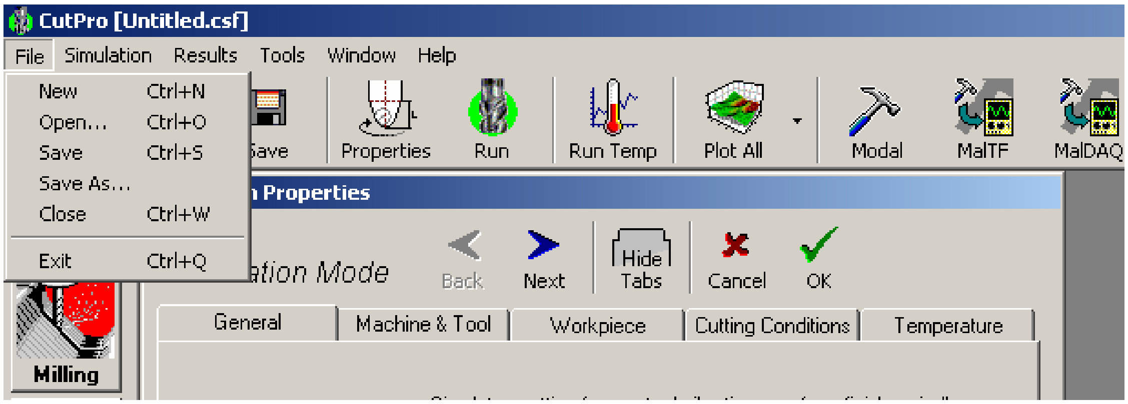


Figure 1.3-2: File menu on CutPro

Table 1.3-2: The drop-down menu of File command

New	*Create a new simulation*
Open	*Open an existing simulation*
Save	*Save the current simulation*
Save As	*Save the current simulation under a different name*
Close	*Close the current simulation*
Recent Files	*Select recent files to open*
Exit	*Exit CutPro*

⚠ **When you Save a CutPro simulation, all of the currently loaded Results are saved, as well as the Simulation Properties.**

⚠ **You can neither Save nor Print in the DEMO version of CutPro.**

1.3.4.2 SIMULATION

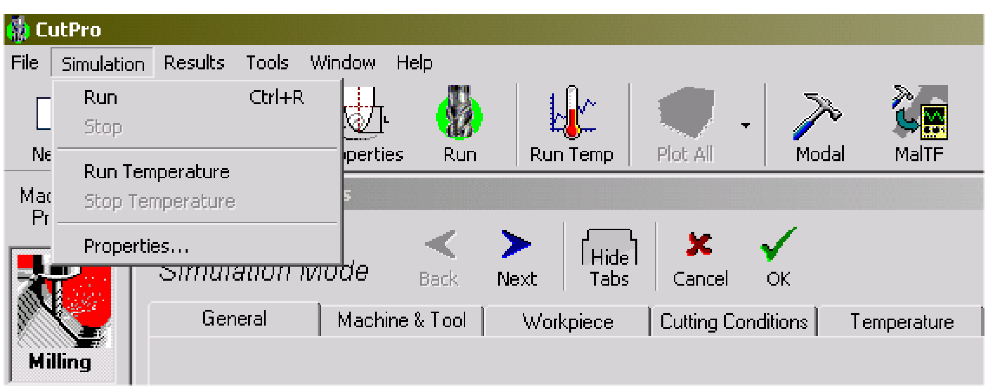


Figure 1.3-3: Simulation menu on CutPro

Table 1.3-3: The drop-down menu of Simulation command

Run	*Run the simulation*
Stop	*Abort the simulation*
Run Temperature	*Run the temperature simulation*
Stop Temperature	*Abort the temperature simulation*
Properties…	*View / edit the parameters defining the current simulation*

1.3.4.3 RESULTS

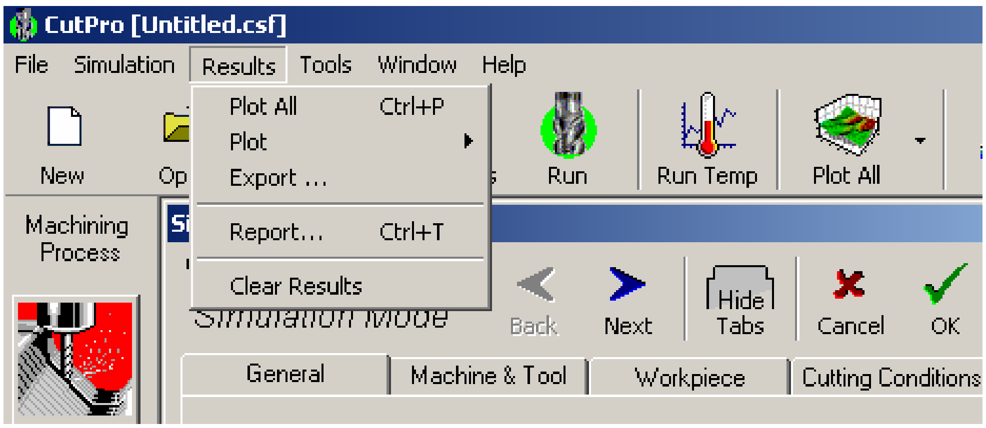


Figure 1.3-4: Results menu in CutPro

Table 1.3-4: The drop-down menu of Results command

Plot All	*Plot all simulation results*
Plot	*Allows you to select a simulation result to plot*
Export	*Brings up the **Export Results** window. Select a result set from the drop-down list, then specify the ASCII text file (*.txt) to which you want to export it. You can either type the name of a text file in the box provided, or find an existing file to write over by pressing the browse (...) button.*
Report	*Brings up the **Reports** window which summarizes the simulation conditions such as cutting conditions, properties of cutter and workpiece and results.*
Clear Results	*Delete all results. This will disable the **Results** menu. You must run a simulation in order to generate new results.*

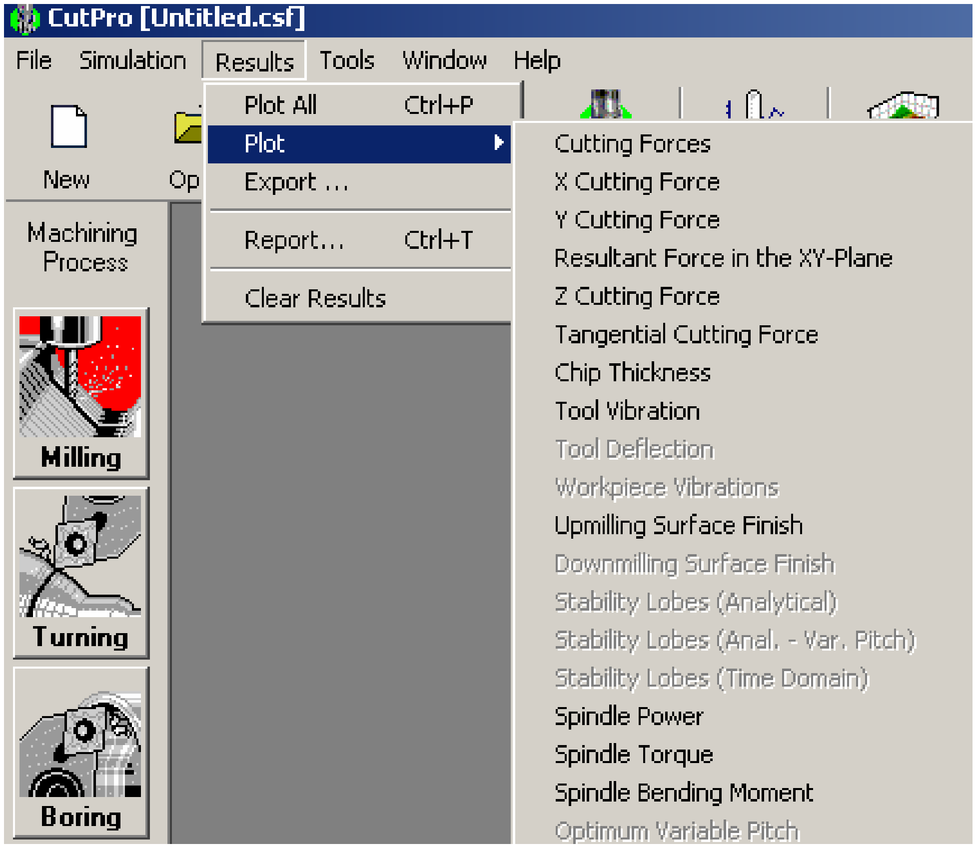


Figure 1.3-5: Results menu in CutPro (Plot window)

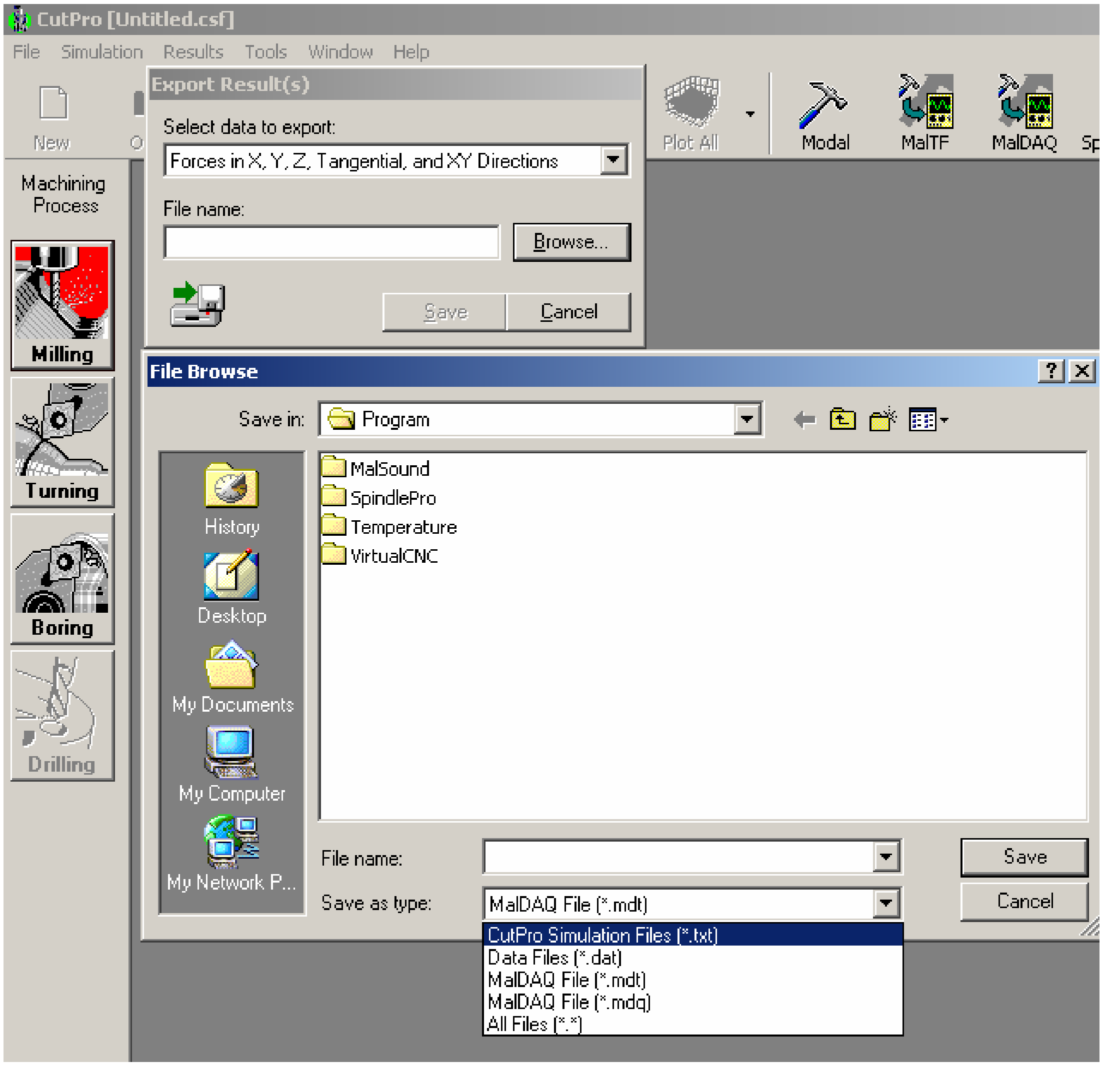


Figure 1.3-6: Results menu of CutPro (Export Results window)

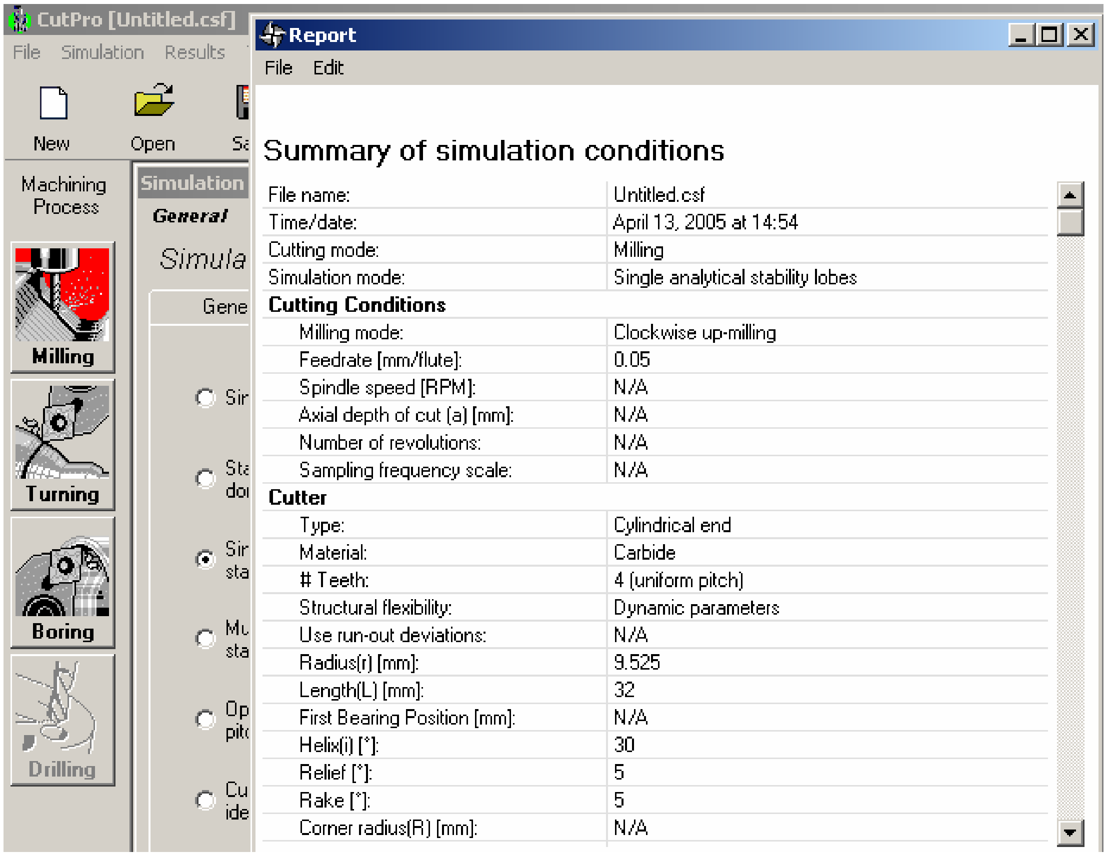


Figure 1.3-7: Results menu in CutPro (Report window)

You can add simulation results to the report by selecting ***Options*** and clicking on ***Add to Report*** from the drop-down menu in the graph window.

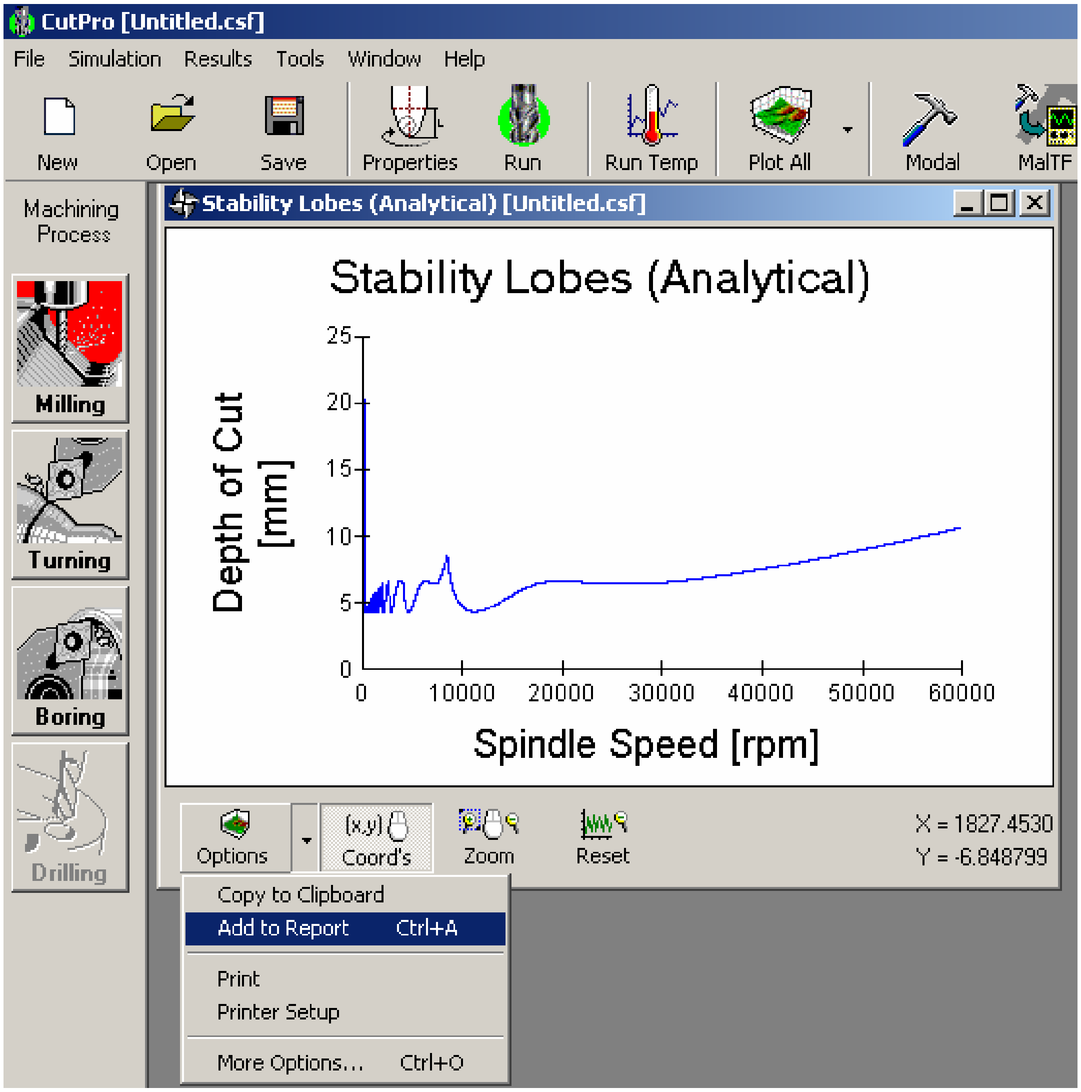


Figure 1.3-8: Adding the simulation results to the Report

1.3.4.4 TOOLS

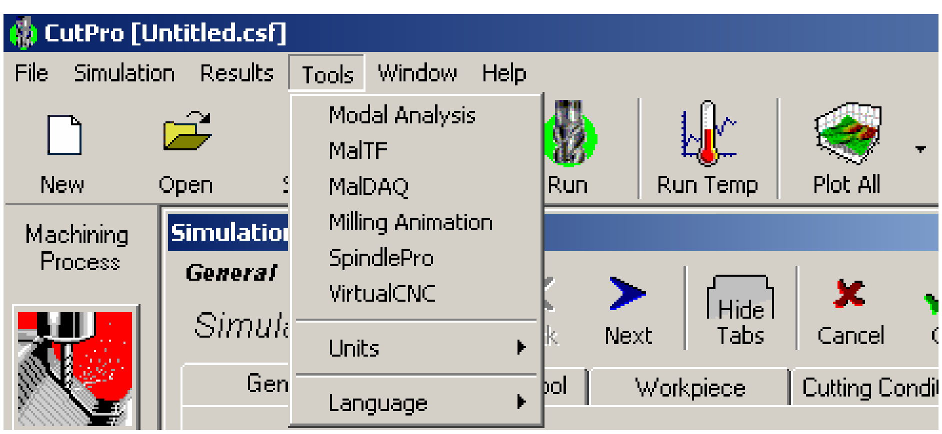


Figure 1.3-9: Tools menu in CutPro

Table 1.3-5: The drop-down menu of Tools command

Modal Analysis	*Run the Modal Analysis program.*
Modal Analysis	*Run MalTF, the transfer function measurement program.*
MalDAQ	*Run MalDAQ, the data acquisition and analysis program.*
Milling Animation	*Run the Milling Animation program.*
SpindlePro	*Run SpindlePro which is used to design and analyze the spindle systems.*
VirtualCNC	*Run VCNC which simulates the performance-related properties of Cartesian-Configuration CNC machine tools before the actual machining process.*
Units	*Choose to display units in CutPro in **Metric** or **Imperial** units of measurement.*
Language	*Choose the language of CutPro. The options are: English, German and French.*

1.3.4.5 WINDOW

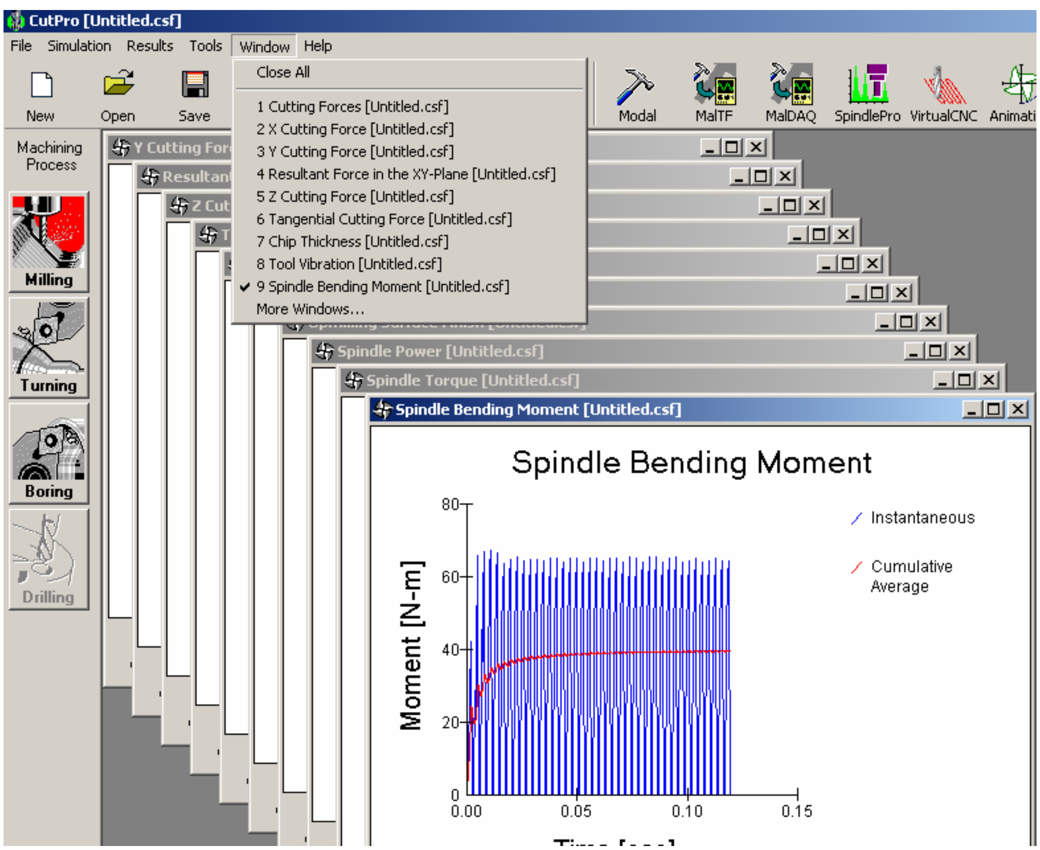


Figure 1.3-10: Window menu in CutPro

Table 1.3-6: The drop-down menu of Window command

Close all	*Close all open graphs*
Figure Names	*Select the figure that you want to display on the screen.*

1.3.4.6 HELP

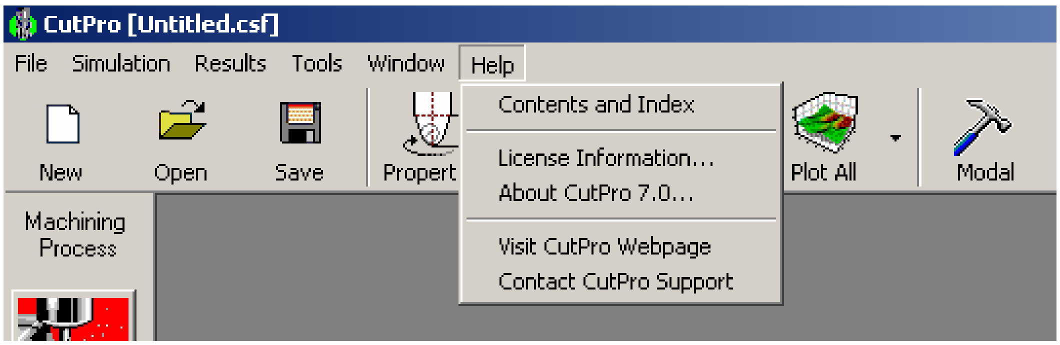


Figure 1.3-11: Help menu in CutPro

Table 1.3-7: The drop-down menu of Help command

Contents and Index	*Display Help files for CutPro. Allows you to click on an object in the CutPro graphical interface from either the content or the index or the find options and view the relevant help page(s).*
License Information…	*Activate CutPro modules with valid passwords you have obtained from MAL Inc.*
About CutPro	*Display information about CutPro*
Visit CutPro Webpage	*Visit website* ***http://www.malinc.com***
Contact CutPro Support	*Send your questions to MAL Inc.*

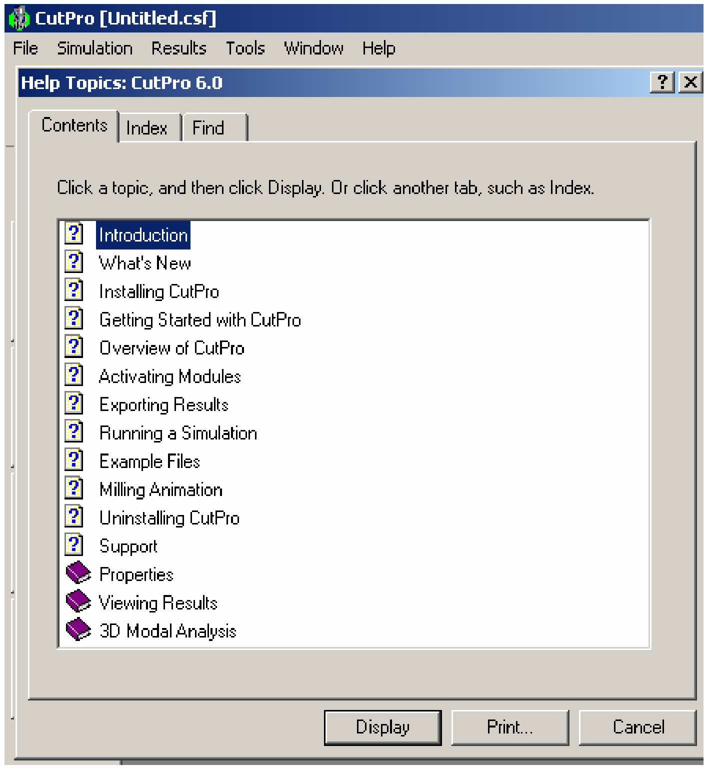


Figure 1.3-12: Help menu in CutPro (Contents and Index window – Contents option)

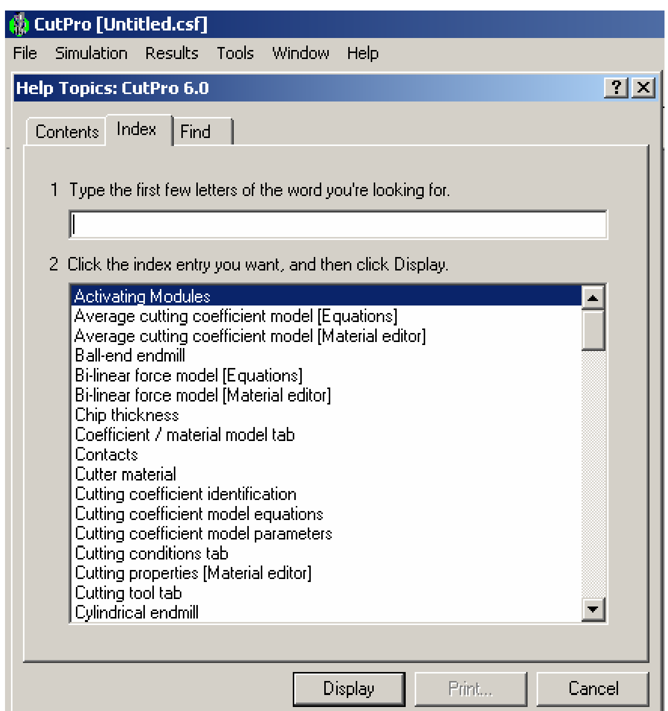


Figure 1.3-13: Help menu in CutPro (Contents and Index window – Index option)

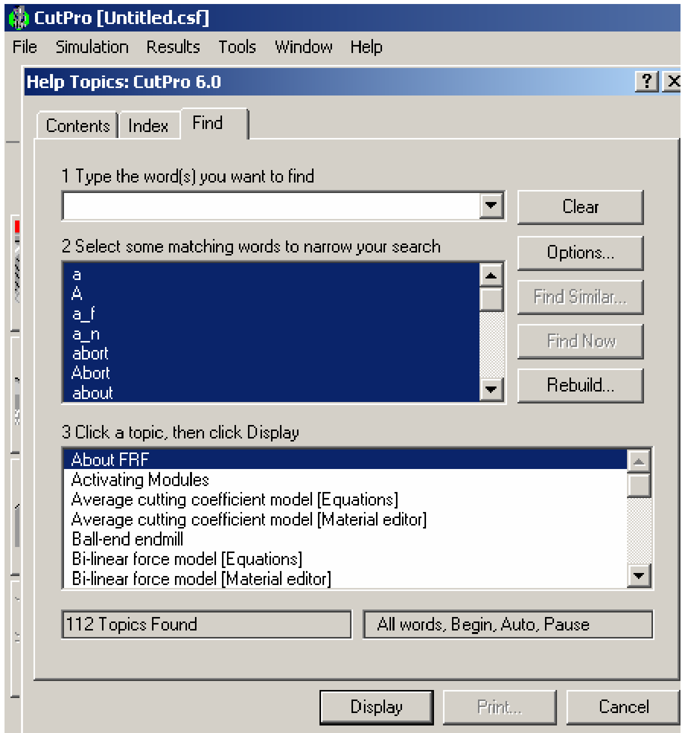


Figure 1.3-14: Help menu in CutPro (Contents and Index window – Find option)

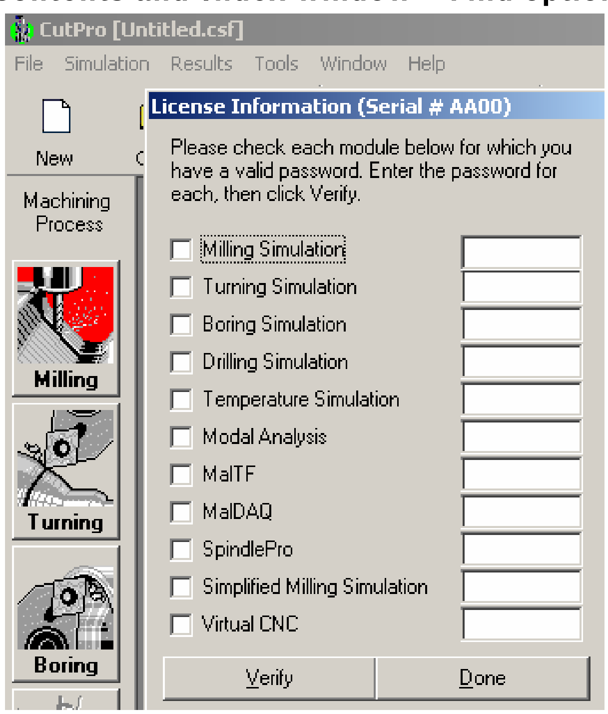


Figure 1.3-15: Help menu in CutPro (License information window)

1.4 ACTIVATING MODULES

In order to use the FULL version of CutPro, you must have a CutPro hardlock (security key) and a valid password for each module you wish to use. You will be prompted to enter these passwords the first time you run CutPro. To obtain your passwords, please contact ***MAL Inc.***

To enter your passwords, select ***License Information*** from the ***Help*** menu in the main CutPro window. Once you have entered the passwords for the modules you are authorized to use, press the ***Verify*** button. Finally, press ***Done*** to close the window and you can continue using CutPro.

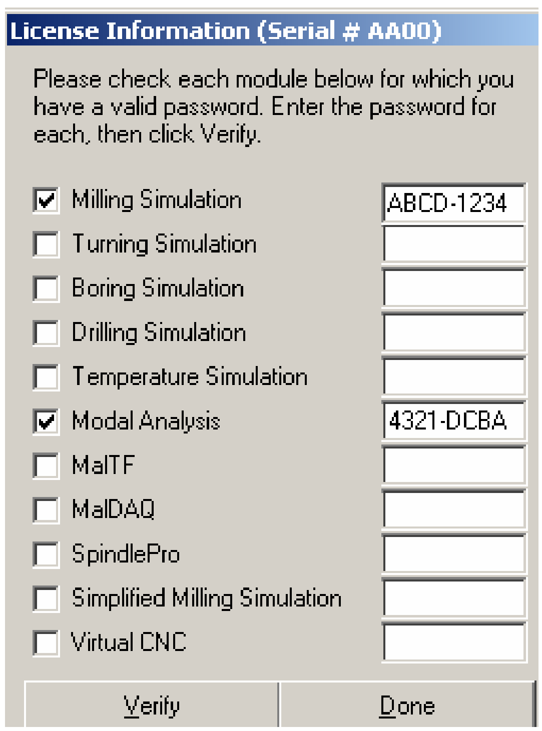


Figure 1.4-1: License Information window where the passwords of the modules are entered

2 MODULES

2.1 MILLING MODULE

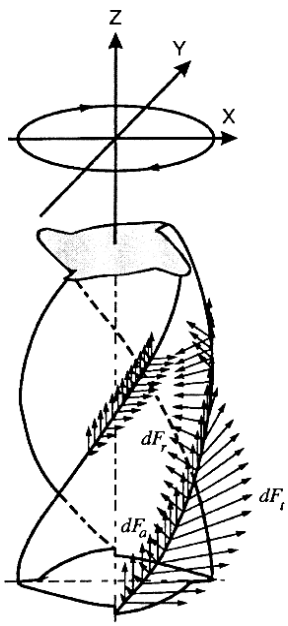


Figure 2.1-1: Axes definition of a milling process. Note that the X-direction is the feed direction.

2.1.1 2½ AXIS MILLING MODULE

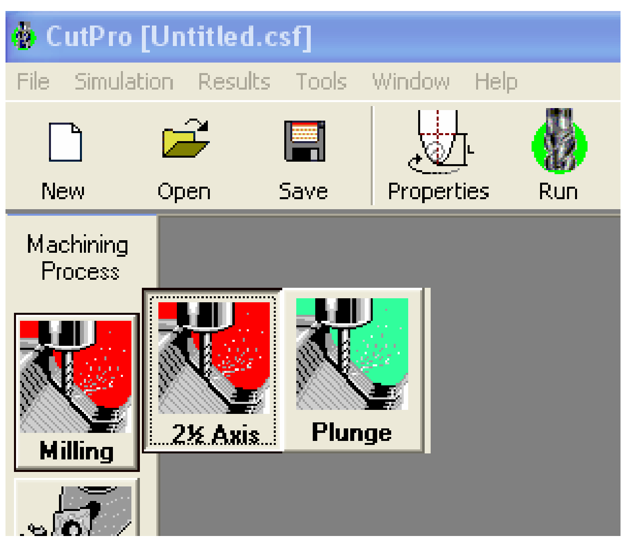


Figure 2.1-2: 2½ Axis Milling module

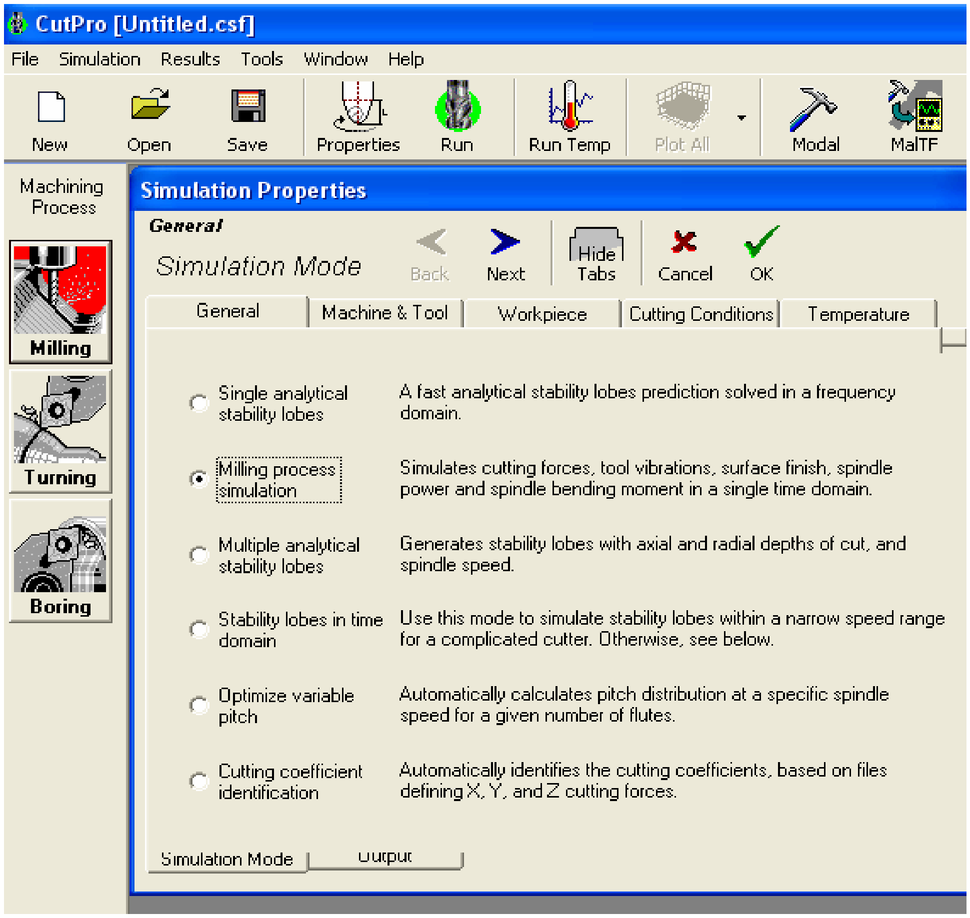
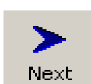
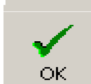


Figure 2.1-3: General tab of 2½ Axis Milling module

Table 2.1-1: Buttons on Simulation Properties window

	*Back*	*Switch to the previous tabs*
	*Next*	*Switch to the next tabs*
	*Hide Tabs*	*Hide tabs*
	*Show Tabs*	*Show tabs*
	*Cancel*	*Cancel the simulation*
	*Ok*	*Save the simulation parameters*

CutPro starts with the ***Simulation Properties*** window of the ***2½ Axis Milling*** module by default. You will be prompted to enter the necessary parameters for the selected process, and can switch from one tab to another by clicking the ***Back*** *or* ***Next*** buttons on the

Simulation Properties window. You can hide or show tabs by using the ***Hide Tabs*** or ***Show Tabs*** button. After you enter all the parameters, you have to click the ***OK*** button to be able to save the process parameters you have defined, and to run the simulation mode you chose. If you click on the ***Cancel*** button, you will lose the data you entered and cancel the simulation. By clicking on the ***Run*** button on the ***Toolbar*** of CutPro, you begin running your simulation.

There are six simulation modes:

- **single time domain**
- **stability lobes in time domain**
- **single analytical stability lobes**
- **multiple analytical stability lobes**
- **optimize variable pitch**
- **cutting coefficient identification**

In this section, each of them will be summarized step by step and you can find more details about the simulation properties window's tabs and definitions in **Section 3.1 2½ Axis Milling Module**. When you select a simulation mode, the ***Sample Results window*** will give an example of the output figures for the specified simulation mode.

2.1.1.1 MILLING PROCESS SIMULATION

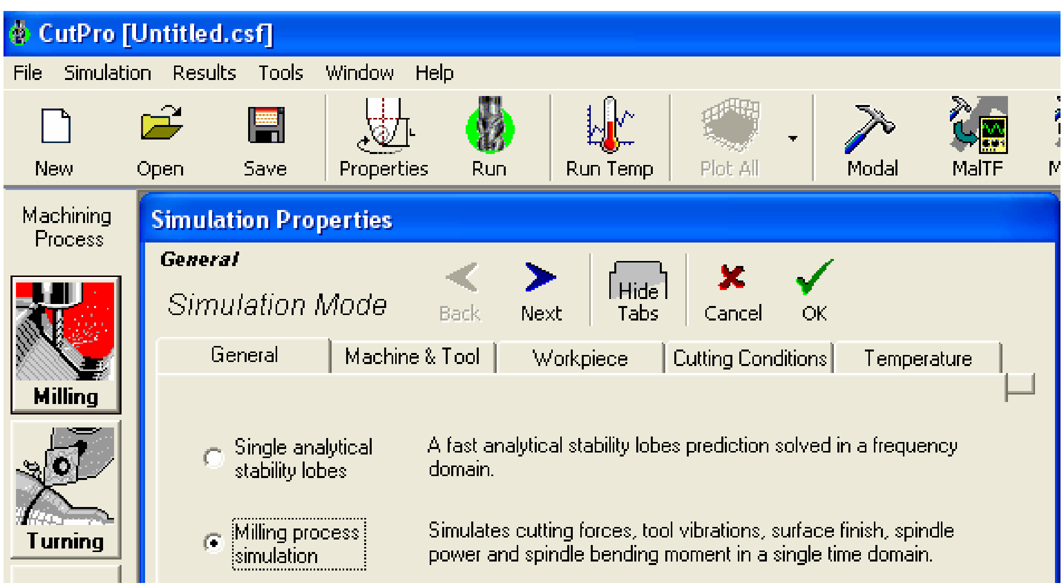


Figure 2.1-4: Milling Process Simulation mode is selected in General tab of the 2½ Axis Milling module.

In this simulation mode, cutting forces in x, y, z and tangential directions, resultant cutting force in xy plane, chip thickness, tool vibration and deflection, workpiece vibrations, surface finish due to forced and chatter vibrations, spindle power and torque, bending moment acting on the machine tool, and animation of chip removal are simulated based on the cutter geometry, machining parameters and dynamic modal parameters of both the workpiece and tool defined by you.

In this time domain simulation, the process is simulated based on numerical integration algorithm for the defined condition and parameters with small time increments. At the end of the simulation the time history of the process in terms of forces in three directions, torque, power, vibration and etc. is displayed. You also have an option to save any simulation result in an ASCII file in order to use it in other programs such as Matlab, Excel etc. (See **Figure 1.3-6** in Section 1.3.4.3 – the Export Results window in the Results menu of CutPro - for details).

The milling process simulation is very useful for detailed examination of nonlinear effects such as jumping out of the tool from the cut, tool run-out and also complex cutting tool geometry. The benefits of this simulation mode are: you can predict the cutting forces considering the dynamics of the tool and workpiece structure and see if the cutting forces are beyond the limit that the tool can carry; you can check if the chatter vibrations are very drastic which can cause the tool to brake down very easily; you can predict the required torque and power for the simulated process and then check these values with the maximum power and torque limits of your machine; you can predict the chip thickness variation by using either the exact kinematics of chip generation or the approximated chip model; you can display the tool and workpiece vibrations in the x and y directions; you can predict the roughness of the surface finish by looking at the surface finish graph and see if it is within the acceptable tolerances.

This simulation mode is usually used in conjunction with other simulation modes such as stability lobes in time domain and single analytical stability lobes. The sample results window of the milling process simulation mode is shown in the following figure:

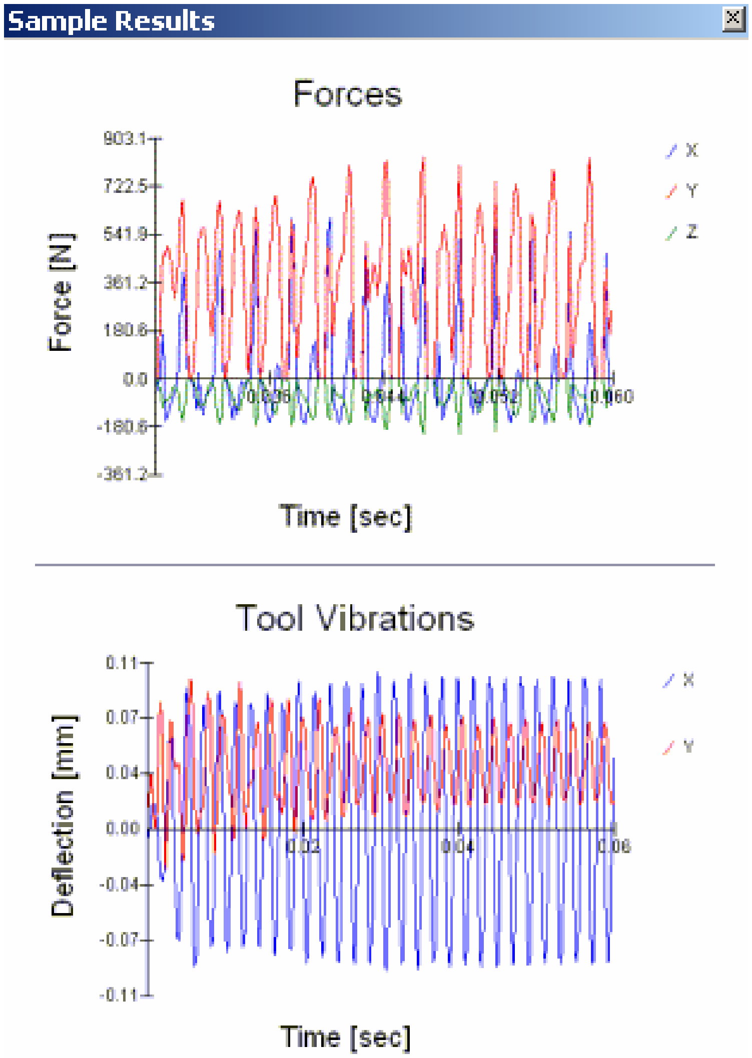


Figure 2.1-5: Sample Results window of Single Time Domain mode

2.1.1.2 STABILITY LOBES IN TIME DOMAIN

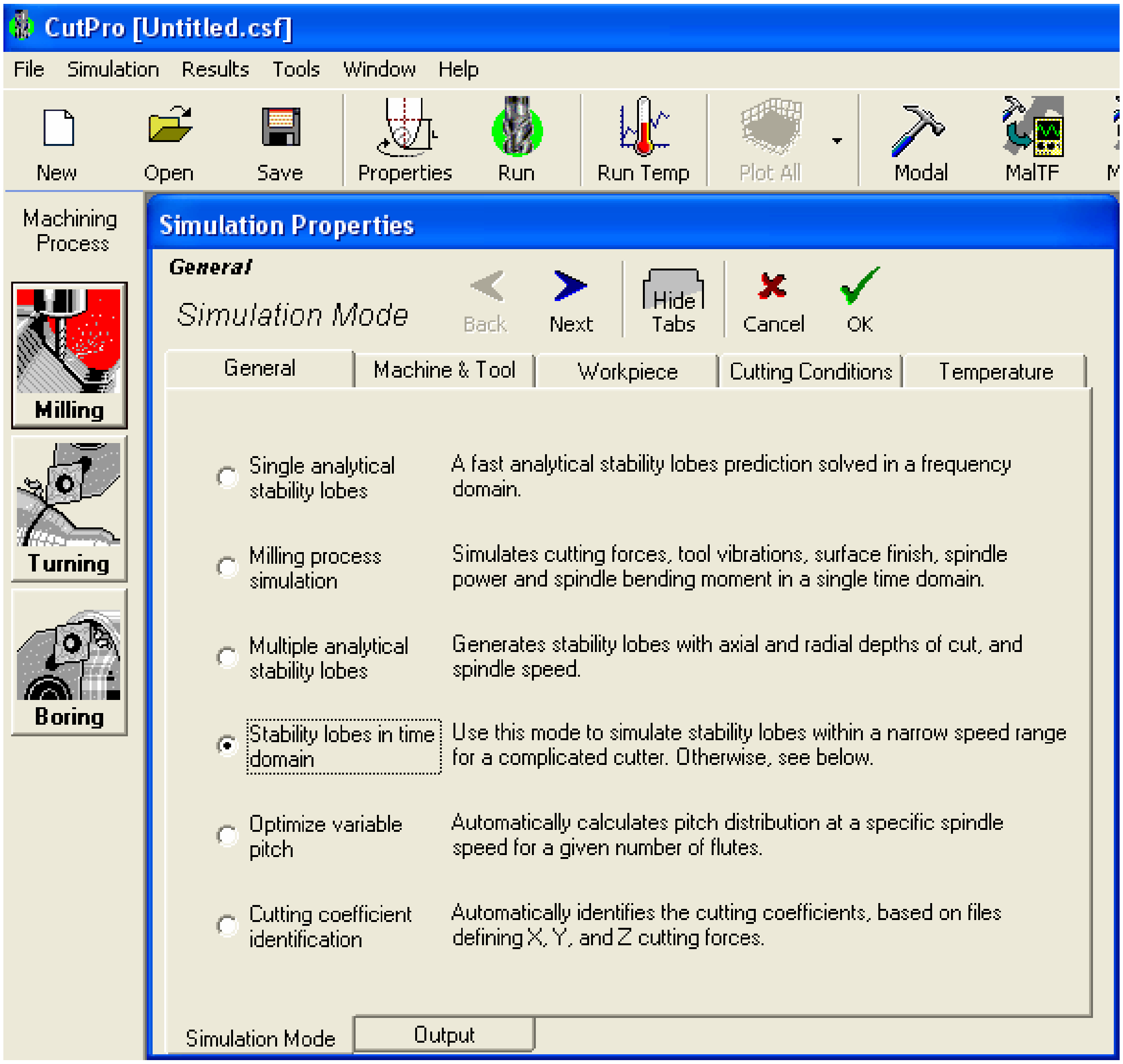


Figure 2.1-6: The Stability Lobes in Time Domain mode is selected in General tab of the 2½ Axis Milling module.

This simulation mode simulates the stability lobes in the time domain to determine stability border for the particular milling process.

Stability lobes: Chatter stability is expressed by the stability lobes figure which defines the boundary that separates stable and unstable machining in the form of axial depth of cut limit versus spindle speed for a fixed radial width of cut and workpiece-tool combination. The region under the stability lobes is stable and the region above the stability lobes is unstable. The sample result window for the "Stability lobes in time domain" mode is given by the following figure:

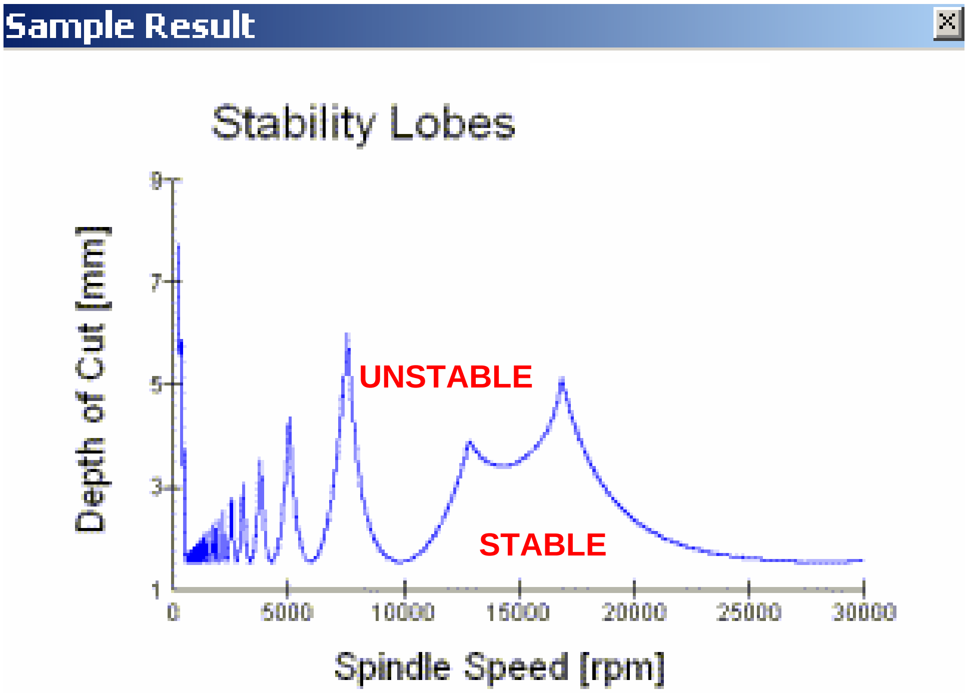


Figure 2.1-7: Sample Result window of Stability Lobes in Time Domain mode

Basically, this mode simulates the process in the time domain with small increments within the spindle speed and depth of cut ranges specified by you (See **Section 3.1.10 Cutting Conditions/Other Parameters**) and decides whether the process is stable for each simulated condition. If stable, it goes to the next higher depth of cut for the same spindle speed repeating the simulation; otherwise it reduces the depth of cut. This procedure goes on until it finds the critical depth of cut value for the stable cutting at the same spindle speed. Then it increases the spindle speed and scans the critical depth of cut for the new spindle speed.

Due to the long computational time, this simulation may take very long time depending on the specified spindle speed range. In order to shorten this time, it would be a wise decision you specify a short range of spindle speed where you potentially wish to operate the machine.

The time domain simulation is executed based on the exact kinematics of a milling process. Due to this fact, some nonlinearities such as the tool jumping out of the cut, or nonlinear variation of the cutting coefficients are taken into account in the time domain simulation. This makes this simulation more accurate compared to the analytical simulation where the system is assumed to be linear.

2.1.1.3 SINGLE ANALYTICAL STABILITY LOBES

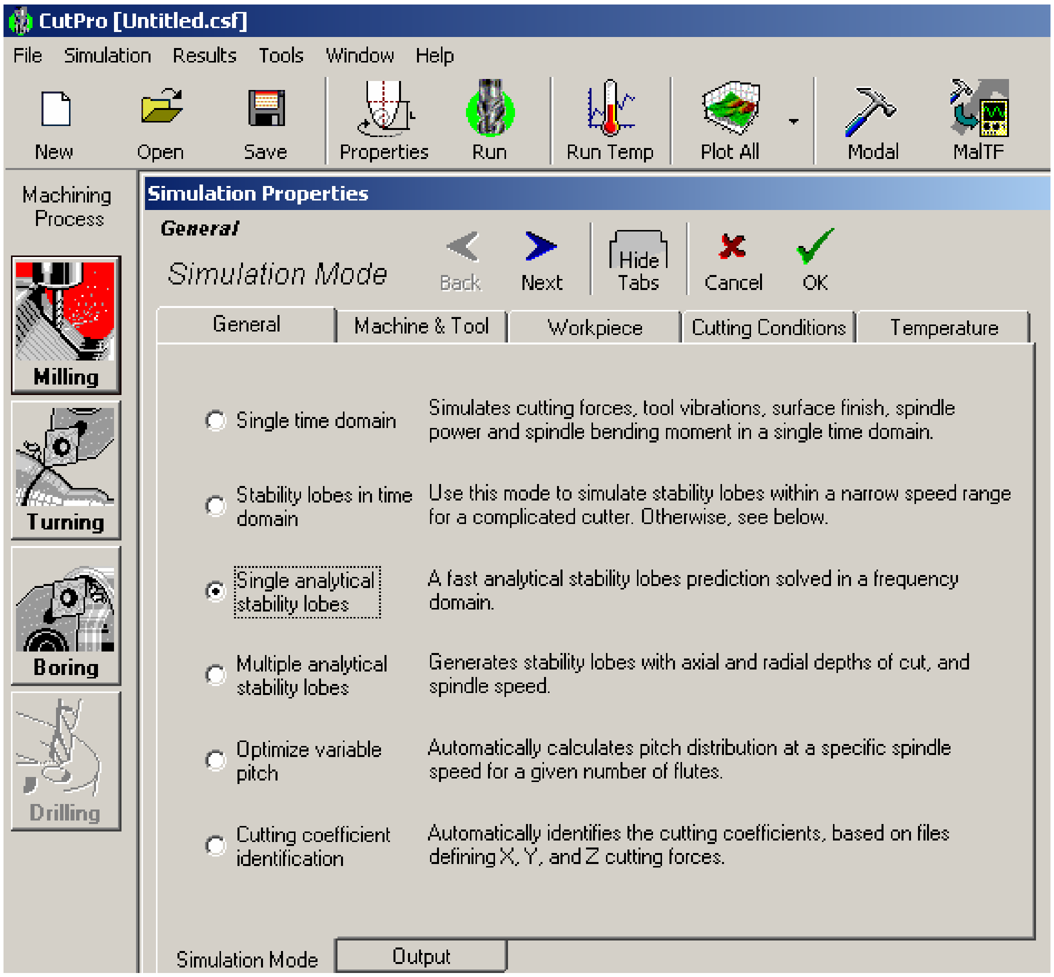


Figure 2.1-8: The Single Analytical Stability Lobes mode is selected in General tab of the 2½ Axis Milling module

This mode simulates the

Stability lobes in frequency domain. In this mode, the process is modeled by using the linear stability theory. Nonlinearities such as the tool jumping out of cut, multiple regeneration, process damping, run-out and nonlinear cutting coefficients are neglected in linear stability analysis which makes it a very quick simulation. It generates the stability lobes by indicating the axial depth of cut and spindle speeds for a fixed radial width of cut. The sample result window of the single analytical stability lobes mode is displayed below:

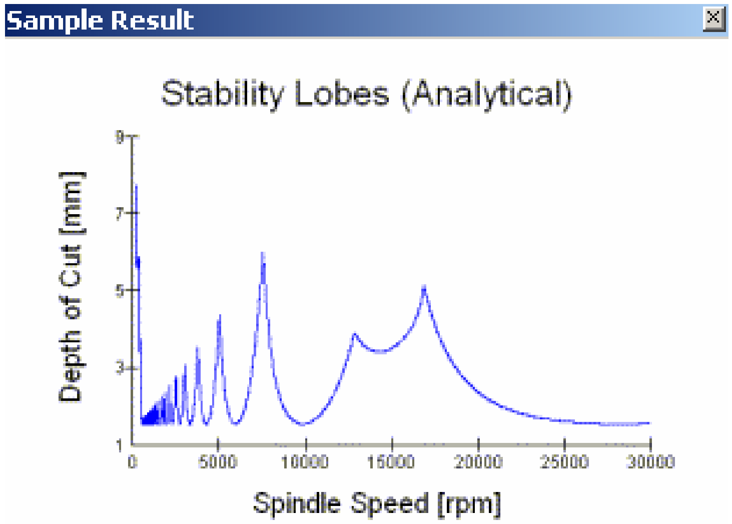


Figure 2.1-9: The sample Result window of the Single Analytical Stability Lobes mode

2.1.1.4 MULTIPLE ANALYTICAL STABILITY LOBES

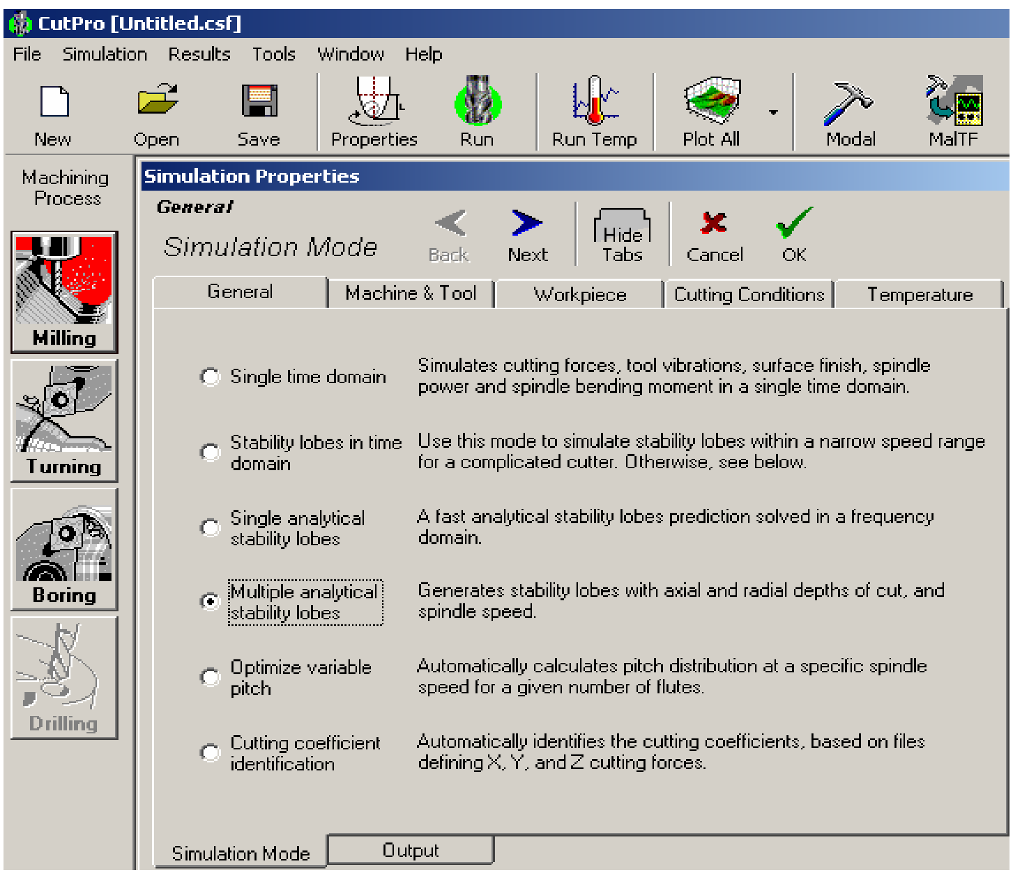


Figure 2.1-10: The Multiple Analytical Stability Lobes mode is selected in General tab of the 2½ Axis Milling module.

This mode simulates the stability lobes in frequency domain for a milling process with several different steps. For example, the process represented by the following diagram involves a half-immersion down-milling, a full immersion milling (slotting) and a half-immersion up-milling.

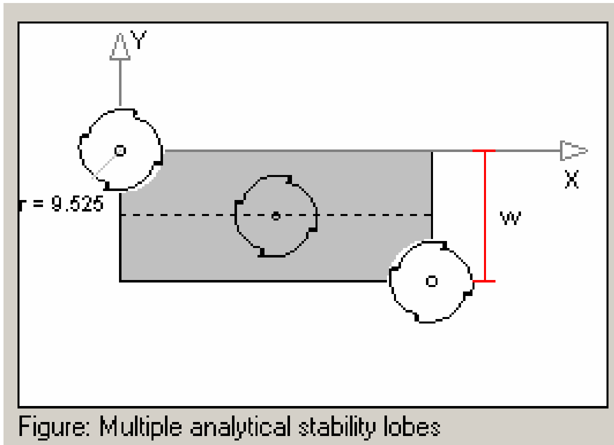


Figure 2.1-11: A sample multiple-steps milling process. Begin with a half-immersion down-milling, then slotting and a half-immersion up-milling

In order to obtain a stable process, the cutting conditions must produce stable results for all the steps involved in the operation. The sample result window of the multiple analytical stability lobes mode is given by the following figure:

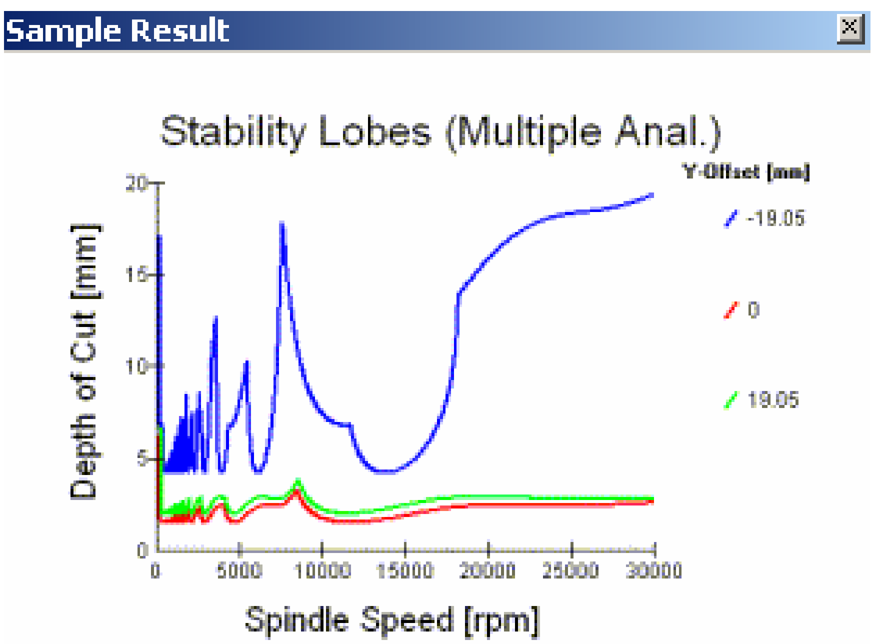


Figure 2.1-12: Sample Result window of Single Analytical Stability Lobes mode

2.1.1.5 OPTIMIZE VARIABLE PITCH

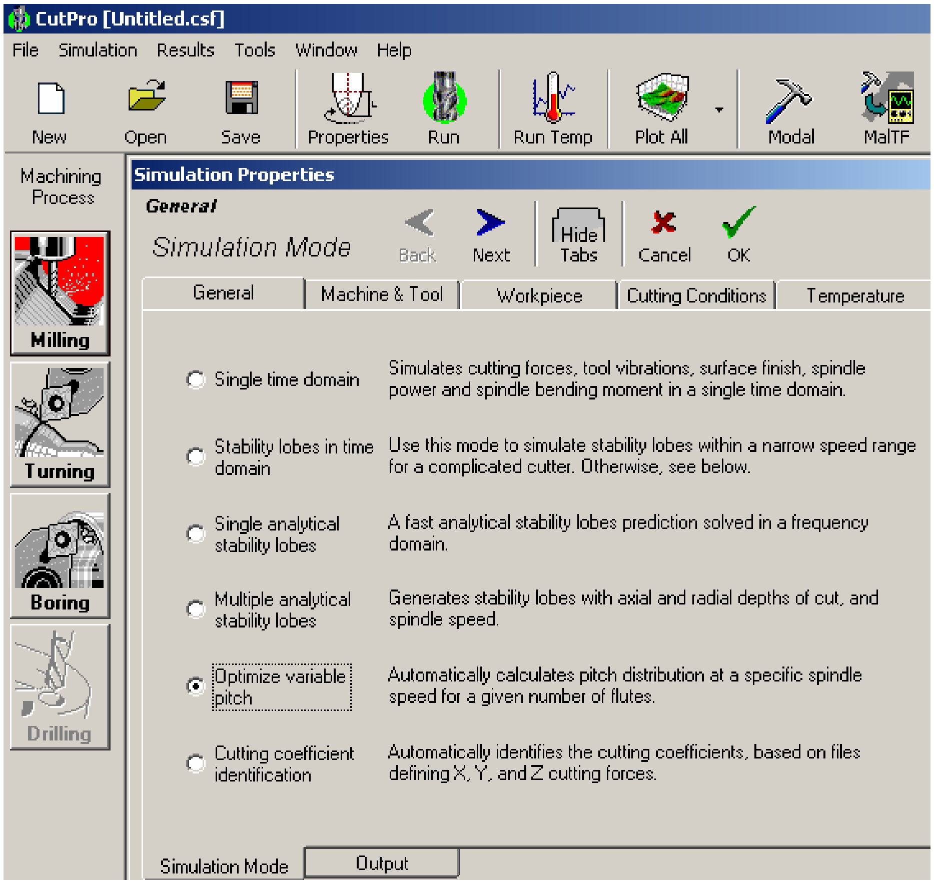


Figure 2.1-13: Optimize Variable Pitch mode is selected in General tab of the 2½ Axis Milling module.

This mode enables you to look for the optimum variable pitch angles in order to make a particular cutting condition stable. This is useful when a desired cutting condition is unstable with a uniform pitch. The result of this mode shows sets of optimum pitch angles and their corresponding maximum depths of cuts allowed for a stable process in the cutting conditions specified. The sample result window of Optimize Variable Pitch mode is shown below:

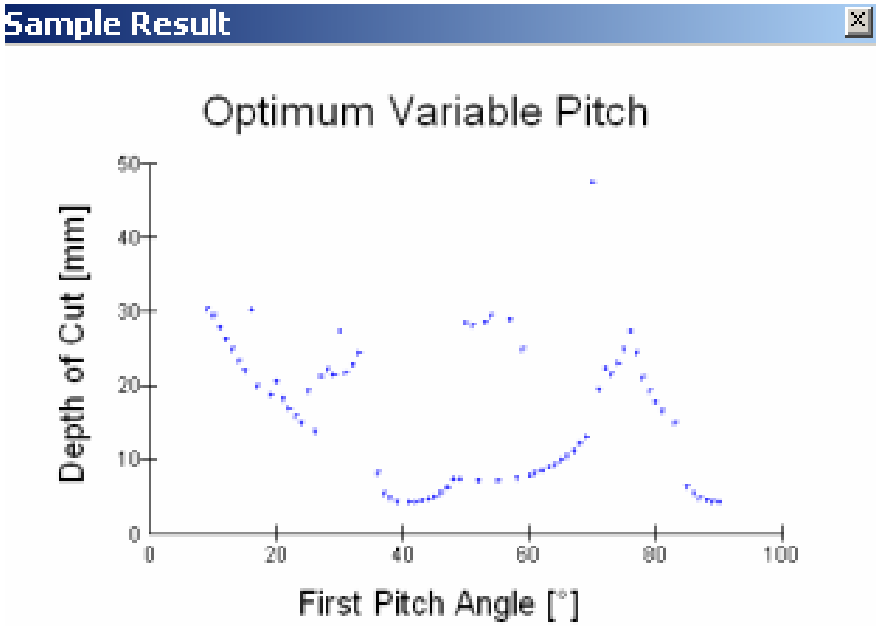


Figure 2.1-14: Sample Result window for Optimize Variable Pitch

2.1.1.6 CUTTING COEFFICIENT IDENTIFICATION

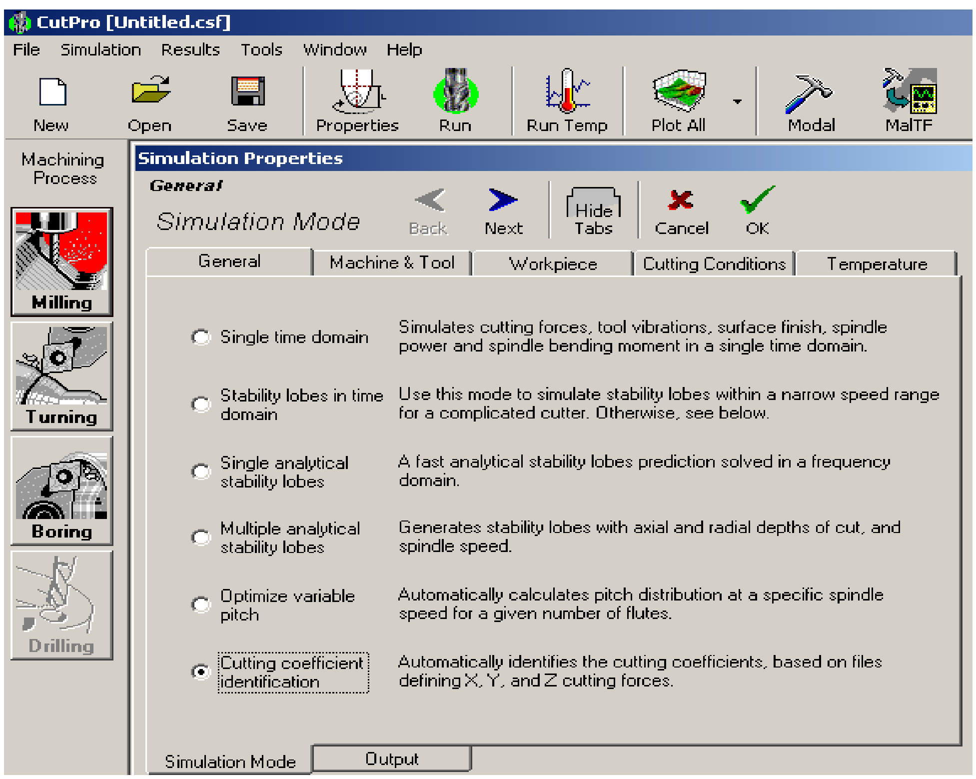


Figure 2.1-15: Cutting Coefficient Identification mode is selected in General tab of the 2½ Axis Milling module.

This mode enables you to identify cutting coefficients of a user defined material. Material cutting coefficients have important roles in the process simulations in CutPro and should be identified accurately for the sake of accuracy of the simulation results. CutPro has already material coefficients data available for some materials. If the workpiece material is not in the material list you need to identify the cutting coefficients before proceeding the simulation. This requires 6-7 force measurement tests with the tool and workpiece material you wish to cut at a constant depth of cut and cutting speed but varying feed rates. After the tests are completed you load the force data files into CutPro. It processes the data and generates the cutting coefficients for you. Then the cutting coefficients are saved in the user defined material list in order to be used in the simulations. The details of the procedure are explained in **Section 3.1.10.6 Cutting Coefficient Identification**. Sample result window of cutting coefficient identification mode is given in the following figure:

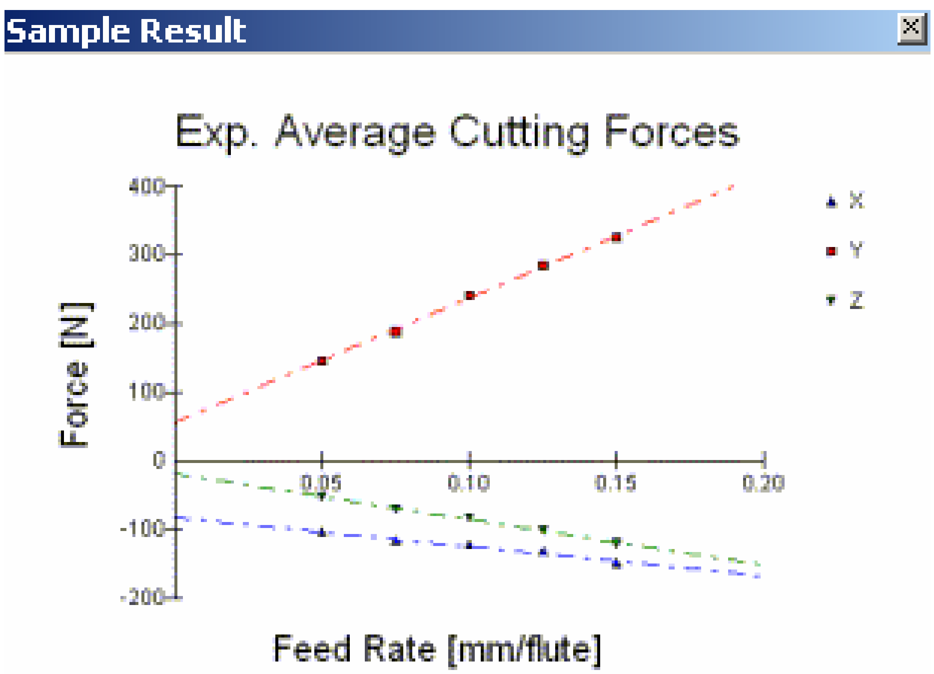


Figure 2.1-16: Sample Result window of Cutting Coefficient Identification mode

2.1.2 PLUNGE MILLING MODULE

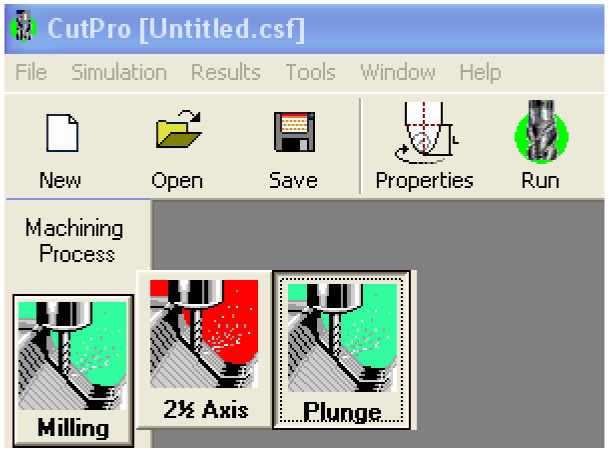


Figure 2.1-17: Plunge Milling module

CutPro simulates the action of plunge milling with this module. The plunge milling module contains three simulation modes: **static analysis of a plunge milling operation**, **dynamic simulation of a plunge milling process**, and **stability lobes** prediction.

2.1.2.1 STATIC ANALYIS OF A PLUNGE MILLING OPERATION

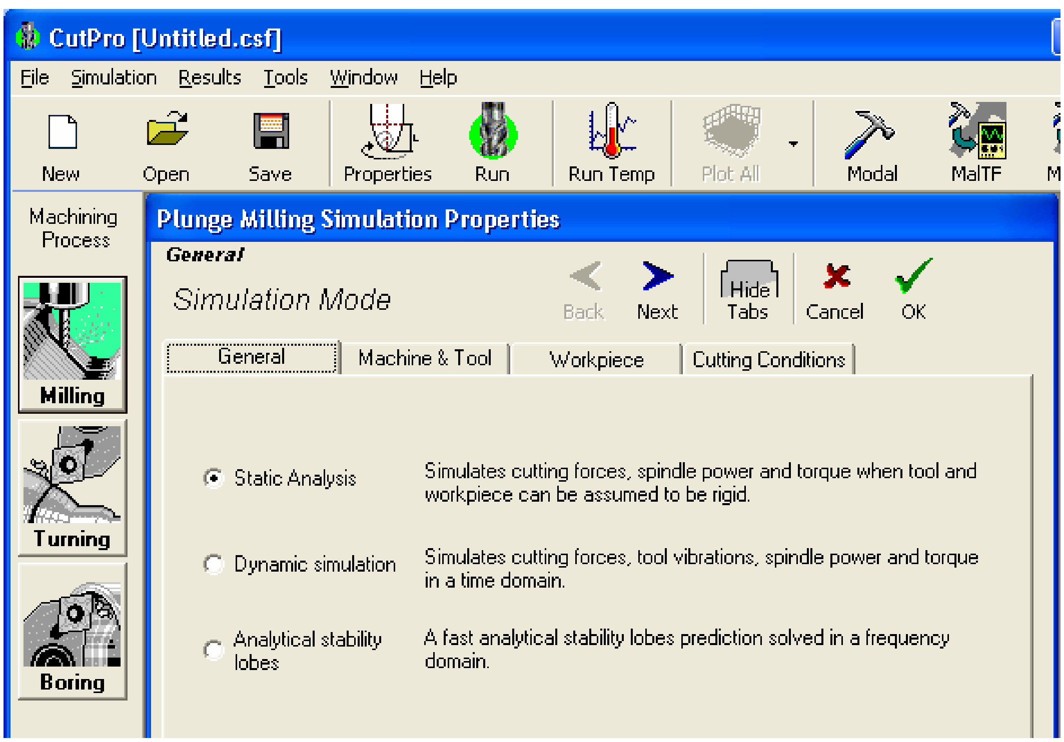


Figure 2.1-18: The Static Analysis simulation mode is selected in the General tab of the Plunge Milling module.

In this simulation mode, the cutting forces in x, y, and z directions, the resultant cutting force in xy-plane, and the spindle torque and power are simulated based on the cutter geometry and the machining parameters. This mode assumes both the workpiece and the tool are rigid.

2.1.2.2 DYNAMIC ANALYSIS

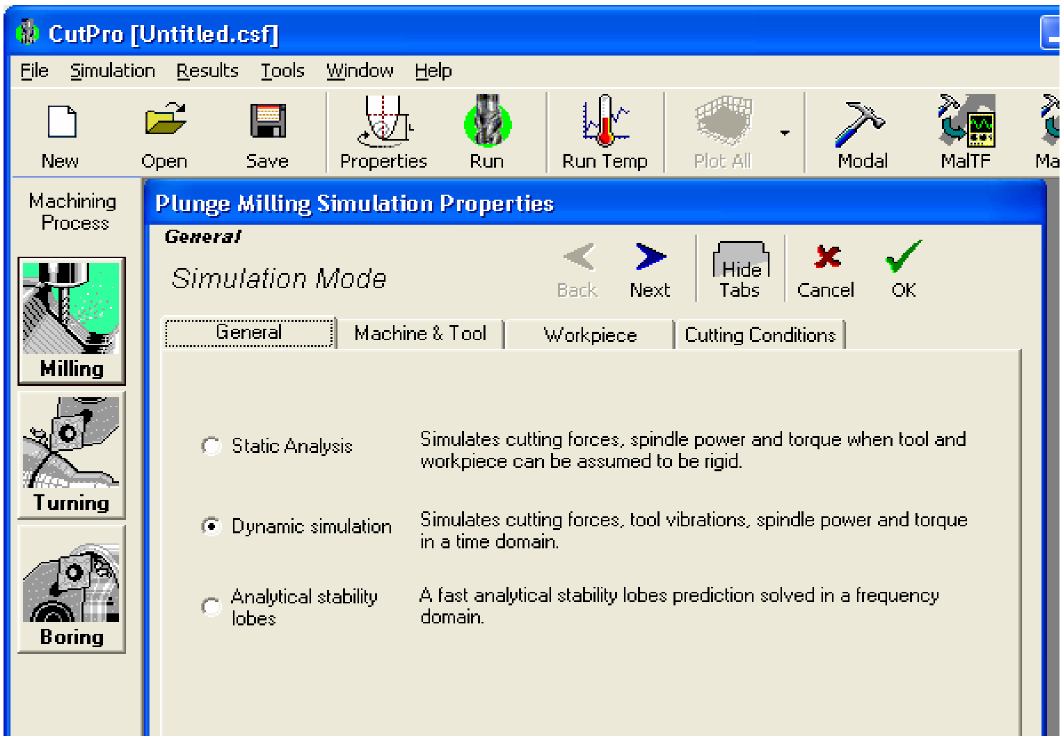


Figure 2.1-19: The dynamic parameters of the tool are entered for the Dynamic Analysis mode of the Plunge Milling module.

This mode is similar to the static analysis of a plunge milling operation, but instead of assuming that the tool is rigid, the dynamic parameters of the tool are entered by the user. Of course the user can enter parameters for multiple modes in each direction and specify any rigid directions.

2.1.2.3 STABILITY LOBES

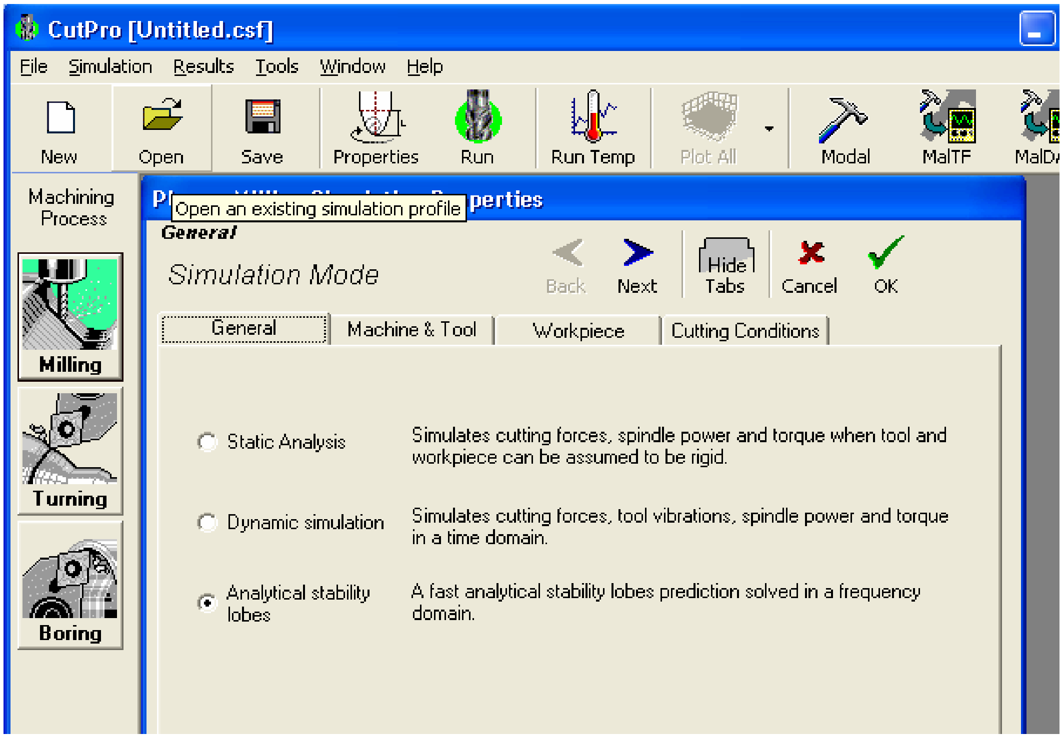


Figure 2.1-20: The Stability Lobes mode is selected in General tab of the Plunge Milling module.

This mode is similar to the single analytical stability lobes mode in the 2½ axis milling module (See **Section 2.1.1.3 Single Analytical Stability Lobes**).

2.2 TURNING MODULE

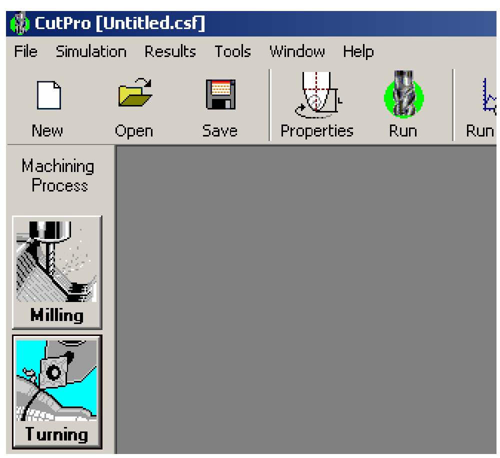


Figure 2.2-1: Turning module

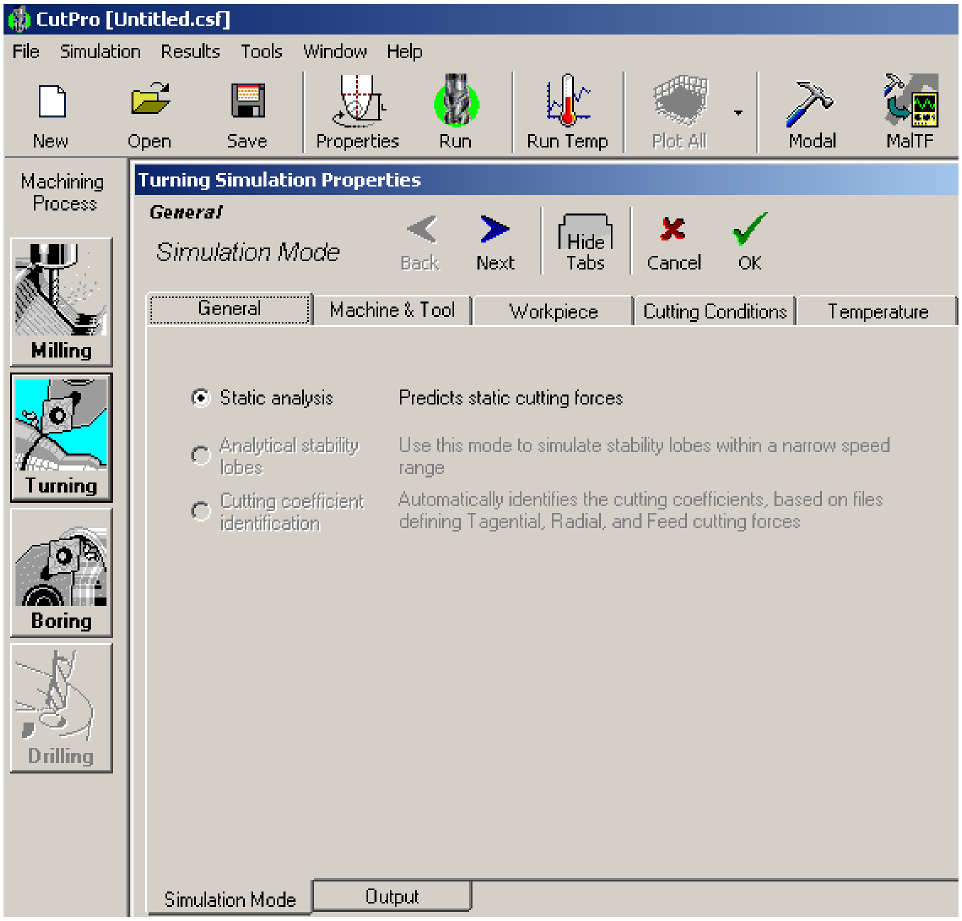


Figure 2.2-2: The General tab of the Turning module

2.2.1 STATIC ANALYSIS

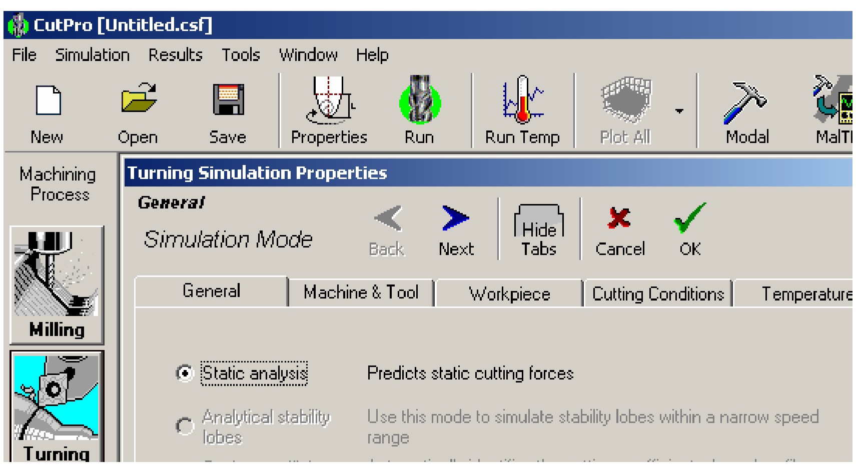


Figure 2.2-3: The Static Analysis mode is selected from the General tab of the Turning module.

This mode executes a static analysis of a turning process and is similar to the static analysis mode under the boring module (See

Section 2.3.1.1 Static Analysis). A sample result of the static analysis mode is shown below:

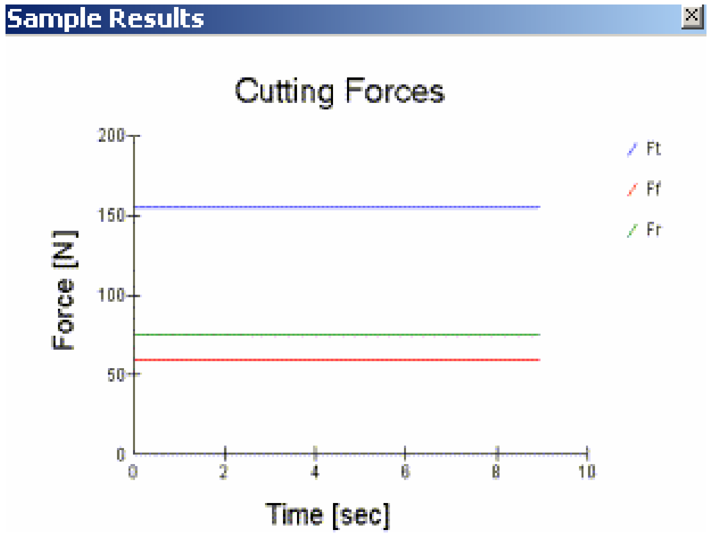


Figure 2.2-4: Sample Result window of Static Analysis mode

2.2.2 ANALYTICAL STABILITY LOBES

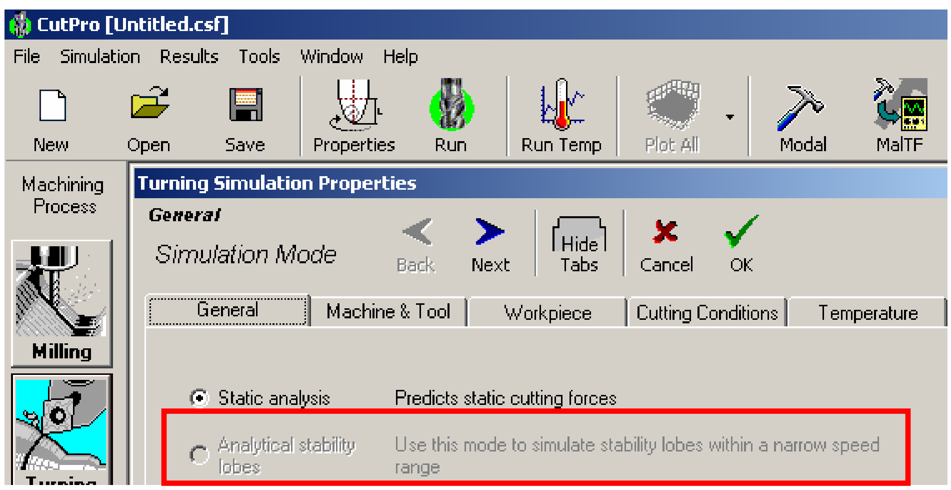


Figure 2.2-5: Analytical Stability Lobes mode is highlighted by the red box in the General tab of Turning module.

This mode is under development.

2.2.3 CUTTING COEFFICIENT IDENTIFICATION

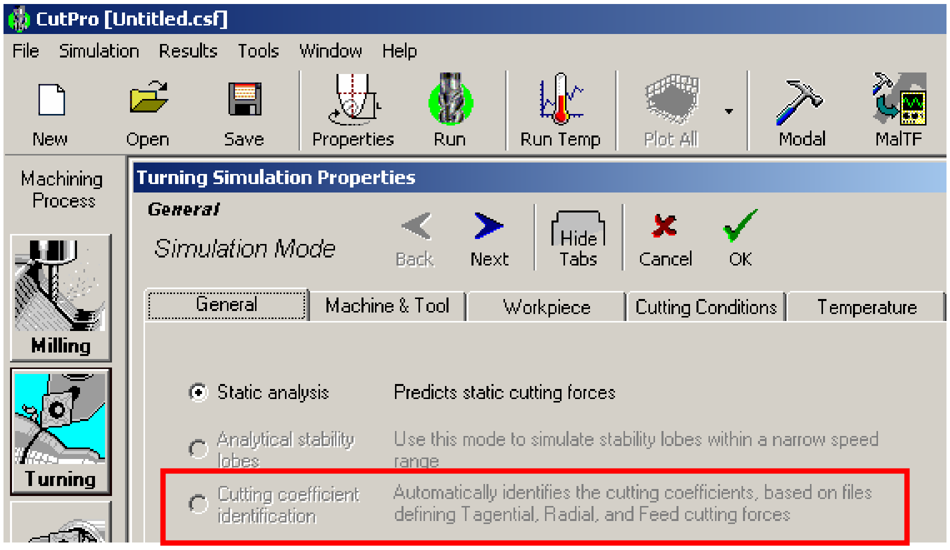


Figure 2.2-6: Cutting Coefficient Identification mode is highlighted by the red box in the General tab of the Turning module.

This mode is under development.

2.3 BORING MODULE

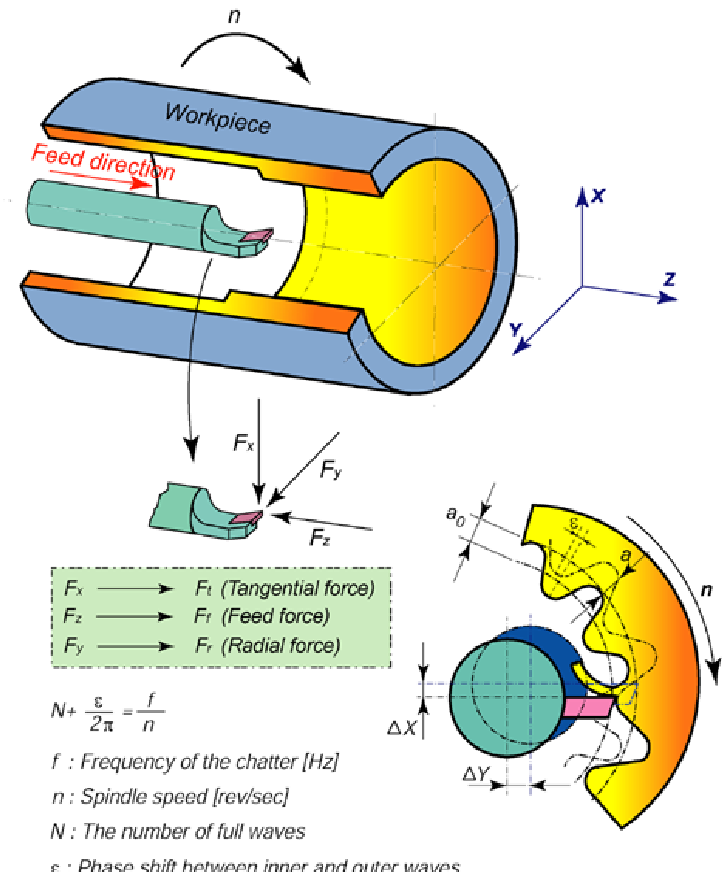


Figure 2.3-1: Geometry and axes definition of boring process

2.3.1 SINGLE INSERT MODULE

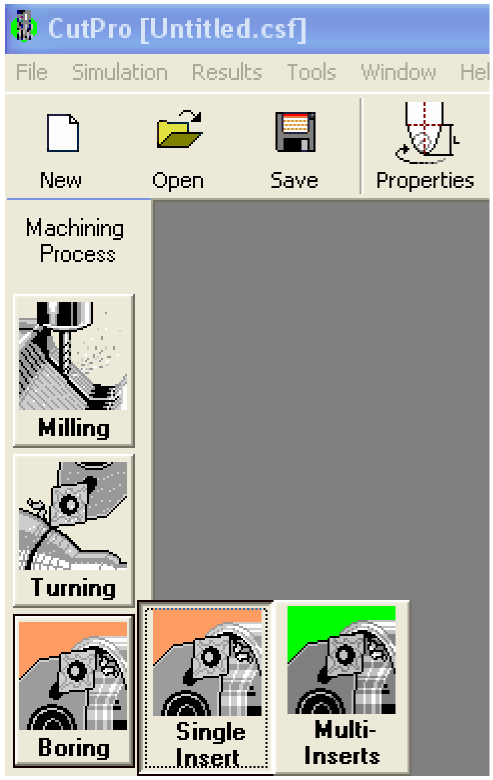


Figure 2.3-1: Single Insert Boring module

2.3.1.1 STATIC ANALYSIS

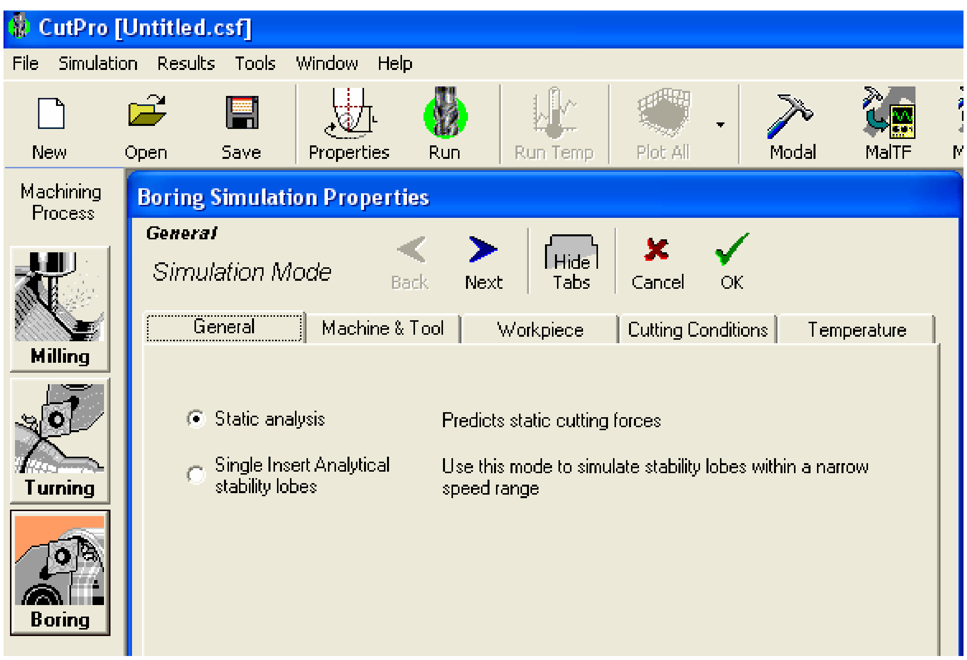


Figure 2.3-2: The Static Analysis mode is selected in General tab of the Single Insert Boring module

This mode predicts the static cutting forces in tangential, radial and feed directions, area of cut, spindle power and torque, and boring bar deflection. The process is assumed to be static in this mode. Sample results window of static analysis mode is displayed in the following figure:

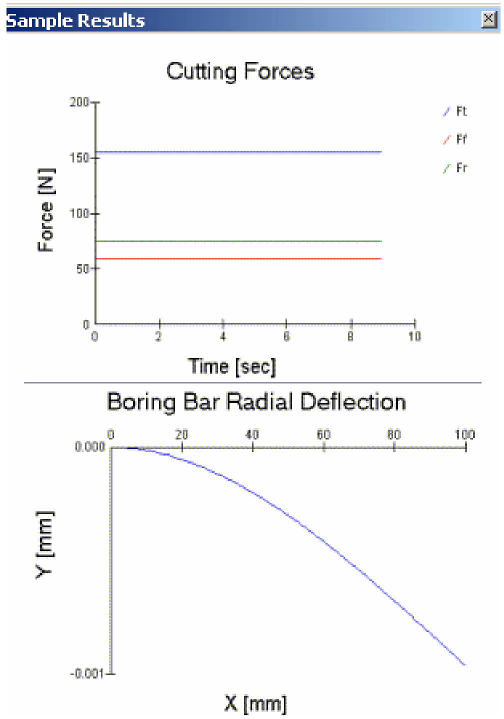


Figure 2.3-3: Sample Results window of Static Analysis mode

2.3.1.2 SINGLE INSERT ANALYTICAL STABILITY LOBES

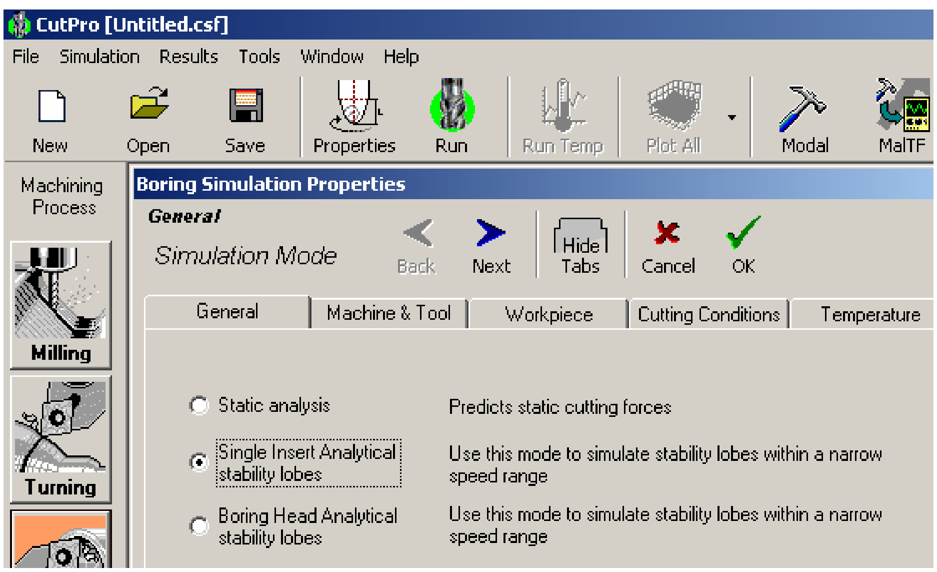


Figure 2.3-4: Single Insert Analytical Stability Lobes mode is selected in General tab of Boring module.

This mode simulates the analytical stability lobes in the frequency domain by using orthogonal chatter stability theory to determine the stability border of the boring process which uses a boring head with a single insert. The sample result window for the single insert analytical lobes mode is the same as the **sample result window of the single analytical stability lobes mode of the 2 ½ axis milling module**.

2.3.2 MULTI- INSERTS MODULE

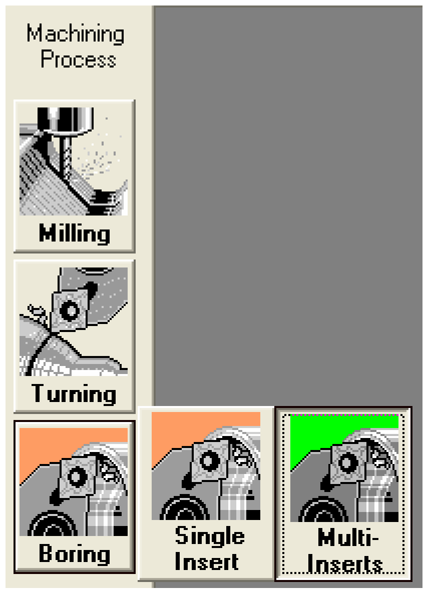


Figure 2.3-5: Multi- Insert Boring module

2.3.2.1 STATIC ANALYSIS

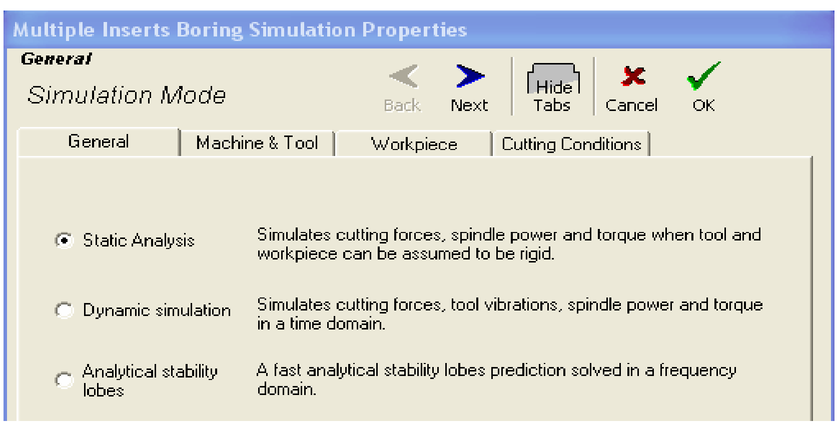


Figure 2.3-6: The Static Analysis mode is selected in General tab of the Multi- Insert Boring module.

This mode is similar to the static analysis mode described in section [2.3.1.1 Static Analysis](#), but instead of having a boring bar with only one insert, you can define multiple inserts on a symmetric or an asymmetric tool.

2.3.2.2 DYNAMIC SIMULATION

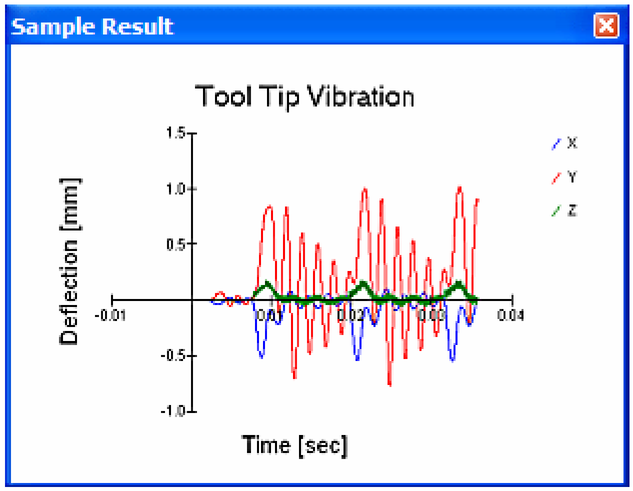


Figure 2.3-7: Sample results window for the Dynamic Simulation mode.

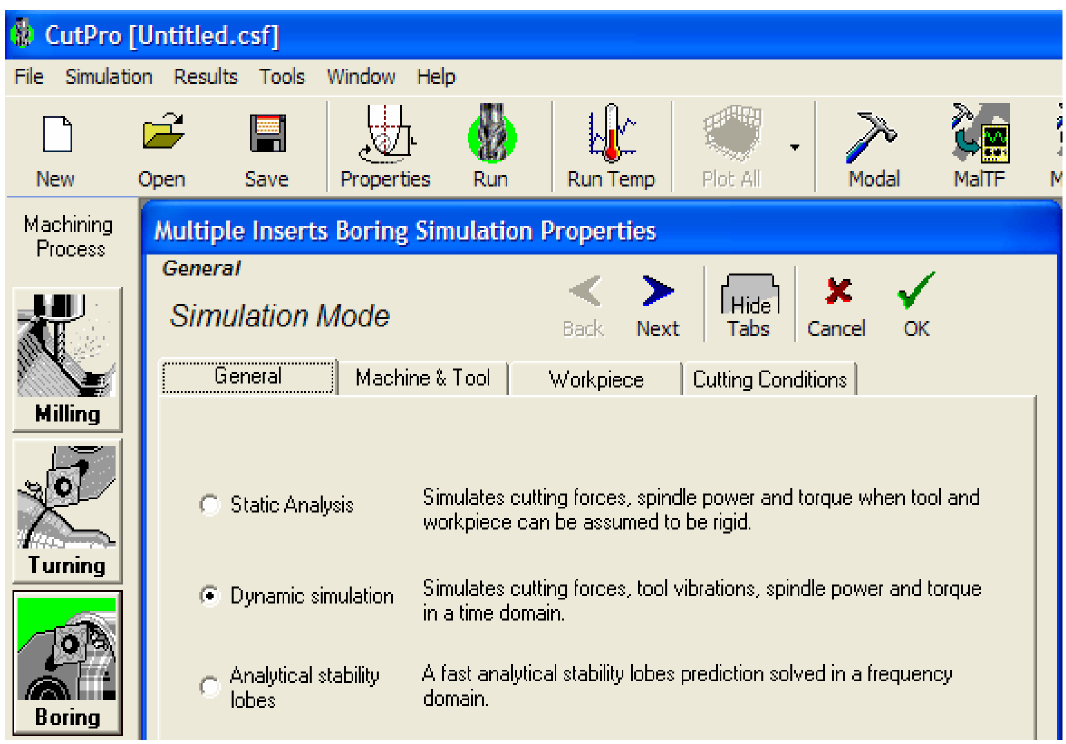


Figure 2.3-8: The Dynamic Simulation mode is selected in General tab of the Multi- Insert Boring module.

This mode is similar to the static analysis for multi-insert boring, but instead of assuming that the tool is rigid, the dynamic parameters of the tool are entered by the user. Of course the user can enter parameters for multiple modes in each direction and specify any rigid directions.

2.3.2.3 ANALYTICAL STABILITY LOBES

This mode simulates the analytical stability lobes in the frequency domain by using 2D chatter stability theory for a boring process. The boring head analytical stability lobes mode of the boring module and the single analytical stability lobes mode of the 2½ axis milling module use the same engine (See **Section 2.1.1.3 Single Analytical Stability Lobes**). The sample results window of the boring head analytical stability lobes mode is the same as the **sample results window of the single analytical stability lobes mode of the 2 ½ axis milling module**.

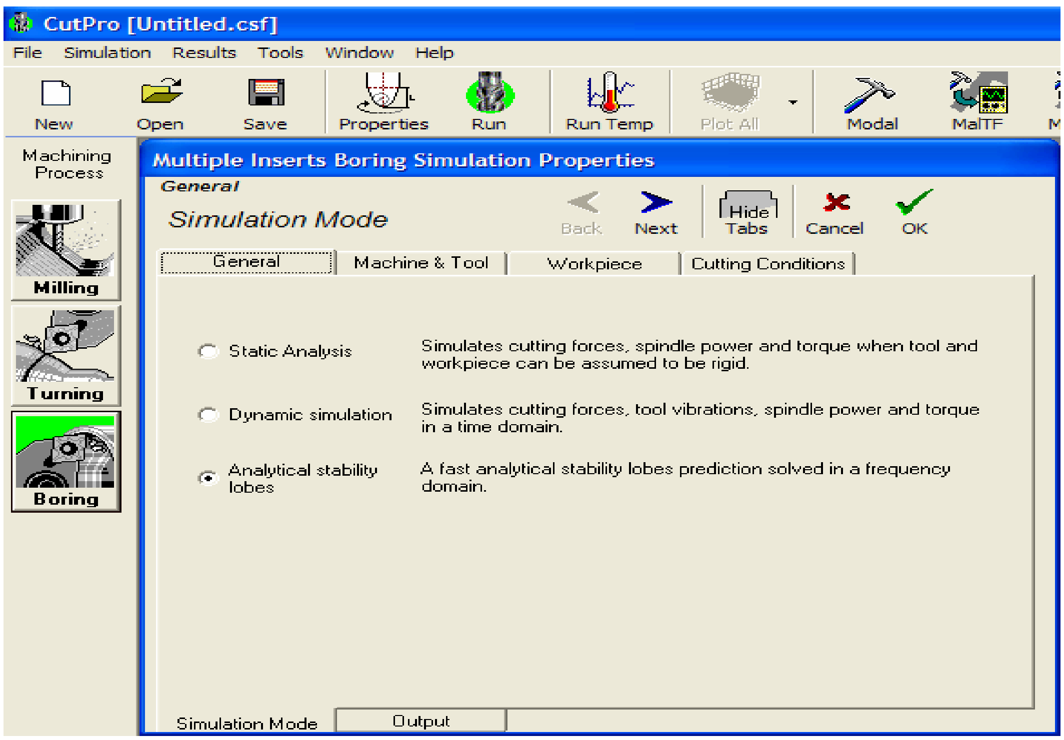


Figure 2.3-9: The Analytical stability lobes mode is selected in the General tab of the Multi- Insert Boring module.

3 SIMULATION PROPERTIES WINDOW'S TABS AND DEFINITIONS

3.1 2 ½ AXIS MILLING MODULE

3.1.1 GENERAL/SIMULATION MODE TAB

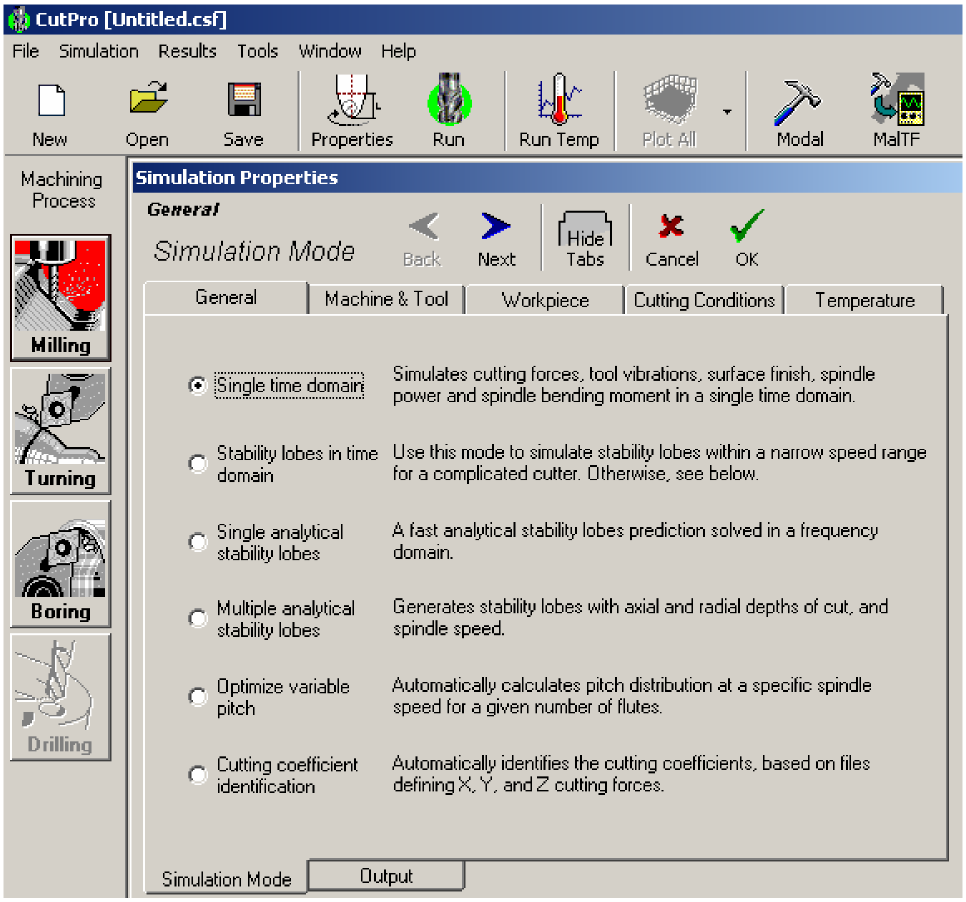


Figure 3.1-1: General/Simulation Mode tab of the 2 ½ Axis Milling module

This tab allows you to choose the simulation mode. There are six simulation modes available in the 2½ Axis Milling module, namely, **single time domain**, **stability lobes in time domain**, **single analytical stability lobes**, **multiple analytical stability lobes**, **optimize variable pitch** and **cutting coefficient identification**. Depending on your selection, you will be led to enter the necessary parameters on the next tabs in order to complete the simulation. You can find more information regarding simulation modes under **Section 2.1 2 ½ Axis Milling module**.

3.1.2 GENERAL/OUTPUT TAB

The ***General/Output*** tab allows you to choose the output data you want to save during the simulation. To include a result in the simulation output, check the box next to it. This tab has different options for different simulation modes.

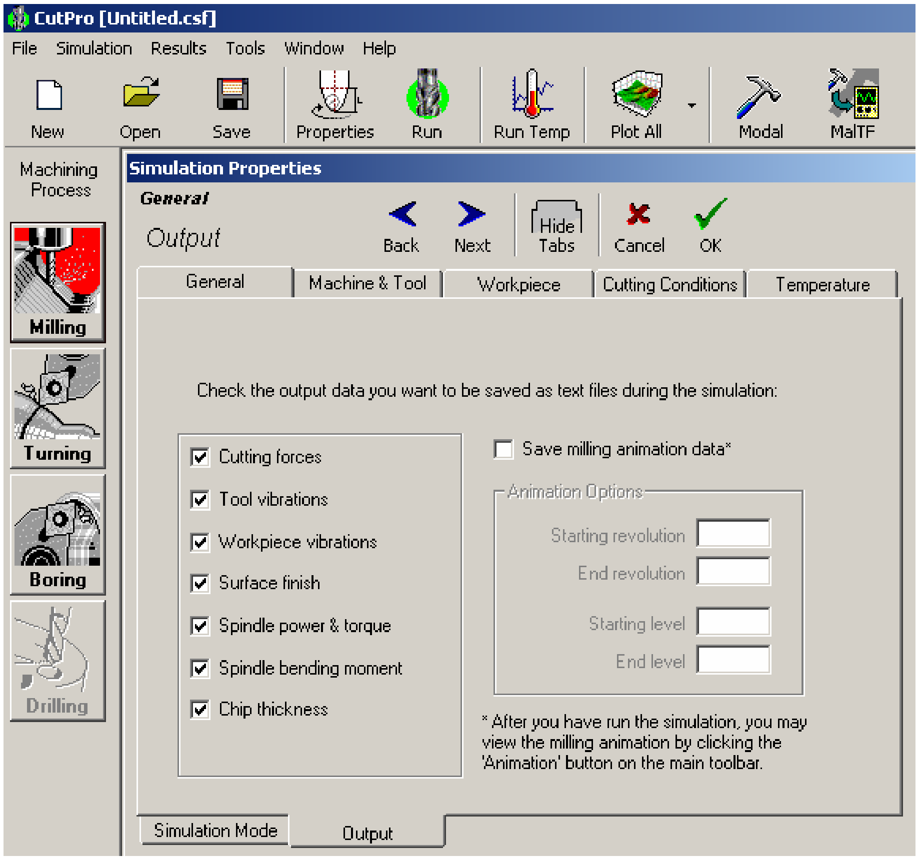


Figure 3.1-2: The General/Output tab of the 2½ Axis Milling module

If you run the simulation modes one by one by using the default parameters in CutPro, you will obtain the following output plots for each simulation mode. After the simulation mode is chosen, the results are obtained by first clicking on the ***OK*** button on the ***Simulation Properties*** window and then the ***Run*** button in the ***Toolbar***. In order to display results of the simulation click on the ***Plot All*** button on the ***Toolbar*** or click the ***drop-down arrow*** on the ***Plot All*** button to select a single result to plot. Please refer to **Figure 2.1-1** in section 2.1 Milling Module for the definitions of the x, y, and z axes.

3.1.2.1 MILLING PROCESS SIMULATION

In the ***General/Output*** tab of the **Milling Process Simulation** mode, you can save the cutting forces in x, y, z and tangential directions; the resultant cutting force in xy plane; the tool vibration in x and y directions; the workpiece vibration in x and y directions; the surface finish; the spindle power and torque; and the spindle bending moment at the first spindle bearing location, based on the tool tip and chip thickness for each flute on the tool:

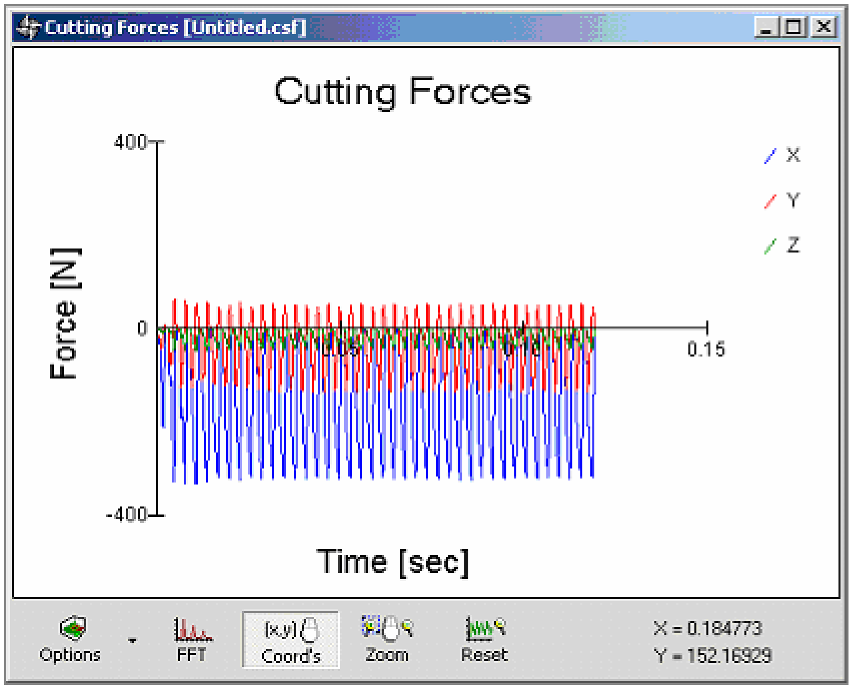


Figure 3.1-3: Cutting forces in x, y and z directions

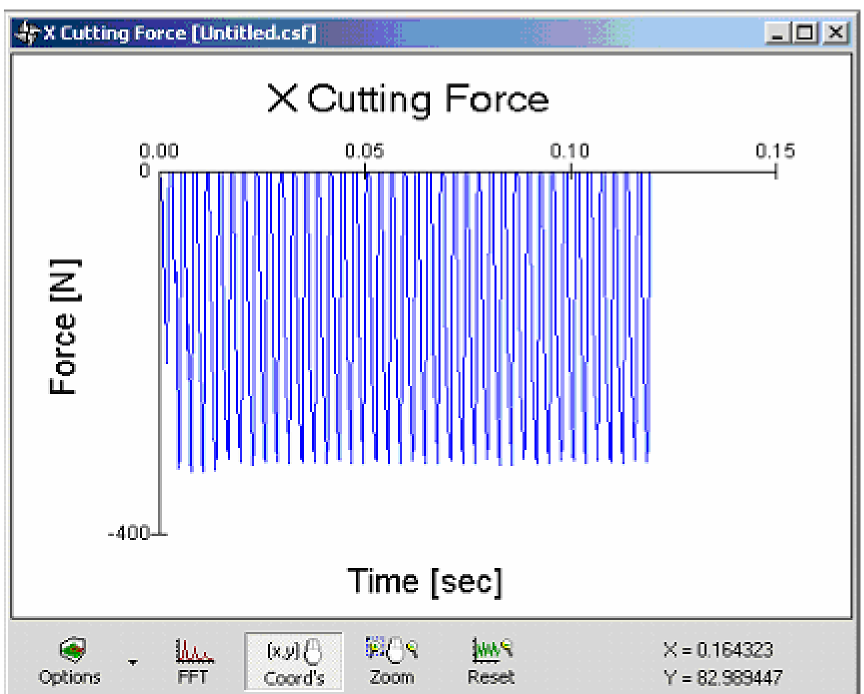


Figure 3.1-4: Cutting forces in x direction

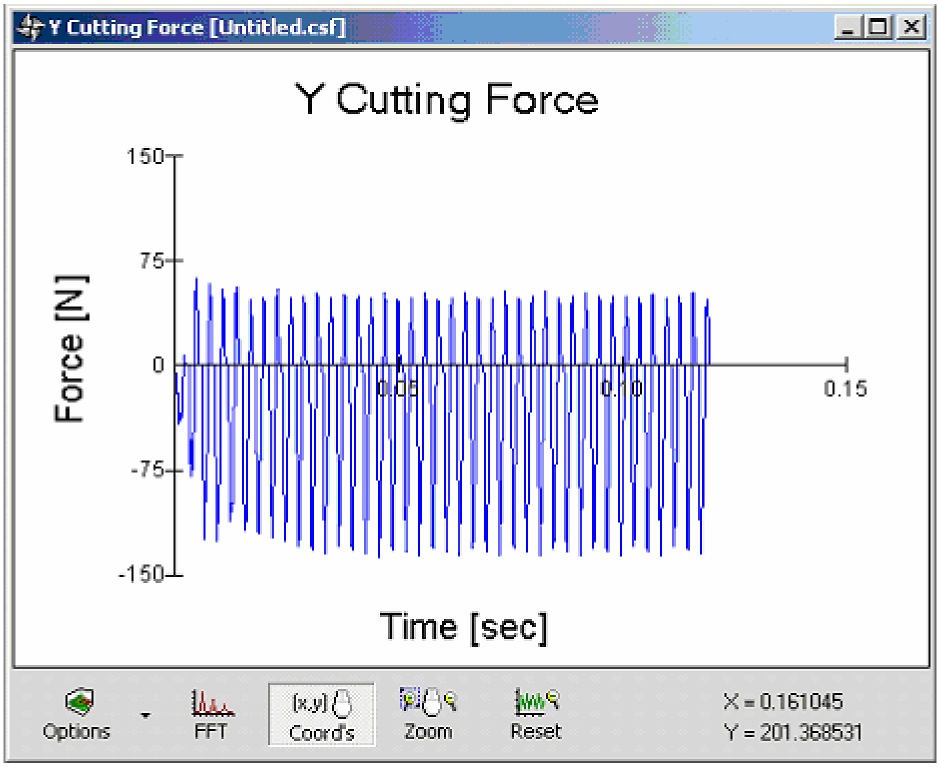


Figure 3.1-5: Cutting forces in y direction

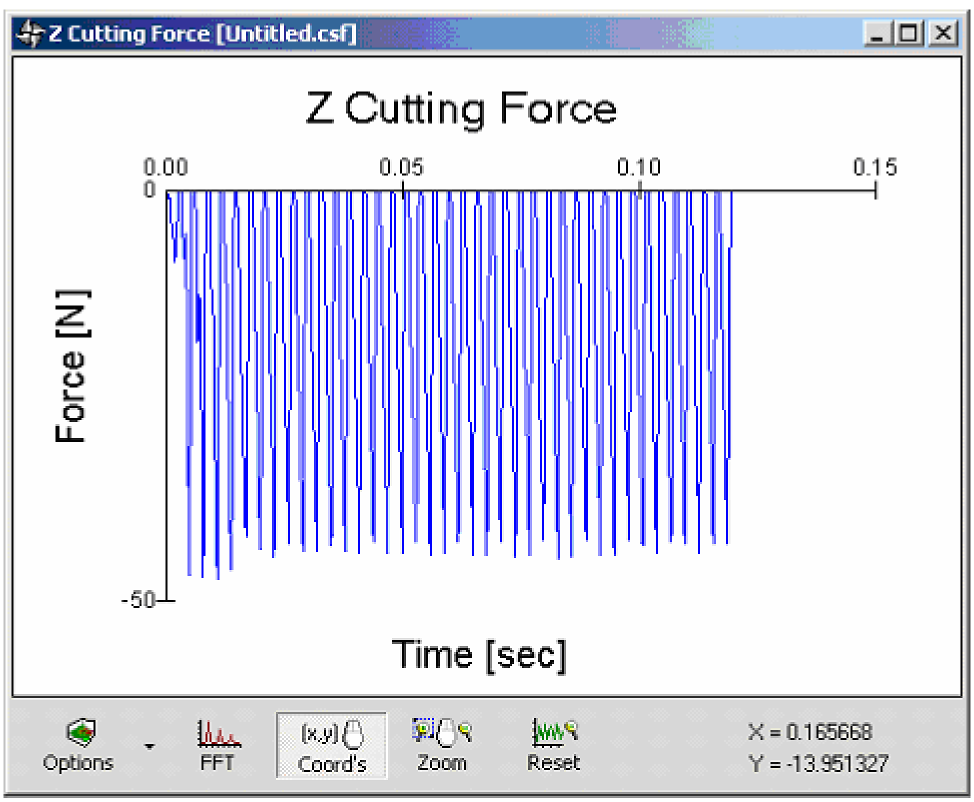


Figure 3.1-6: Cutting forces in z direction

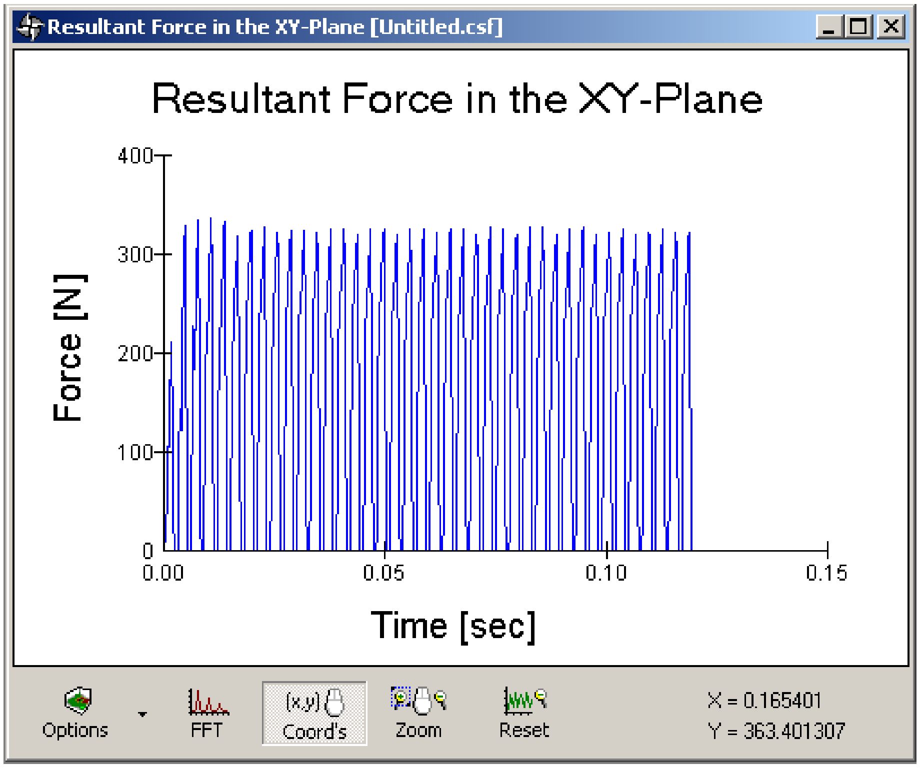


Figure 3.1-7: Resultant cutting forces in xy plane ($F_R = \sqrt{F_x^2 + F_y^2}$ **)**

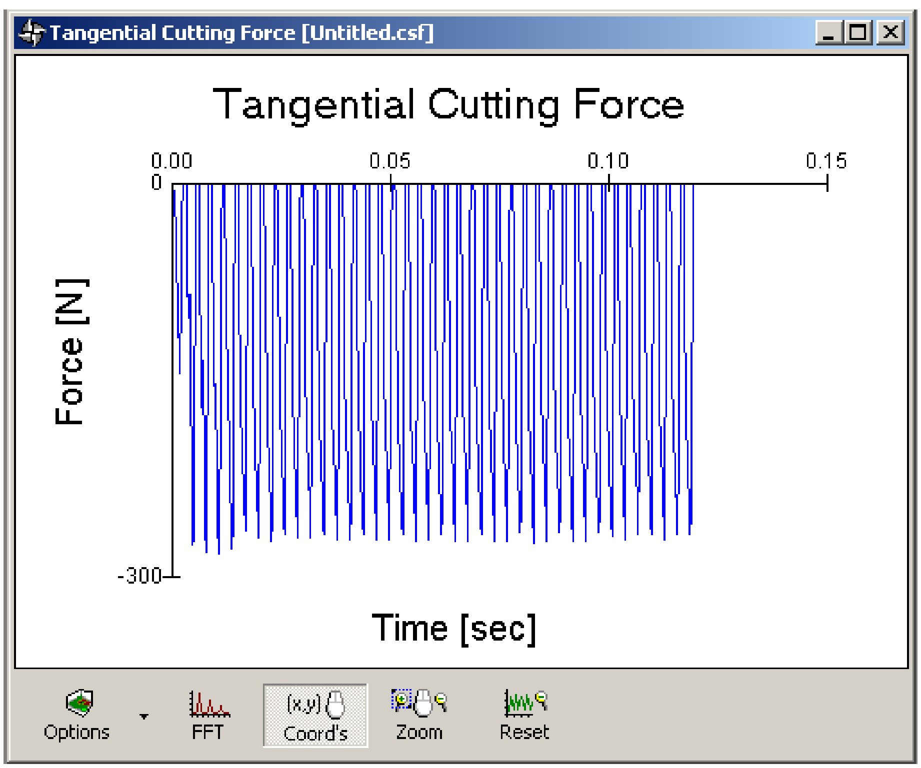


Figure 3.1-8: Cutting forces in tangential direction

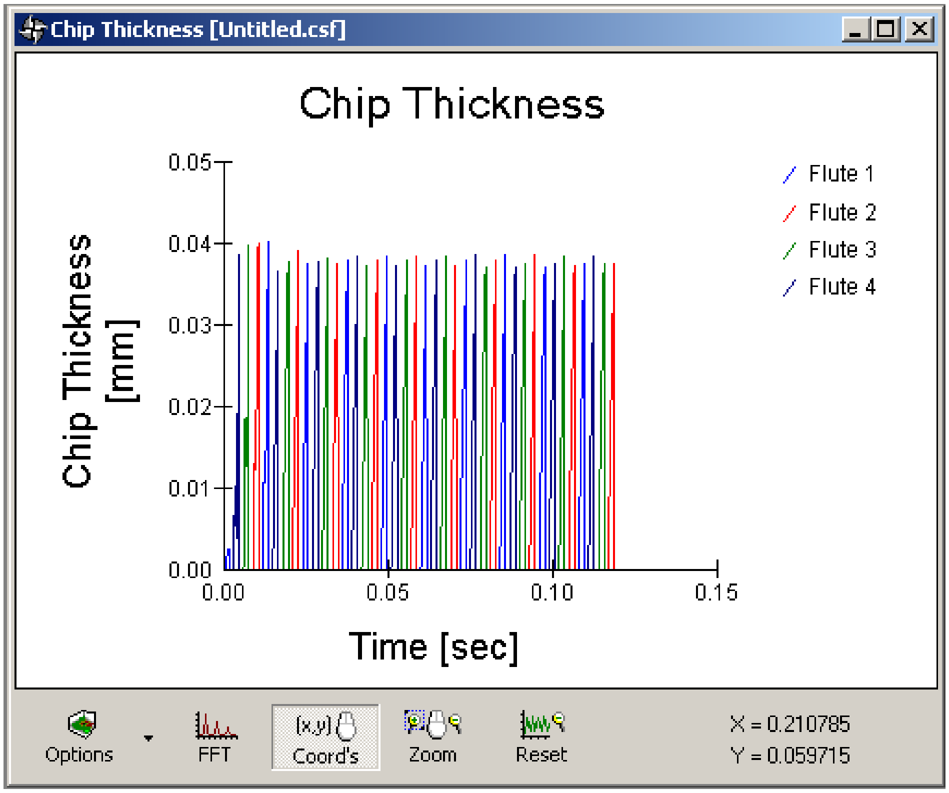


Figure 3.1-9: Chip thickness for each flute

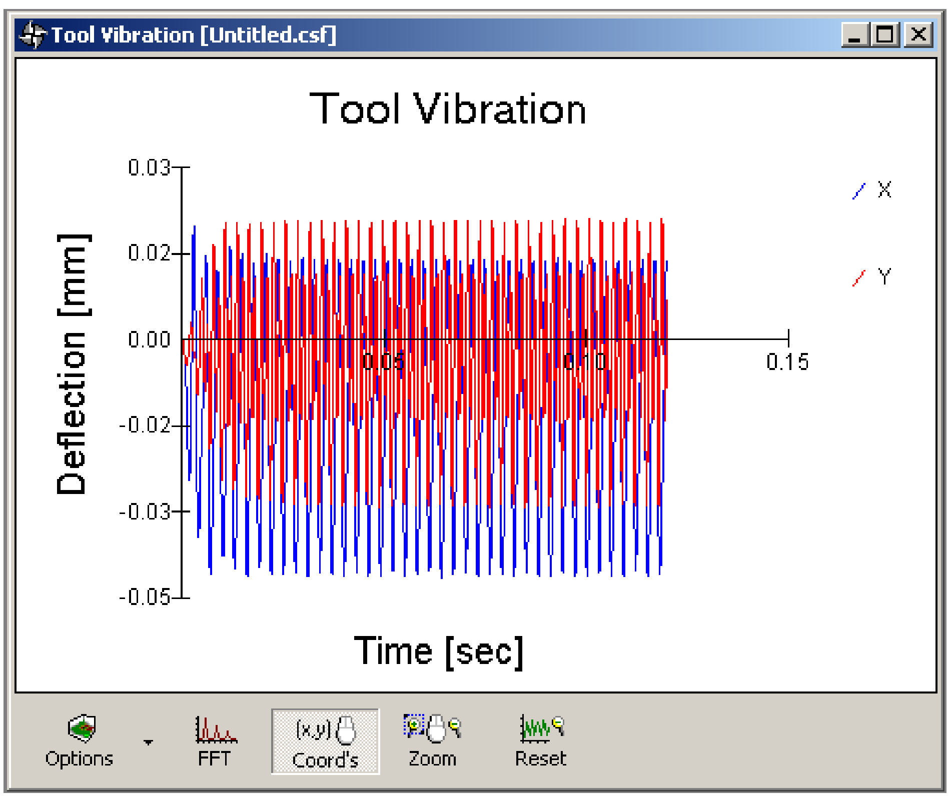


Figure 3.1-10: Tool vibrations in x and y directions

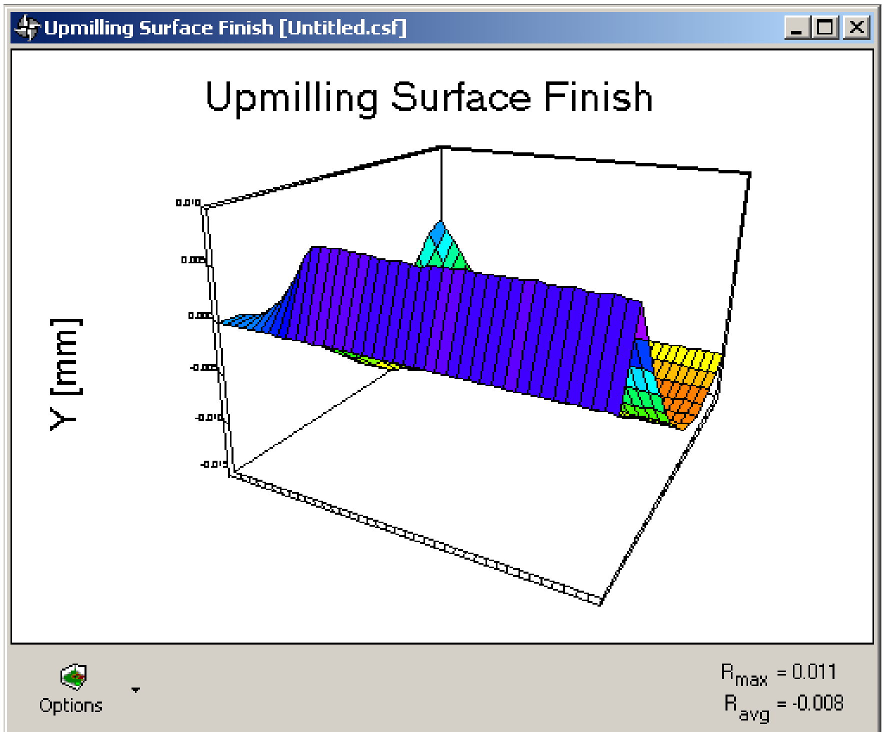


Figure 3.1-11: Up milling surface finish

Two parameters are shown at the bottom right corner of the window. R_{max} is the maximum surface roughness and R_{avg} is the average surface roughness.

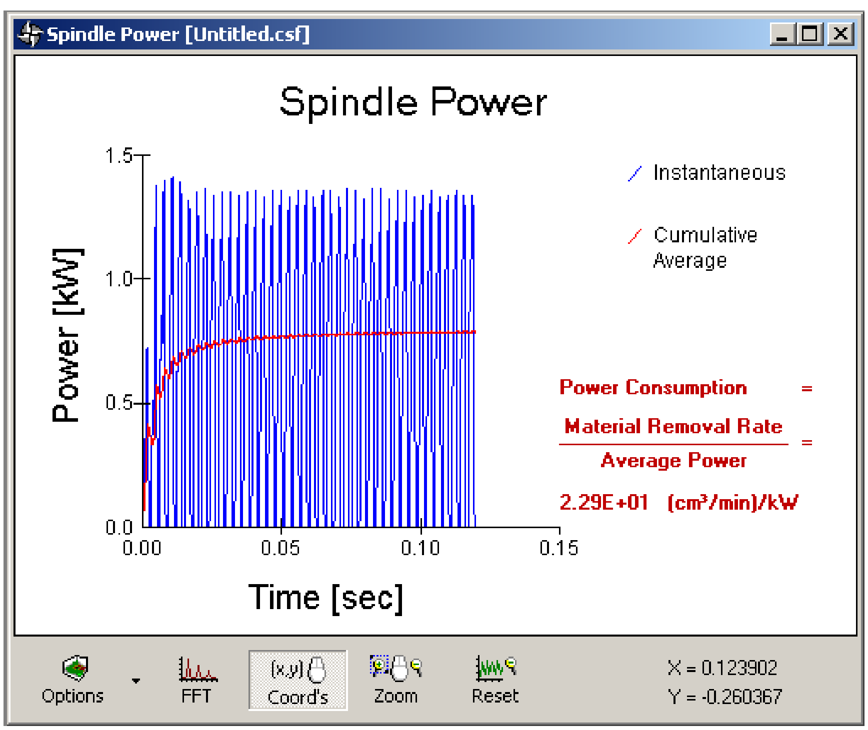


Figure 3.1-12: Spindle power

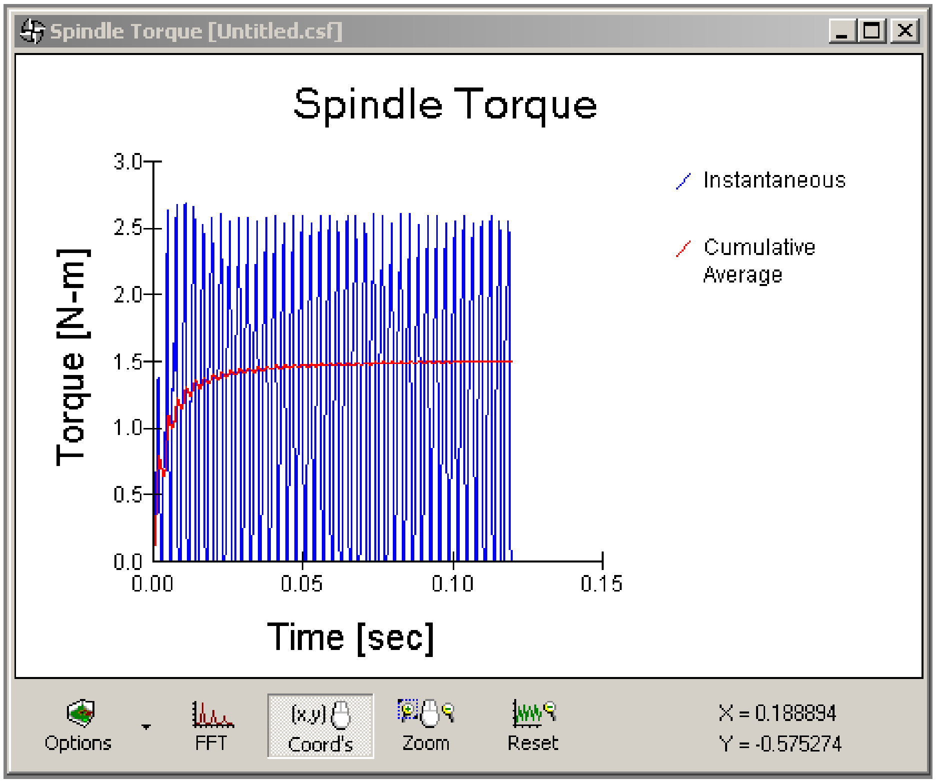


Figure 3.1-13: Spindle torque

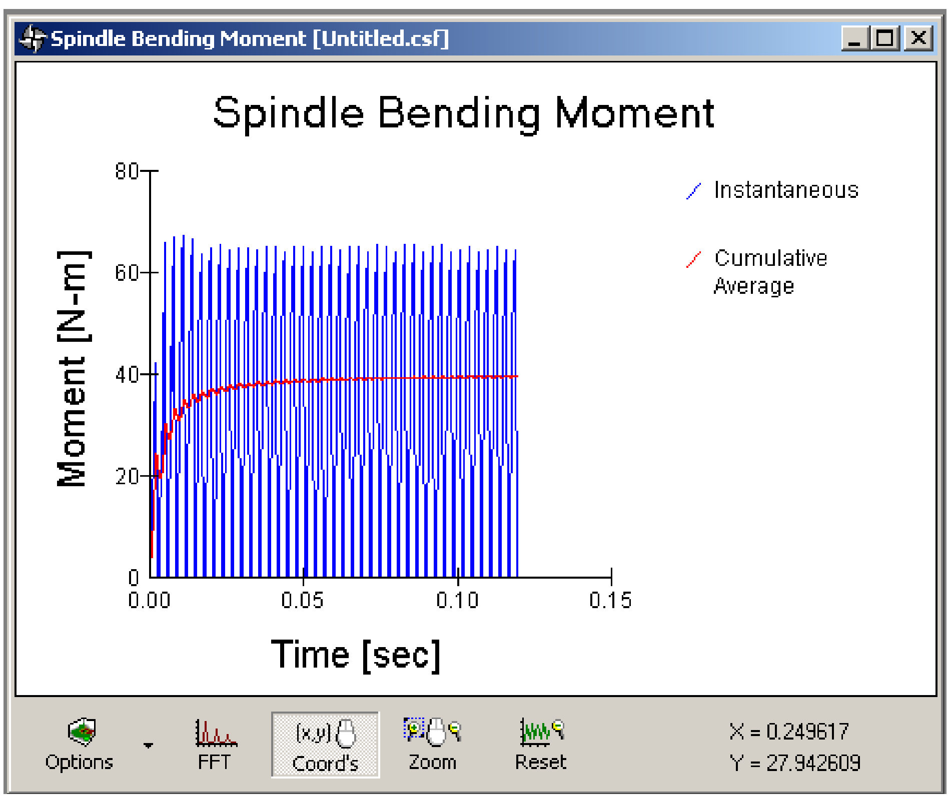


Figure 3.1-14: Spindle bending moment at the first spindle bearing location

The ***General/Output*** tab also allows you to save data for a milling animation. You must check the "Save milling animation data" check box in order to enable this option.

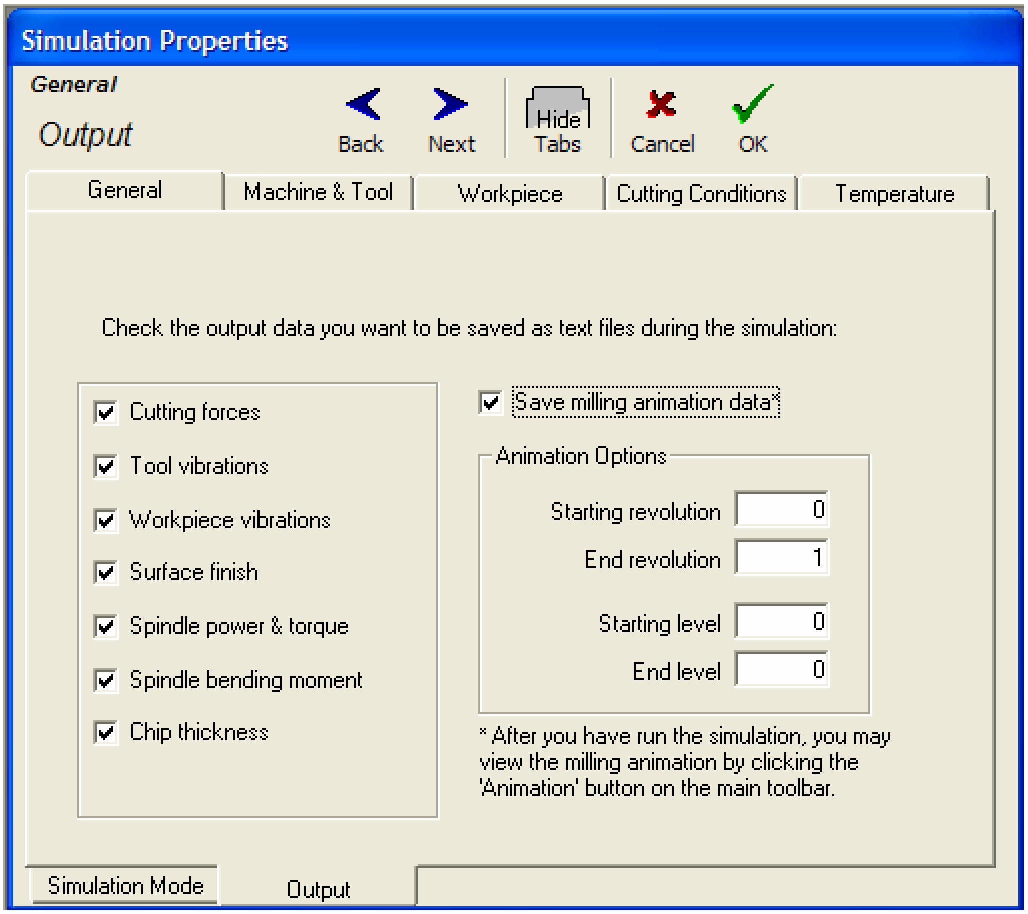


Figure 3.1-15: Save data for milling animation

You have to enter the parameters in the ***Animation Options*** frame, which are described in the following table:

Table 3.1-1: Animation Options of Milling Animation

Starting revolution	*Revolution number at which you start saving animation data. Make the numerical value consistent with the* ***Number of revolutions*** *under the* ***Cutting Conditions/Milling Mode*** *tab.*
End revolution	*Revolution number at which you stop saving animation data. Make these numerical values consistent with the* ***Number of revolutions*** *under the* ***Cutting Conditions/Milling Mode*** *tab.*
Starting level	*The simulation divides the depth of cut*

	*into a number of levels, depending on the cutter type and cutting edge geometry. This value is the level at which to **start** saving animation data.*
End level	*The simulation divides the depth of cut into a number of levels, depending on the cutter type and cutting edge geometry. This value is the level at which to **stop** saving the animation data.*

3.1.2.2 STABILITY LOBES IN TIME DOMAIN

In the ***General/Output*** tab of the **Stability Lobes in Time Domain** mode, all of the options are disabled. CutPro automatically saves the

Stability lobes data which includes axial depth of cut and spindle speed values corresponding to the critically stable state of the milling process:

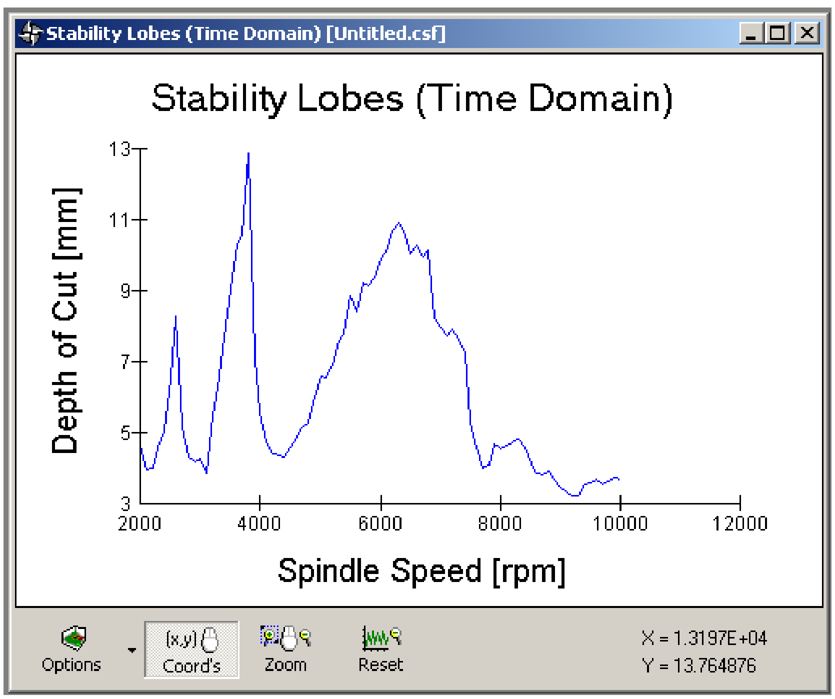


Figure 3.1-16: Stability lobes in time domain

3.1.2.3 SINGLE ANALYTICAL STABILITY LOBES

In the ***General/Output*** tab of the **Single Analytical Stability Lobes** mode, you can save complete results, the analytical

Stability lobes data, which includes axial depth of cut and spindle speed values corresponding to the critically stable state of the milling process:

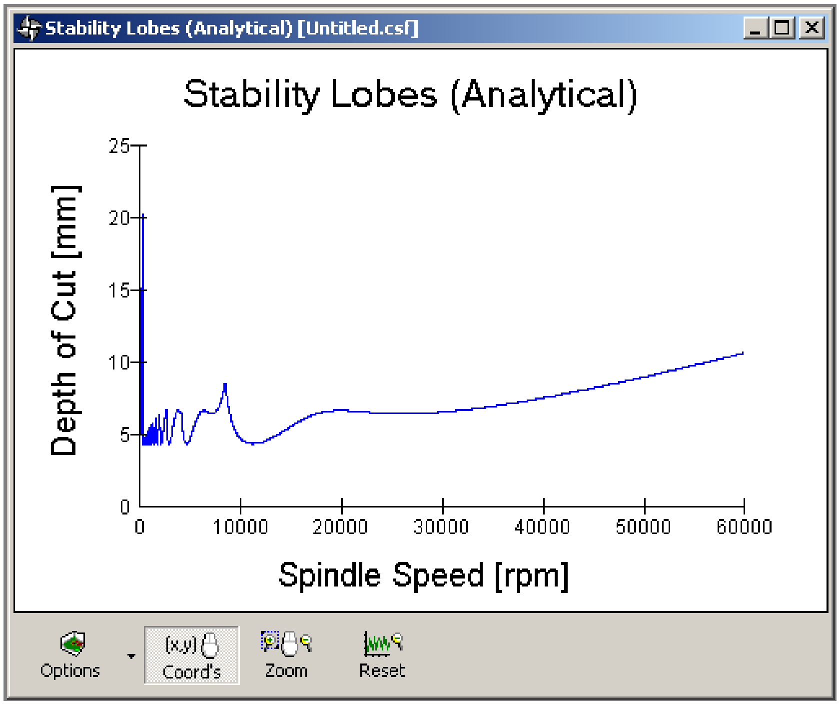


Figure 3.1-17: Single analytical stability lobes

3.1.2.4 MULTIPLE ANALYTICAL STABILITY LOBES

In ***General/Output*** tab of **Multiple Analytical Stability Lobes** mode, all the options are disabled. CutPro automatically saves the analytical stability lobes data which includes axial depth of cut and spindle speed values correspond to critically stable state of the multi step milling process:

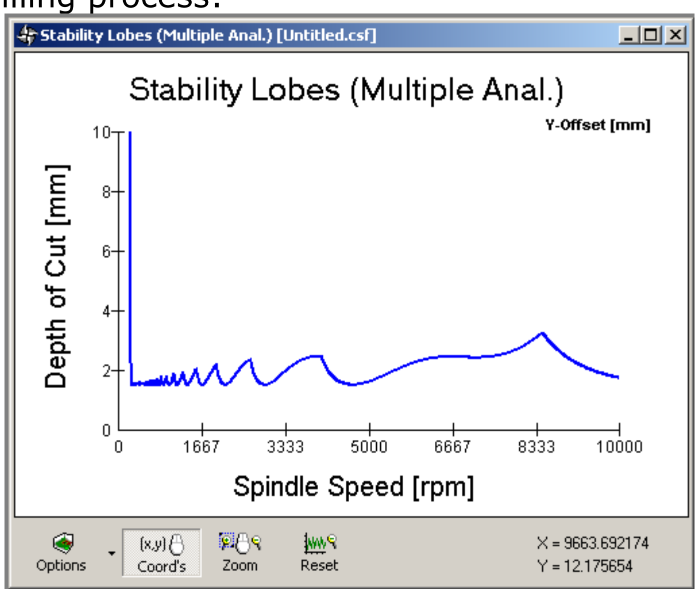


Figure 3.1-18: Multiple analytical stability lobes

3.1.2.5 OPTIMIZE VARIABLE PITCH

In ***General/Output*** tab of **Optimize Variable Pitch** mode, all the options are disabled. CutPro automatically saves the sets of optimum pitch angles and their corresponding maximum depths of cuts allowed for a stable process in the cutting conditions specified:

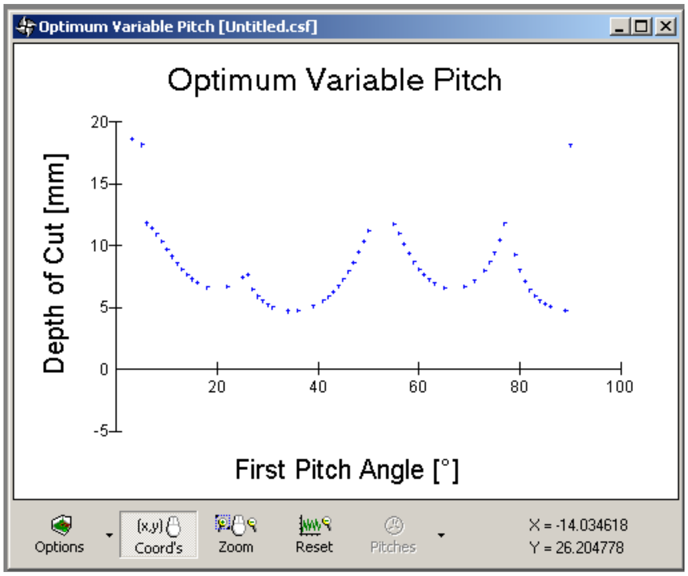


Figure 3.1-19: Optimum pitch angles

Click the right button of the mouse at a point to see the pitch distribution.

3.1.2.6 CUTTING COEFFICIENT IDENTIFICATION

In ***General/Output*** tab of **Cutting Coefficient Identification** mode, all the options are disabled. CutPro automatically saves averages of the experimental cutting forces in x, y and z directions with the corresponding feed rate values:

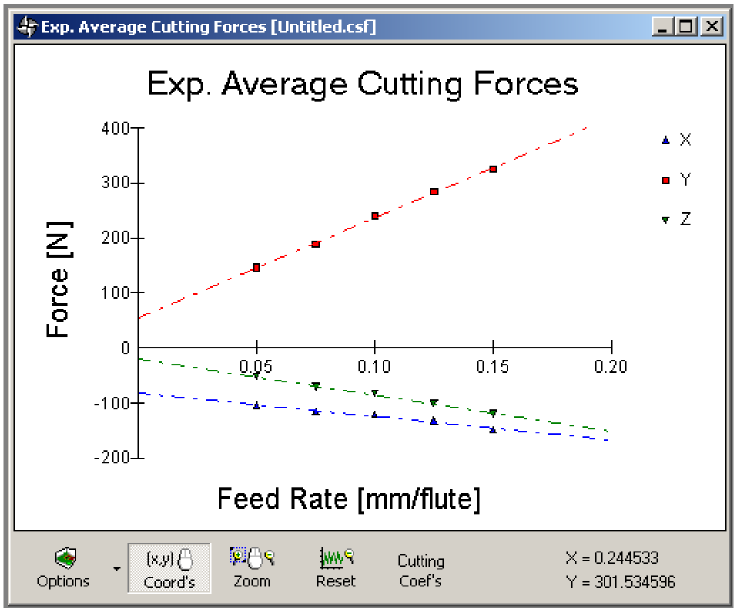


Figure 3.1-20: Average of experimental cutting forces

3.1.3 MACHINE & TOOL/CUTTER TYPE TAB

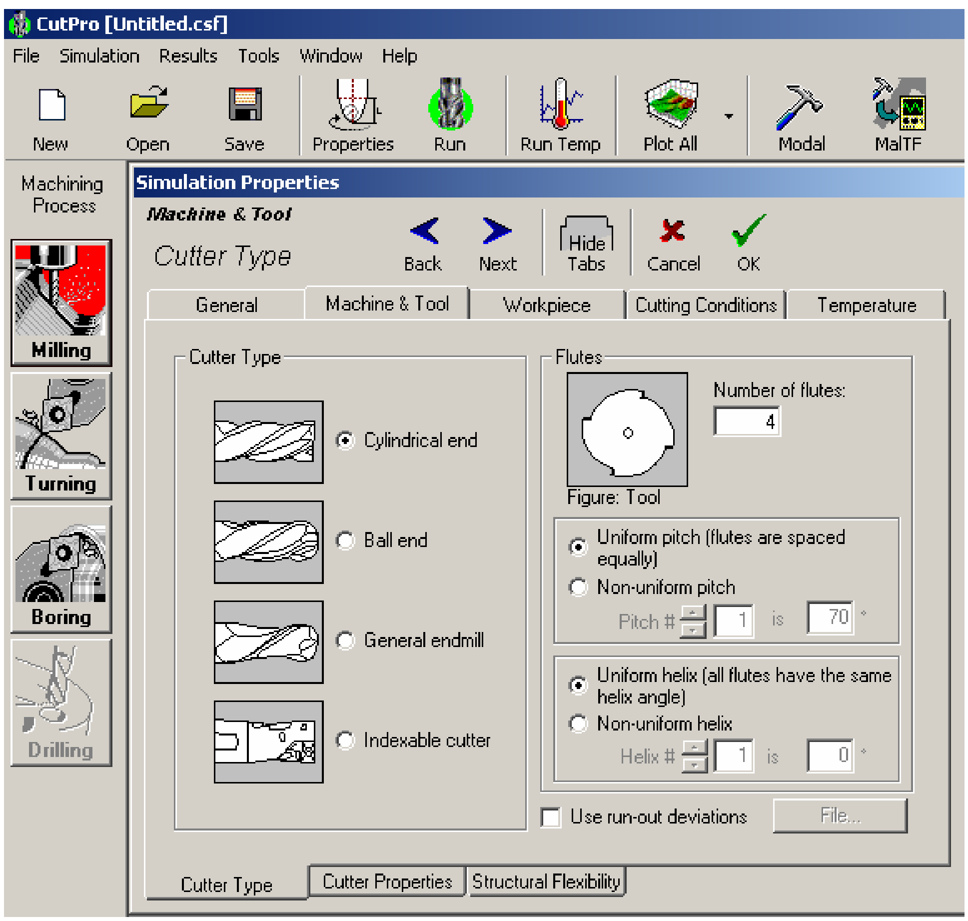


Figure 3.1-21: Machine & Tool/Cutter Type tab

This tab allows you to choose the cutter type and to define number of flutes, the type of pitch and helix angles and run-out deviations. Different options are available for different simulation modes in this tab.

In ***Machine & Tool/Tool Type*** tab, the following options are enabled:

3.1.3.1 CUTTER TYPE

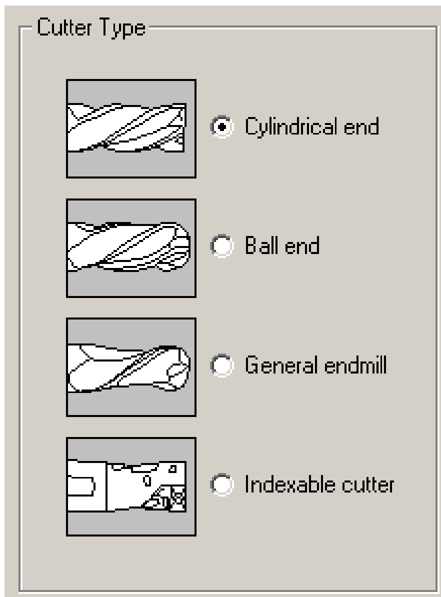


Figure 3.1-22: Cutter Type in Machine & Tool/Cutter Type tab

You have four options for the tool type, namely, cylindrical, ball and general endmills and indexable cutter, on the list given in **Figure 3.1-22**. When you choose the tool type, a figure will show general look of the selected tool on the right hand side of the ***Simulation Properties***. The figure will also help you visualize the parameters on the tool when you change them on the next tabs. The following buttons appear in the figure window:

Table 3.1-2: Buttons on Tool Geometry window

Zoom In	*Increase magnification of the figure; the scale of the figure to the endmill's actual dimensions is displayed in the lower right corner of the figure. You can also zoom in by clicking the figure with the left mouse button.*
Zoom Out	*Decrease magnification of the figure; the scale of the figure to the endmill's actual dimensions is*

	displayed in the lower right corner of the figure. You can also zoom out by clicking the figure with the right mouse button.
Print	*Bring up a print dialog which allows you to print the figure at its current magnification.*
Close	*Close the figure window.*

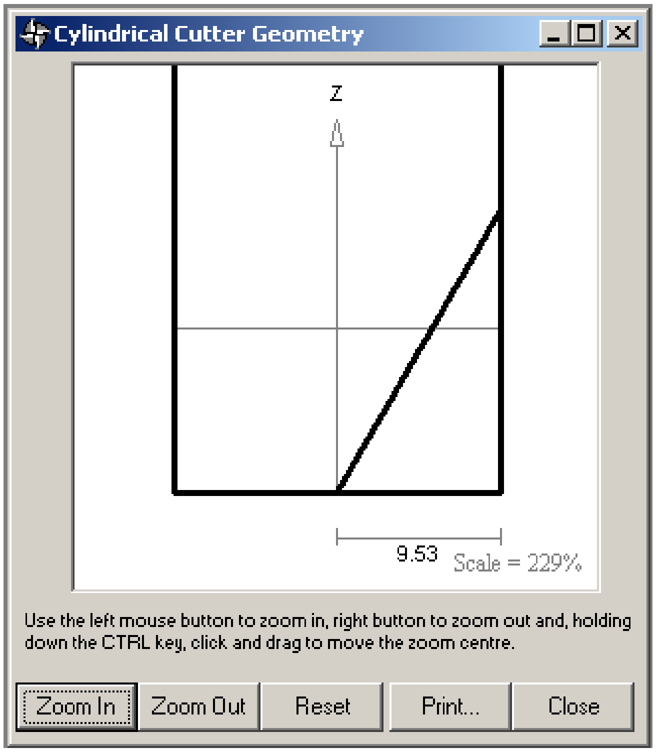


Figure 3.1-23: Cylindrical endmill cutter geometry

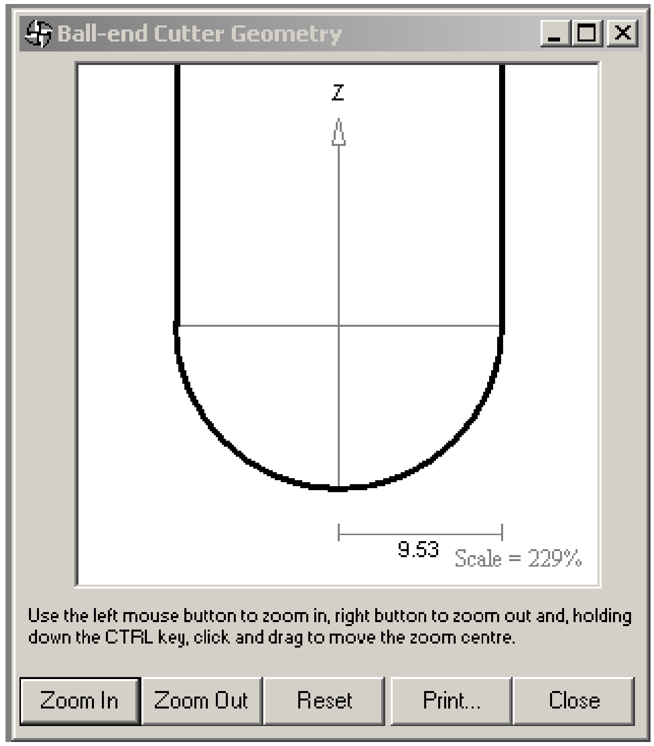


Figure 3.1-24: Ball endmill cutter geometry

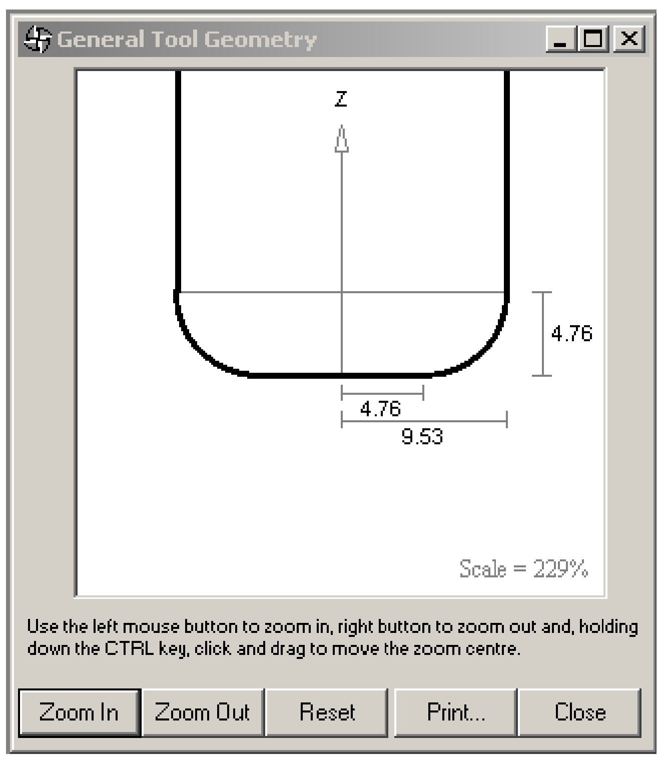


Figure 3.1-25: General endmill cutter geometry

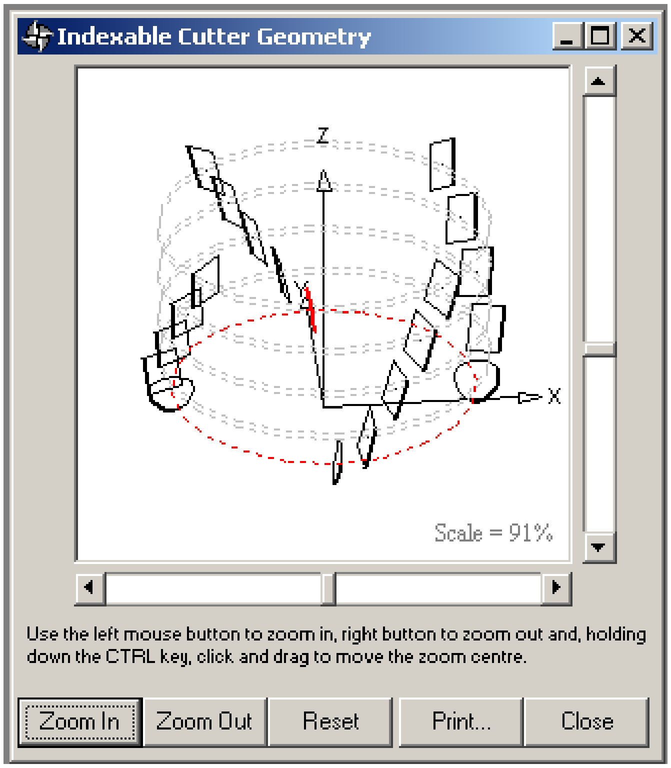


Figure 3.1-26: Indexable cutter geometry

Please refer to **Section 10.5 Appendix A5** for the detailed illustrations of these tools.

3.1.3.2 FLUTES

In ***Machine & Tool/Tool Type*** tab, you will also enter the parameters of the tool given as follows:

3.1.3.2.1 NUMBER OF FLUTES ON THE TOOL

Simply type the number of flutes in the text box. After the number is entered, the small figure next to the text box showing the top view of the tool is updated.

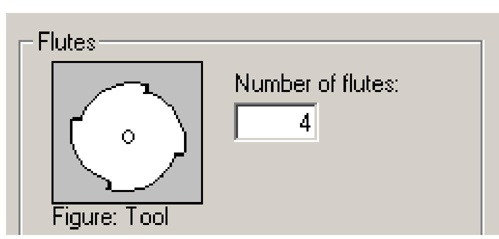


Figure 3.1-27: Number of flutes text box in Machine & Tool/Cutter Type tab

3.1.3.2.2 PITCH ANGLE TYPE ON THE TOOL

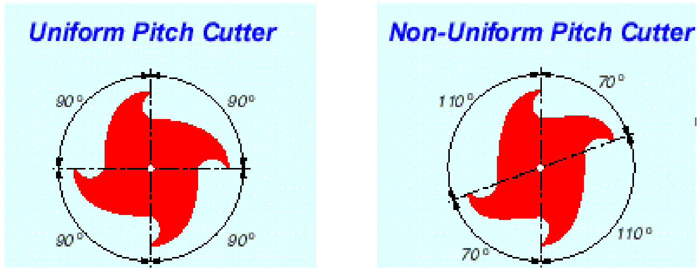


Figure 3.1-28: Uniform and Non-Uniform pitch cutters

You can choose the pitch angle type on the tool. The pitch angle type can be either uniform or non-uniform. For uniform pitch cutters, the pitch angles are equal and are evaluated from the following expression: **(360°/number of flutes)**. For the tools with non-uniform pitch distribution, you must enter the pitch angles between successive flutes. The Pitch angles must be bigger than zero and the summation of all pitch angles must be 360°.

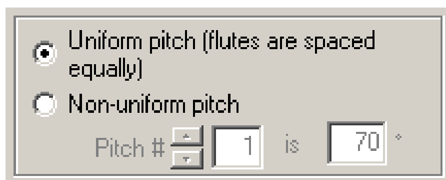


Figure 3.1-29: Pitch type of the tool in Machine & Tool/Cutter Type tab

3.1.3.2.3 HELIX ANGLE TYPE ON THE TOOL

You can choose the helix angle type on the tool. It can be either uniform or non-uniform. For the tools with uniform helix angle, all the flutes have the same helix angle. For the tools with non-uniform helix angle, you must enter the helix angle for each flute. The helix angles must be bigger than zero and less than 90°.

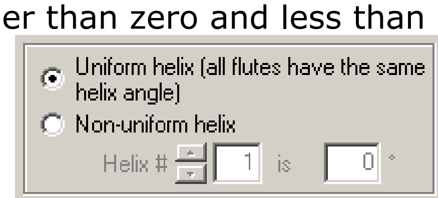


Figure 3.1-30: Helix angle type of the tool in Machine & Tool/Cutter Type tab

3.1.3.2.4 RUN-OUT DEVIATIONS OF FLUTES

Run-outs are defined as deviations from the ideal/design coordinates of the cutter. You digitize the cutter at small increments along the axial direction, and provide the digitized envelope in a run-out file.

Figure 3.1-31: Run-out deviations of flutes in Machine & Tool/Cutter Type tab

By checking the box next to ***Use run-out deviations*** in [Figure 3.1-31](#) you can include the effects of run-out deviations of the flutes. When you check the box, ***Run-out File*** window shows up:

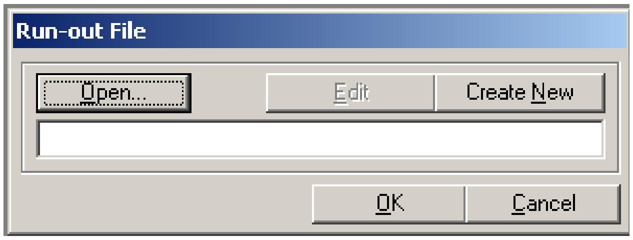


Figure 3.1-32: Run-out File window

Table 3.1-3: Buttons on Run-out File window

Open	*Open an existing run-out (*.cro) file.*
Edit	*Edit the currently selected run-out file. This brings up the* ***Run-out Editor*** *window.*
Create New	*Create a new run-out file. This brings up the* ***Run-out Value Editor*** *window.*
OK	*Select the current file and close the window.*
Cancel	*Close the* ***Run-out File*** *window and revert to the previously selected file.*

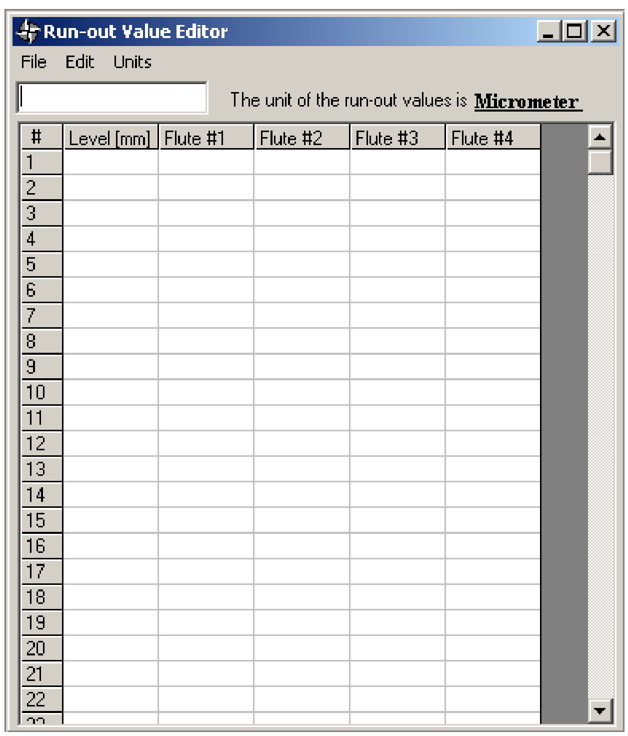


Figure 3.1-33: Run-out Value Editor window

In [Run-out Value Editor](#) window, you define deviations of each flute at a series of axial locations along the depth-of-cut. The ***Run-***

out Value Editor window consists of a table. The first column lists the axial locations at which deviations are measured and the other columns correspond to the deviations of each flute. Menu commands on the ***Run-out Value Editor*** window are given in the following:

- ***FILE COMMAND***

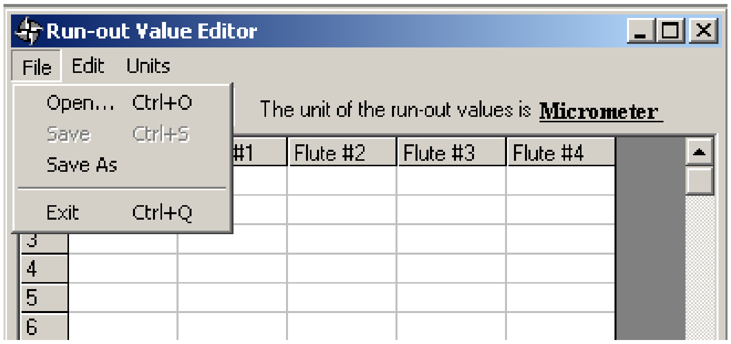


Figure 3.1-34: File command on Run-out Value Editor window

Table 3.1-4: The drop-down menu of File command on Run-out Value Editor window

Open	*Open an existing run-out (*.cro) file.*
Save	*Save the currently open run-out file under the same name.*
Save As	*Save the currently open run-out file under a different name.*
Exit	*Exit the **Run-out Editor** window.*

- ***EDIT COMMAND***

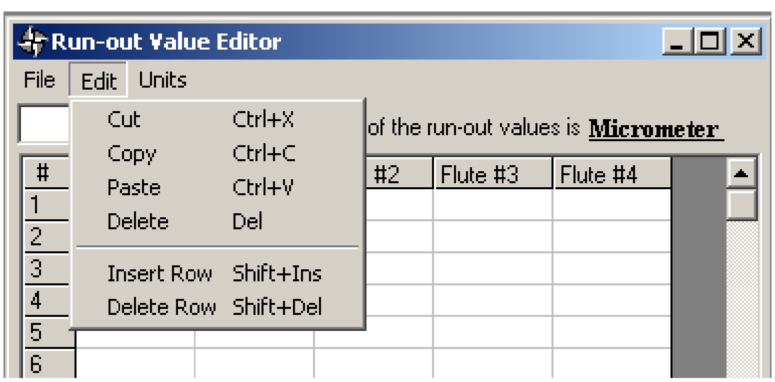


Figure 3.1-35: Edit command on Run-out Value Editor window

Table 3.1-5: The drop-down menu of Edit command on Run-out Value Editor window

Cut	*Cut the selected range of cells.*

Copy	*Copy the selected range of cells.*
Paste	*Paste the clipboard contents onto the table at the selected place.*
Delete	*Delete the selected range of cells.*
Insert Row	*An empty row at the selected place.*
Delete Row	*Delete the selected row.*

- ***UNITS COMMAND***

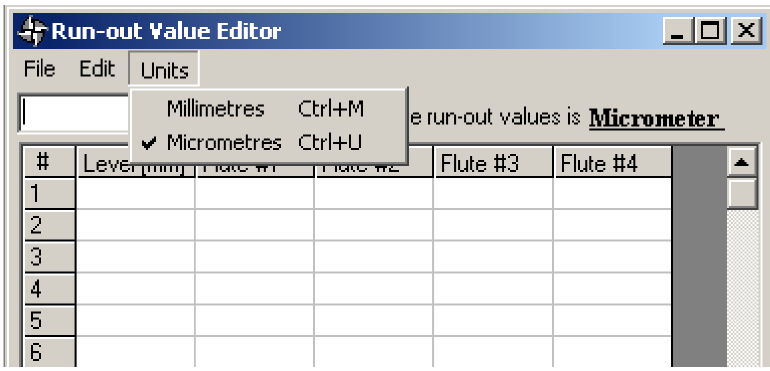


Figure 3.1-36: Units command on Run-out Value Editor window

Table 3.1-6: The drop-down menu of Units command on Run-out Value Editor window

Millimeters	*Display all measurements in millimeters [mm].*
Micrometers	*Display all measurements in micrometers [μm].*

⚠ **The Units menu commands do not affect the level measurements, contained in the first column of the run-out table.**

EXAMPLE:

The run-out deviations of flutes has been measured for the following cutter:

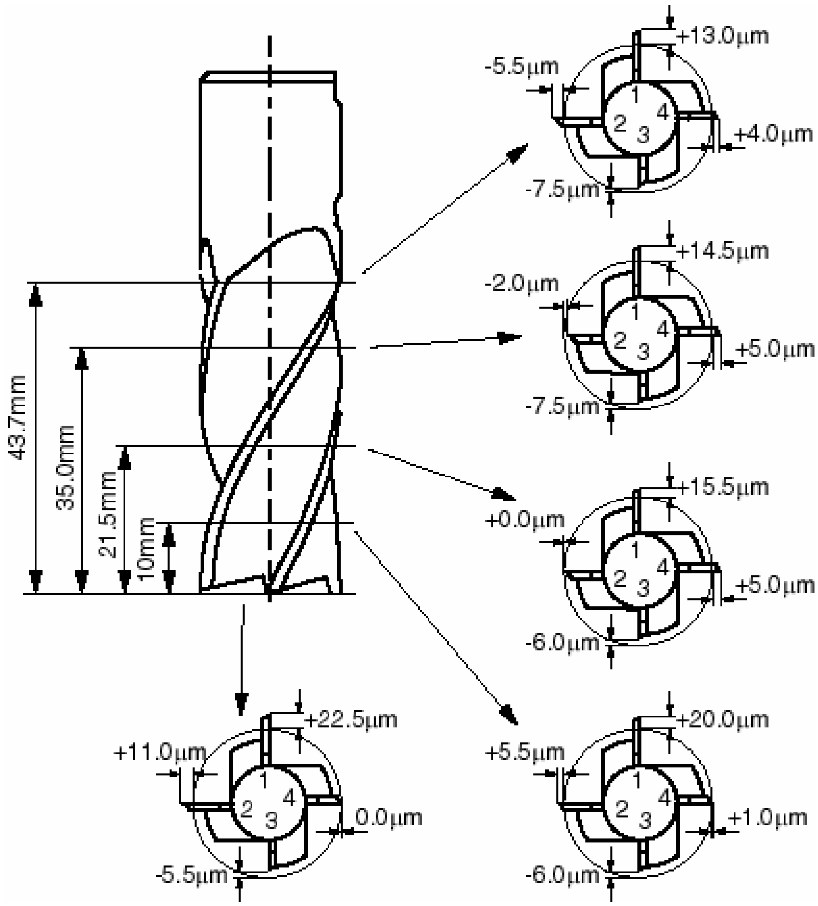


Figure 3.1-37: A sample cutter with its run-out parameters

The run-out deviations of flutes will be entered to the file as follows:

Run-Out Editor [C:\CutPro\Program\Example_Run_...

File Edit Units

The unit of the run-out values is **Micrometer**

#	Level [mm]	Flute #1	Flute #2	Flute #3	Flute #4
1	0	22.5	11	-5.5	0
2	10	20	5.5	-6	1
3	21.5	15.5	2	-6	5
4	35	14.5	-2	-7.5	5
5	43.7	13	-5.5	-7.5	4

Figure 3.1-38: The run-out parameters entered for the sample cutter in Figure 3.1-37

3.1.4 MACHINE & TOOL/CUTTER PROPERTIES TAB

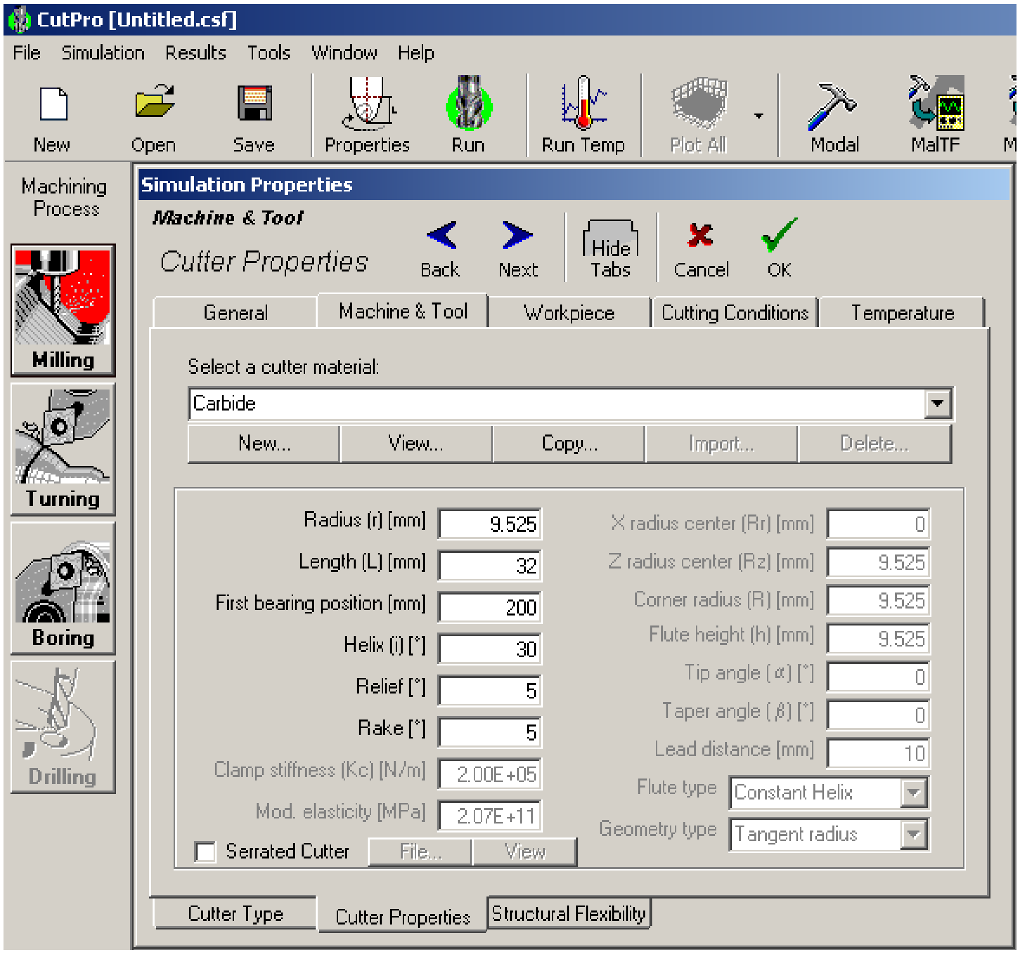


Figure 3.1-39: Machine & Tool/Cutter Properties tab

Machine & Tool/Cutter Properties tab allows you to select or define tool material and enter tool properties. In this tab only the necessary parameters for the selected tool type are enabled and the parameters you define can change depending on your selection in the previous tabs.

3.1.4.1 SELECT A CUTTER MATERIAL

In ***Machine & Tool/Cutter Properties*** tab, you can select the tool material from the list or define a new material with its specifications such as thermal conductivity, density, specific heat capacity and maximum allowable temperature:

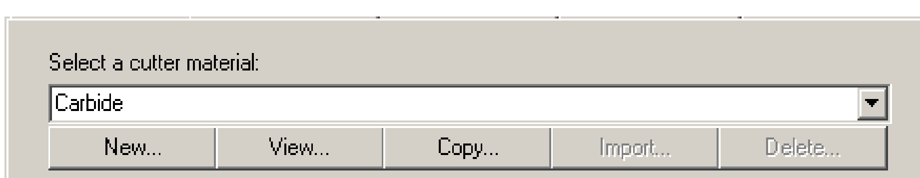


Figure 3.1-40: Select a cutter material

There are two different materials in this list defined as ***Fixed Material*** and ***User Defined Material***. You are not allowed to make any modification on ***Fixed Material*** properties but can create your own material (***User Defined Material)*** and enter all specifications of the material manually.

Figure 3.1-41: Fixed material list in Machine & Tool/Cutter Properties tab

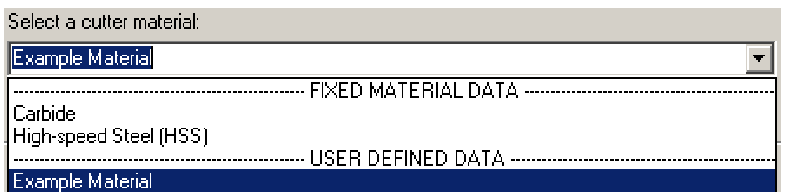


Figure 3.1-42: User defined material list in Machine & Tool/Cutter Properties tab

The following functions are available in order to edit materials:

Table 3.1-7: Buttons of "Select a cutter material"

New	*Create a new, user-defined material and display it in the **Material Editor** window.*
View	*View (fixed materials) or edit (user-defined materials) the specifications of currently selected material in the **Material Editor** window.*
Copy	*Create a copy of the currently selected material and display it in the **Material Editor** window.*
Delete	*Delete the currently selected material. This button is only enabled for user defined materials.*

When you click on the ***New*** button in **Figure 3.1-40**, the following ***Material Editor*** window pops up. Please scroll down in order to enter all the specifications. After you enter the parameters, click on the ***Save*** button to save the values you entered or click on the ***Cancel*** button to cancel and close the ***Material Editor*** window without saving the parameters.

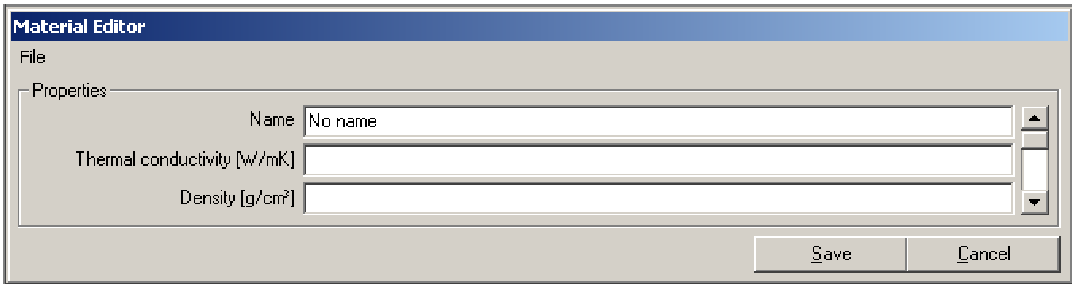


Figure 3.1-43: Material Editor window for User Defined Materials

If you click on the ***View*** button in [Figure 3.1-40](#), the following ***Material Editor*** window shows up:

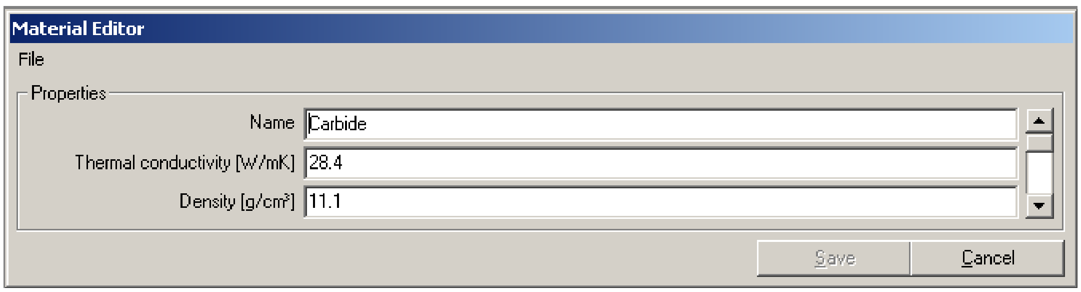


Figure 3.1-44: Material Editor window for Fixed Materials

The window displayed in [Figure 3.1-40](#) allows you to view the properties of a tool material that has fixed data. Since the data is fixed, you cannot save any changes you make to the parameters.

3.1.4.2 TOOL PROPERTIES

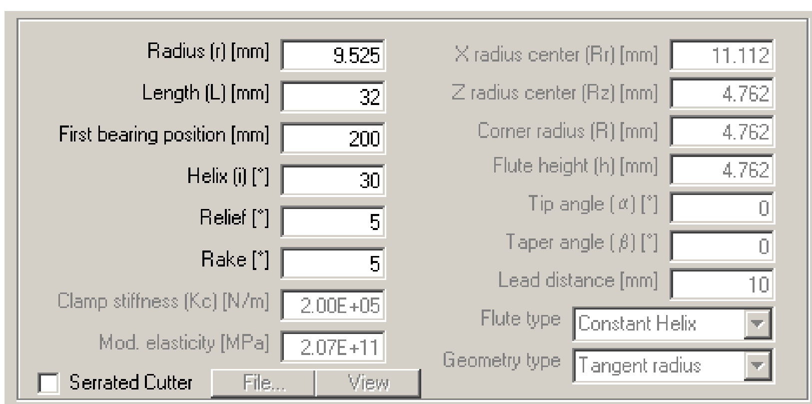


Figure 3.1-45: Tool Properties in Machine & Tool/Cutter Properties tab

On the ***Machine & Tool/Cutter Properties*** tab, you can define parameters of the tool such as radius, length, first bearing position, helix, relief and rake angles, clamp stiffness, modulus of elasticity, x and z radius centers, corner radius, flute height, tip and taper angles, lead distance, flute type and geometry type based on the tool type you have specified in **Section 3.1.3 Machine & Tool/Cutter Type tab**.

The window shown in **Figure 3.1-23** that displays the general look of the selected tool on the right hand side of the ***Simulation Properties*** changes automatically when any of the tool parameters is changed.

On the ***Machine & Tool/Cutter Properties*** tab, you can also define a profile for serrated cutters:

Figure 3.1-46: Serrated Cutter

When you click the ***Serrated Cutter*** check box, the ***Spline File*** window shows up:

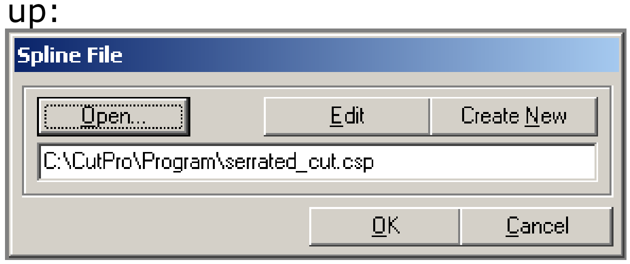


Figure 3.1-47: The Spline File window

You can also open the **The Spline** File window window by clicking on the ***File*** button in **Figure 3.1-46**.

Table 3.1-8: Functions of the buttons on Spline File window

Open	*Open an existing Spline (*.csp) file.*
Edit	*Edit the currently selected* ***Spline*** *file. This brings up the* ***Spline Editor*** *window.*
Create New	*Create a new* ***Spline*** *file. This brings up the* ***Spline Value Editor*** *window.*
OK	*Select the current file and close the window.*
Cancel	*Close the* ***Spline File*** *window and revert to the previously selected file.*

When you click ***OK*** in the **The Spline** File window window, the ***Spline Value Editor*** window pops up in which you define coordinates of the point on the serration profile:

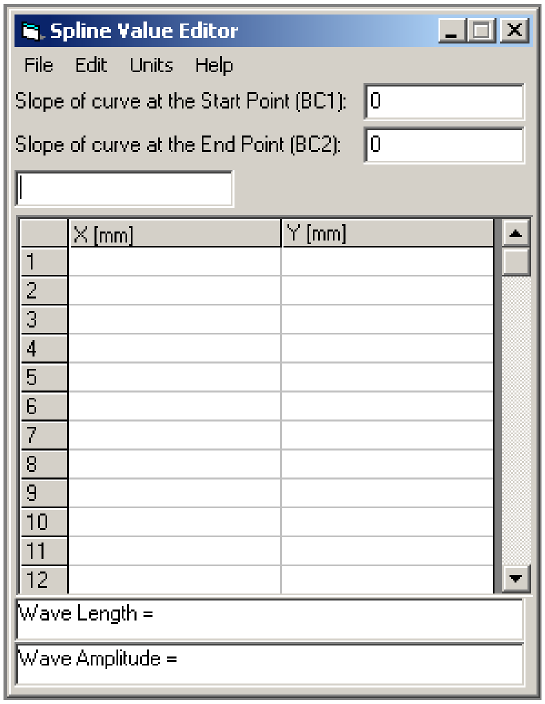


Figure 3.1-48: The Spline Value Editor window

The ***Spline Value Editor*** window consists of a table. In **Figure 3.1-48**, the first column lists x coordinates of the points while the second one shows y coordinates. The spline could be defined by the tool manufacturer or be measured by surface measurement devices. In the following, you can also find information regarding the menu items in the **Spline Value Editor** window:

- ***FILE COMMAND***

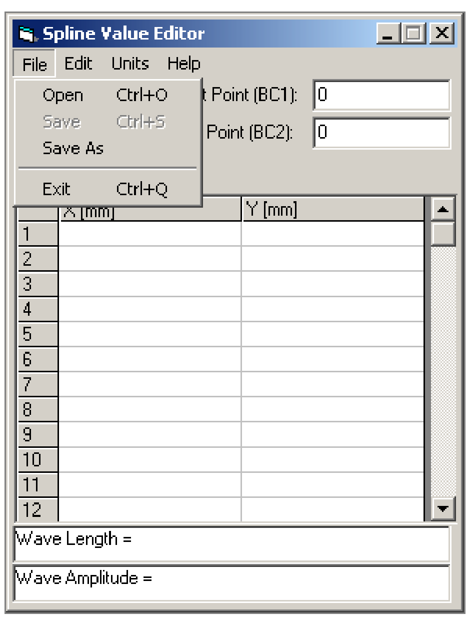


Figure 3.1-49: File command on the Spline Value Editor window

Table 3.1-9: The drop-down menu of File command on Spline Value Editor window

Open	*Open an existing **Spline** file.*
Save	*Save the currently open **Spline** file under the same name.*
Save As	*Save the currently open **Spline** file under a different name.*
Exit	*Exit the **Spline Editor** window.*

▪ *EDIT COMMAND*

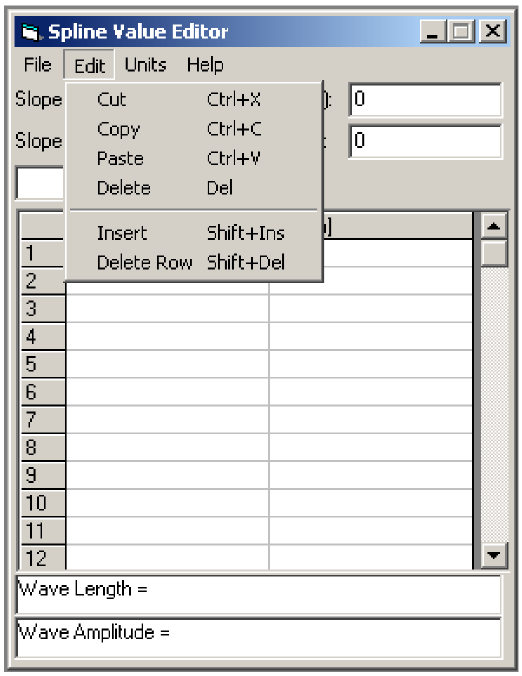


Figure 3.1-50: Edit command on the Spline Value Editor window

Table 3.1-10: The drop-down menu of Edit command on Spline Value Editor window

Cut	*Cut the selected range of cells.*
Copy	*Copy the selected range of cells.*
Paste	*Paste the clipboard contents onto the table at the selected place.*
Delete	*Delete the selected range of cells.*
Insert Row	*Insert an empty row at the selected place.*
Delete Row	*Delete the selected row.*

▪ *UNITS COMMAND*

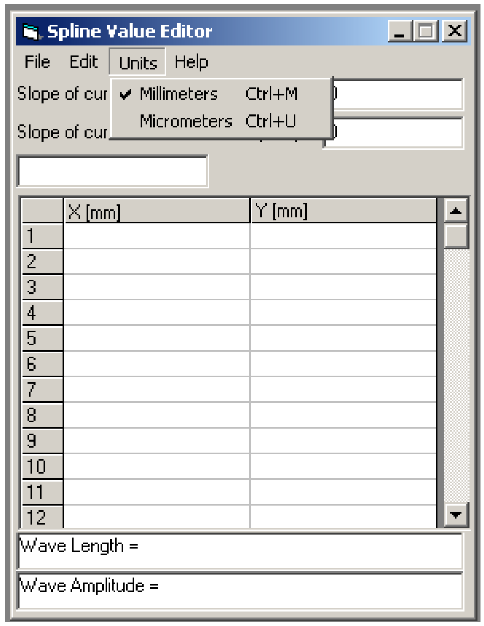


Figure 3.1-51: Units command on the Spline Value Editor window

Table 3.1-11: The drop-down menu of Units command on Spline Value Editor window

Millimeters	*Display all measurements in millimeters [mm].*
Micrometers	*Display all measurements in micrometers [μm].*

- ***HELP COMMAND***

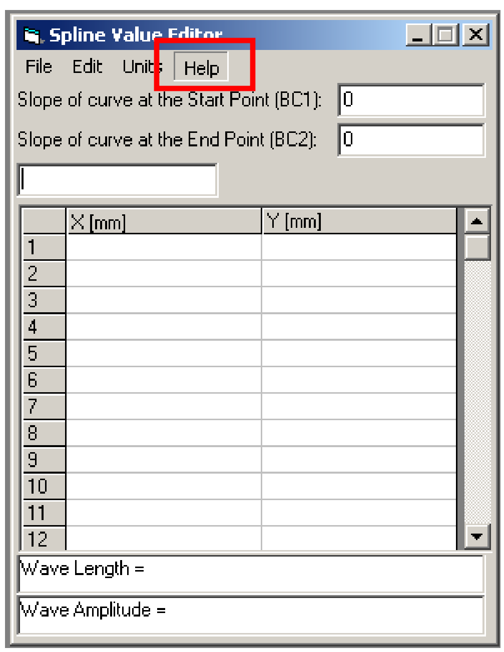


Figure 3.1-52: Help command on the Spine Value Editor window is highlighted by red box

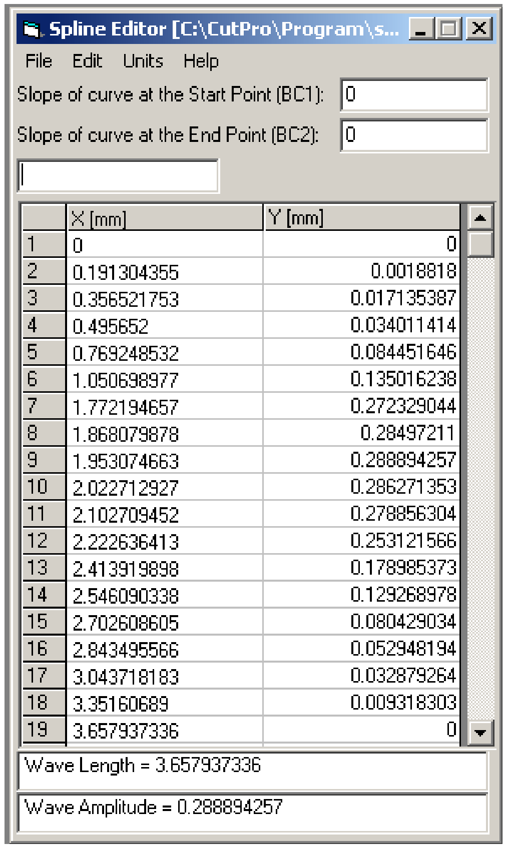


Figure 3.1-53: The Spline Editor window with example parameters entered

Once the parameters are defined, CutPro fits a spline to the given coordinates. Please note that the serrations on the other flutes are defined with 360°/N shifts in axial direction, where N is the number of the flutes on the tool. After you finish defining or editing the parameters, save the file by clicking ***Save*** in the drop-down menu of ***File*** command in **Spline Value Editor** window and then click ***OK*** in the **The Spline File window** window in order to use the file in the simulation. When you click ***OK*** in the **The Spline File window** window, ***Serrated Cutter Spline*** window pops up showing the profile of the serration and you can close this window afterwards:

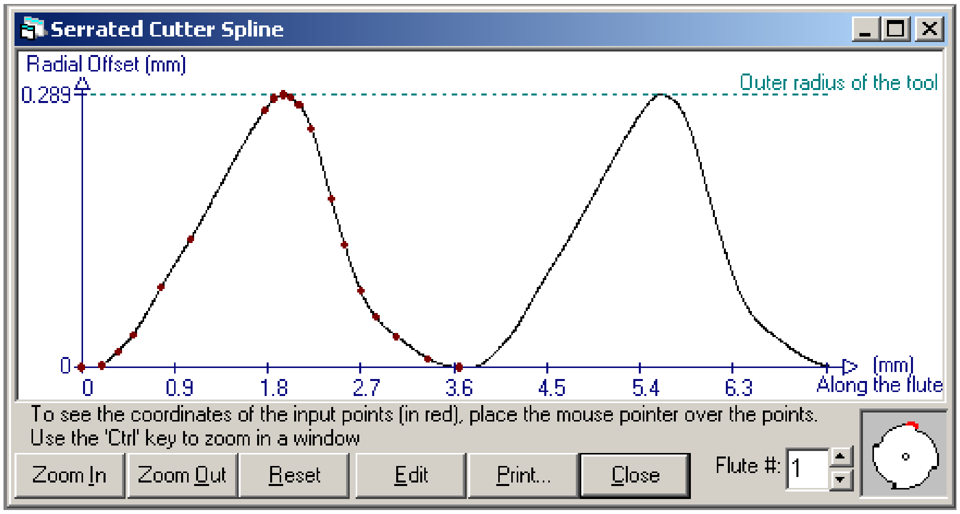


Figure 3.1-54: Serrated Cutter Spline

You can also open the **Serrated Cutter Spline** window by clicking on ***View*** button in **Figure 3.1-46**.

Table 3.1-122: Buttons on Serrated Cutter Spline window

Zoom In	*Increase magnification of the figure.*
Zoom Out	*Decrease magnification of the figure.*
Reset	*Reset magnification of the figure.*
Edit	*Opens the **Spline Value Editor** window and allows you to edit the current file*
Print	*Brings up a print dialog which allows you to print the figure at its current magnification*
Close	*Closes the figure window*
Flute #	*Selects the flute number to see the serration profile*

In order to see the coordinates of the inputs (red points) in **Serrated Cutter Spline** window, place the mouse pointer over the points and use the "Ctrl" key and left mouse button at the same time to zoom in a window.

3.1.4.3 INDEXABLE CUTTER PARAMETERS

For **Indexable cutter** geometry option under **Machine & Tool/Cutter Type**, **Machine & Tool/Cutter Properties** tab has different options which are given in the following figure:

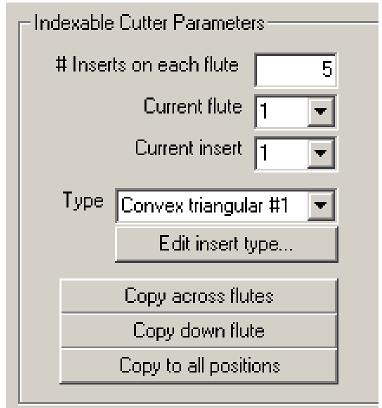
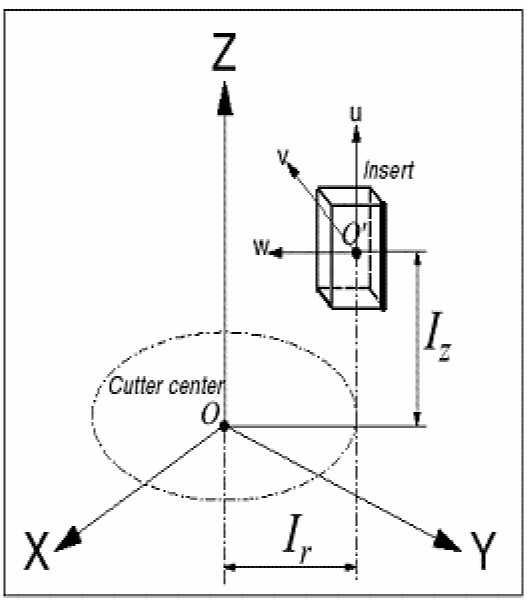
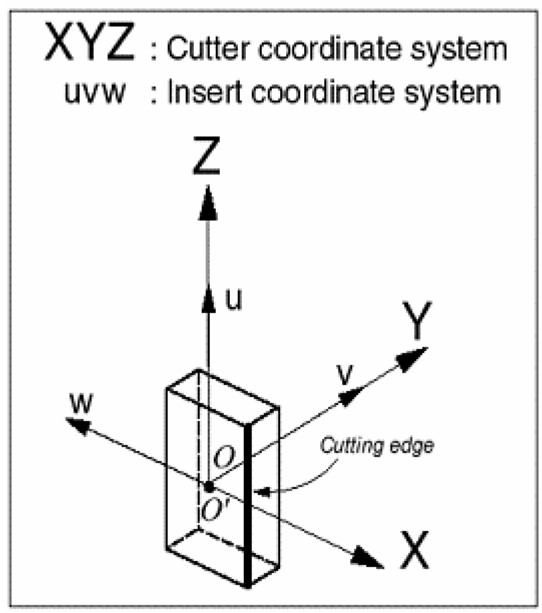


Figure 3.1-55: Indexable Cutter Parameters on the Machine & Tool/Cutter Properties tab

You can enter the number of inserts on each flute and define different insert types for each insert on the tool. Rectangular and convex triangular inserts are the default insert types defined in CutPro. Rectangular inserts are defined by width (a) and length (b):





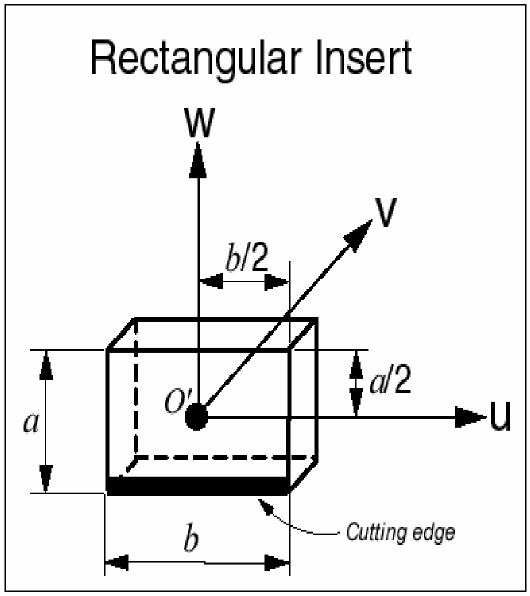


Figure 3.1-56: Geometry of a Rectangular Insert

Convex triangular inserts are defined by arc radius (r) and center offset (f):

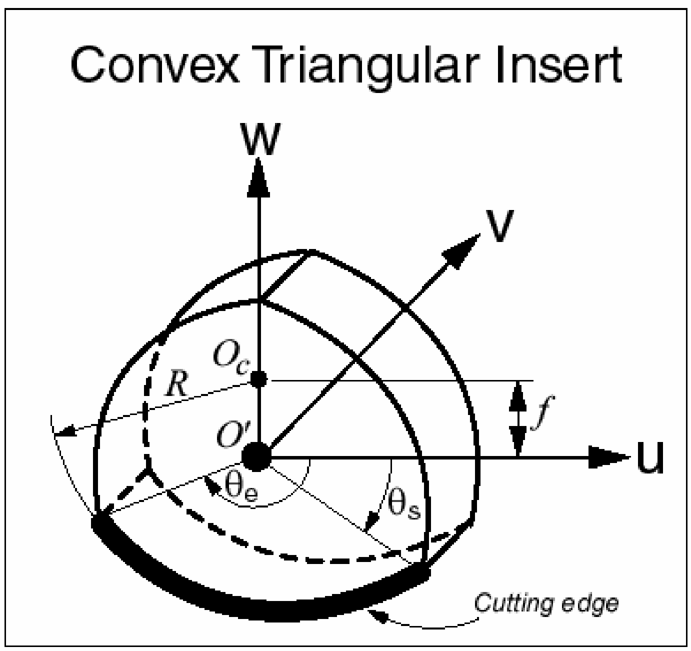


Figure 3.1-57: Geometry of a Convex Triangular Insert

Table 3.1-133: Buttons on Indexable Cutter Parameters

Edit Insert Type	*Allow you to edit insert type. This brings up the **Edit Insert Cutter Types** window.*
Copy across flutes	*When you click on this button, the inserts on the same axial level have the same insert type*

Copy down flute	*When you click on this button, the inserts on the same flute have the same insert type*
Copy to all positions	*When you click on this button, all the inserts on the tool have the same insert type*

When you click on the ***Edit insert type*** button in Figure 3.1-55, the ***Edit Insert Cutter Types*** window pops up and you can edit the insert type:

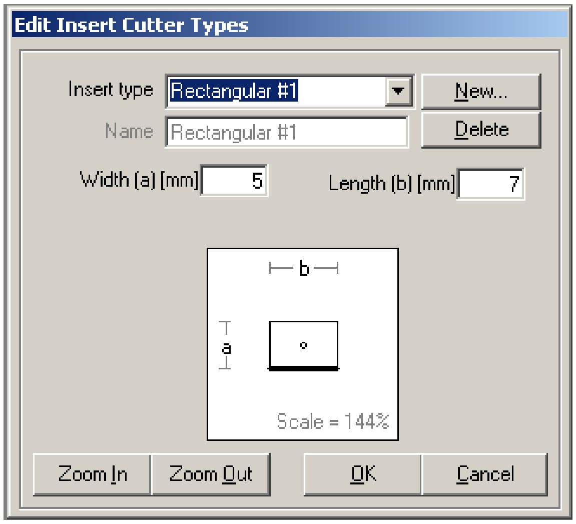


Figure 3.1-58: Edit Insert Cutter Types window

Table 3.1-144: Buttons on Edit Insert Cutter Types window

New	*Allow you to create a new insert. The new type must be either Rectangular or Convex Triangular.*
Delete	*Delete the currently selected insert type. Any inserts of this type currently on the indexable cutter will also be removed.*
Zoom In	*Increase magnification of the figure. You can also zoom in by clicking the figure with the left mouse button.*
Zoom Out	*Decrease magnification of the figure. You can also zoom out by clicking the figure with the right mouse button.*
Save	*Save any change you have made editing the insert type, and close the Insert Editor window.*
Cancel	*Close the Insert Editor without saving any changes.*

If you click on the ***New*** button in the ***Edit Insert Cutter Types*** window, the ***New Insert*** window pops up in which you can select the shape of the new insert type:

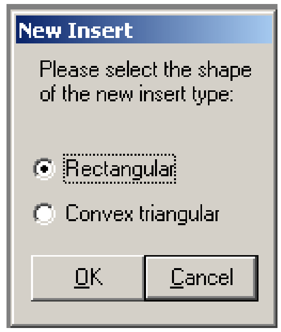


Figure 3.1-59: New Insert window

3.1.5 MACHINE & TOOL/STRUCTURAL FLEXIBILITY TAB

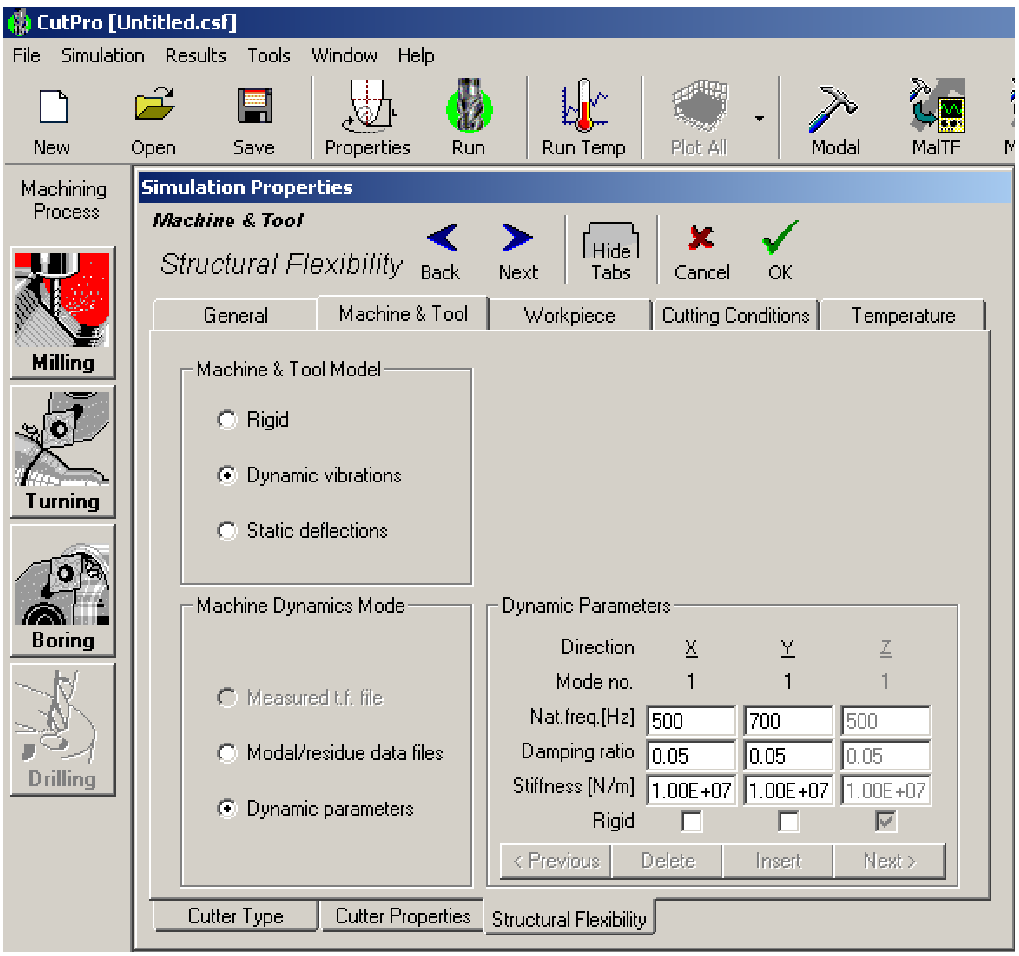


Figure 3.1-60: Machine & Tool/Structural Flexibility tab

Machine & Tool/Structural Flexibility tab allows you to enter machine & tool dynamic parameters. In this tab, you have different parameters to define for your different selections.

3.1.5.1 MACHINE & TOOL MODEL

You can model the machine & tool in three different ways. You can assume that during the process machine & tool is rigid or dynamic vibrations occur in the system or machine & tool deflect statically:

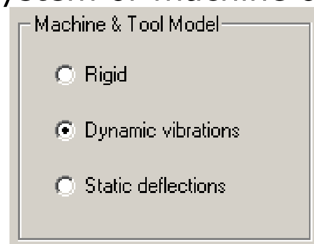


Figure 3.1-61: Machine & Tool Model in Machine & Tool/Structural Flexibility tab

The choice of ***Rigid*** option in ***Machine & Tool Model*** brings up the following frame:

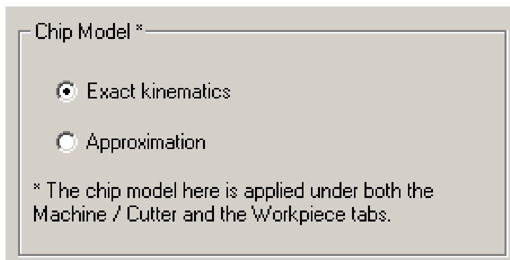


Figure 3.1-62: Chip Model frame

In ***Chip Model*** frame, you can model the chip by using either the ***Exact Kinematics*** option or the ***Approximation*** option. For the ***Exact Kinematics*** option, the exact kinematics of the process is considered, therefore the simulation time can be longer. In ***Approximation*** option, chip thickness is modeled as a function of feed rate (c) and immersion angle (ϕ). The chip thickness expression used in the ***Approximation*** option is given by the following equation:

$$h = c \sin \phi \qquad (1)$$

If you prefer using the ***Approximation*** option for the chip model, you will have an error which is negligible in the simulation results.

3.1.5.2 MACHINE DYNAMICS MODE

There are three different machine dynamics modes, namely, ***Measured t.f. file***, ***Modal/residue data files***, and ***Dynamic parameters***, available in this tab:

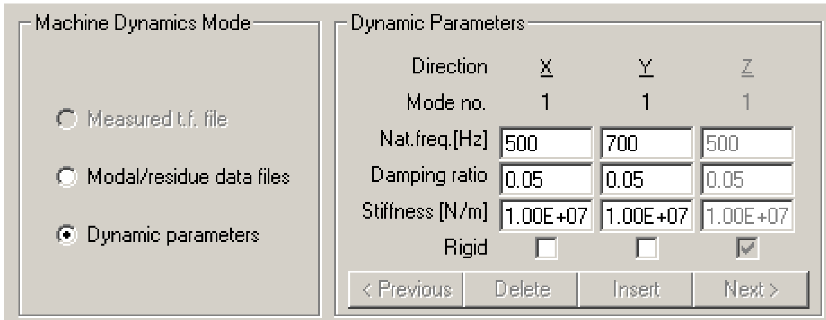


Figure 3.1-63: Machine Dynamics Mode in Machine & Tool/Structural Flexibility tab

3.1.5.2.1 MEASURED T.F. FILE

When you select the *Measured t.f. file* option in *Machine Dynamics Mode* given by Figure 3.1-63, you can include the dynamic parameters of the machine and tool to the simulation by downloading transfer function files (*.frf) which are measured in the x, y and z directions by using the **MalTF** module of CutPro. The transfer function files, typically ASCII *frf* files, have the real and imaginary parts of the transfer functions with corresponding the frequency values.

The ***FRF Type*** frame that opens with this option is shown in the following figure:

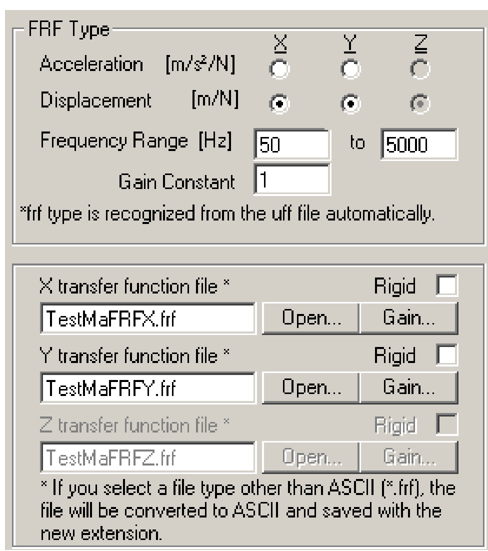


Figure 3.1-64: FRF Type frame in Machine & Tool/Structural Flexibility tab

In the ***FRF Type*** frame, you define the type of transfer function file (acceleration or displacement) in the x, y and z directions, the frequency range you wish to consider in the simulation, and the gain constant of the calibration setup (i.e. impact hammer and accelerometer or displacement sensor – leave the gain as 1 if you entered the sensitivity of the sensors in MalTF).

The existing transfer function files (*.frf files) can be downloaded by clicking on the ***Open*** button in **FRF Type** frame in Machine & Tool/Structural Flexibility tab frame. You can also create a new transfer function file by changing the gain constant value of the current file from the ***Apply Gain Constant*** window which pops up when you click on the ***Gain*** button in the **FRF Type** frame in Machine & Tool/Structural Flexibility tab:

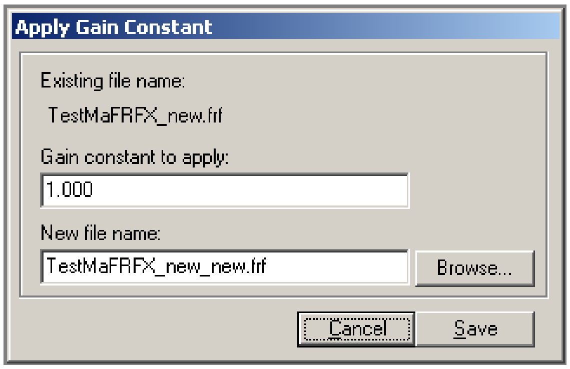


Figure 3.1-65: Apply Gain Constant window

You can exclude the dynamic effects of the direction you want on the structure by checking the box next to the ***Rigid*** option in the **FRF Type** frame in Machine & Tool/Structural Flexibility tab.

3.1.5.2.2 MODAL/RESIDUE DATA FILES

When you select the ***Modal/residue data files*** option in the ***Machine Dynamics Mode*** given by Figure 3.1-63, you can include the dynamic parameters of the machine and tool in the simulation by downloading the **.cmp* files created in the **Modal Analysis** module of CutPro. After a transfer function measurement, the data is processed in the **Modal Analysis** module. The ***Modal Analysis*** module fits a curve to the measurement and predicts the dynamic parameters. If you wish, you can save these parameters in a file named with **.cmp* extension, then load this file into CutPro by using the following frame that shows up with the choice of ***Modal/residue data files*** option:

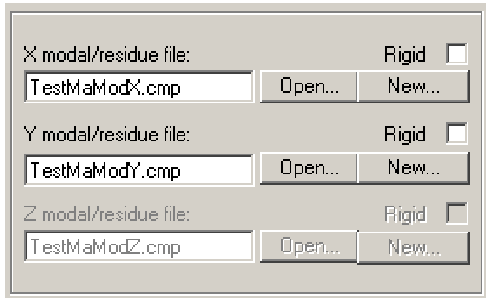


Figure 3.1-66: Downloading (*.cmp) files frame in Machine & Tool/Structural Flexibility tab

You can download existing **.cmp* files by clicking on the *Open* button in Figure 3.1-66. If you click on the *New* button in Figure 3.1-66, the *New Residue File* window, in which you can create a new **.cmp* file from an existing transfer function file (*.frf file), pops up:

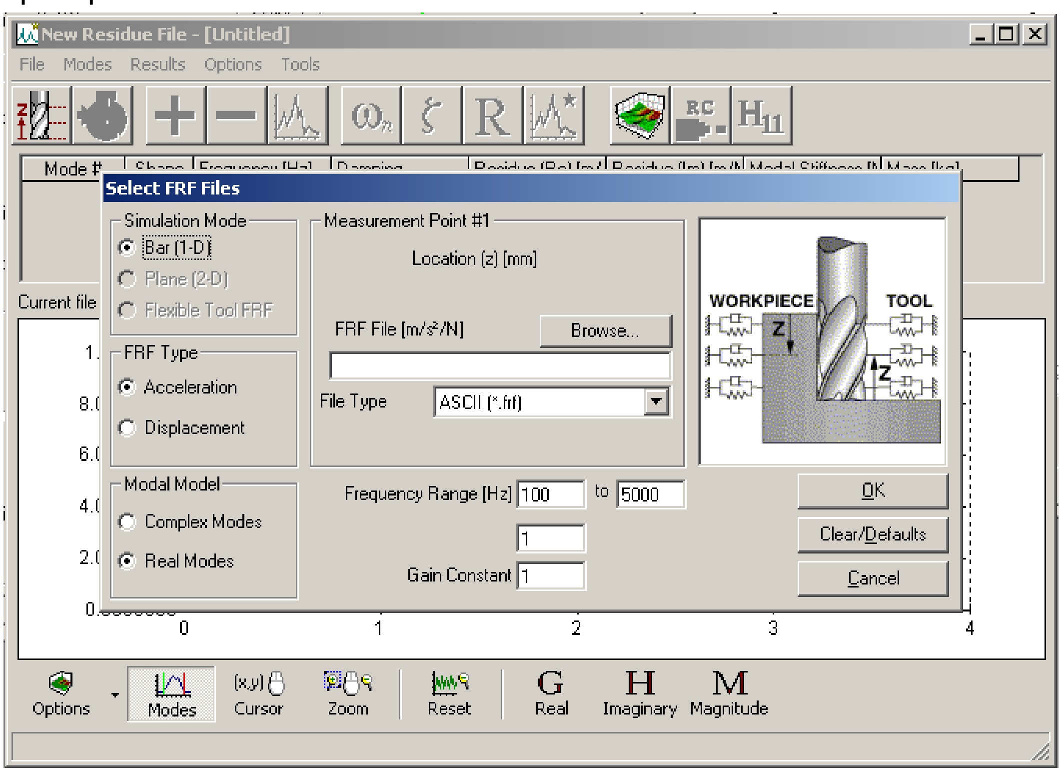


Figure 3.1-67: New Residue File window

You can exclude the dynamic effects of the direction you want on the structure by checking the box next to the ***Rigid*** option in **Figure 3.1-66**. Please see **Section 10.2 Appendix A2: Modal/residue data files** for more information.

3.1.5.2.3 DYNAMIC PARAMETERS

If you know the dynamic parameters of the system such as natural frequencies, damping ratios and stiffness values of the modes, you can simply enter them by choosing the ***Dynamic Parameters*** option. When you select this option, the following frame shows up:

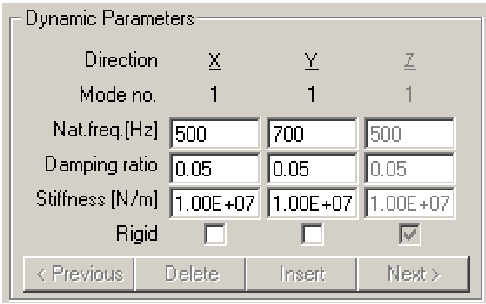


Figure 3.1-68: The Dynamic Parameters frame on the Machine & Tool / Structural Flexibility tab

Table 3.1-155: Buttons in the Dynamic Parameters frame

Previous	*Switch to previous modes to view and edit the dynamic parameters of the modes*
Delete	*Delete the current mode with its dynamic parameters*
Insert	*Add a new mode with its dynamic parameters*
Next	*Switch to next modes to view and edit the dynamic parameters of the modes*

For any of the above modes you have an option to make any direction of the structure rigid by clicking the related check box below the parameter text boxes.

Please see **Section 10.3 Appendix A3: Dynamic Parameters** for more information.

⚠ **If you select the Static deflections option for the machine & tool model, the workpiece model options are disabled.**
⚠ **If you select the Rigid option for the machine & tool model and the workpiece model, the only simulation modes available are Single time domain and Cutting coefficient identification.**
⚠ **If you select the Dynamic vibrations option for the machine & tool model, go to the Dynamics tab to specify parameters or source data files.**

3.1.6 WORKPIECE/MATERIAL TAB

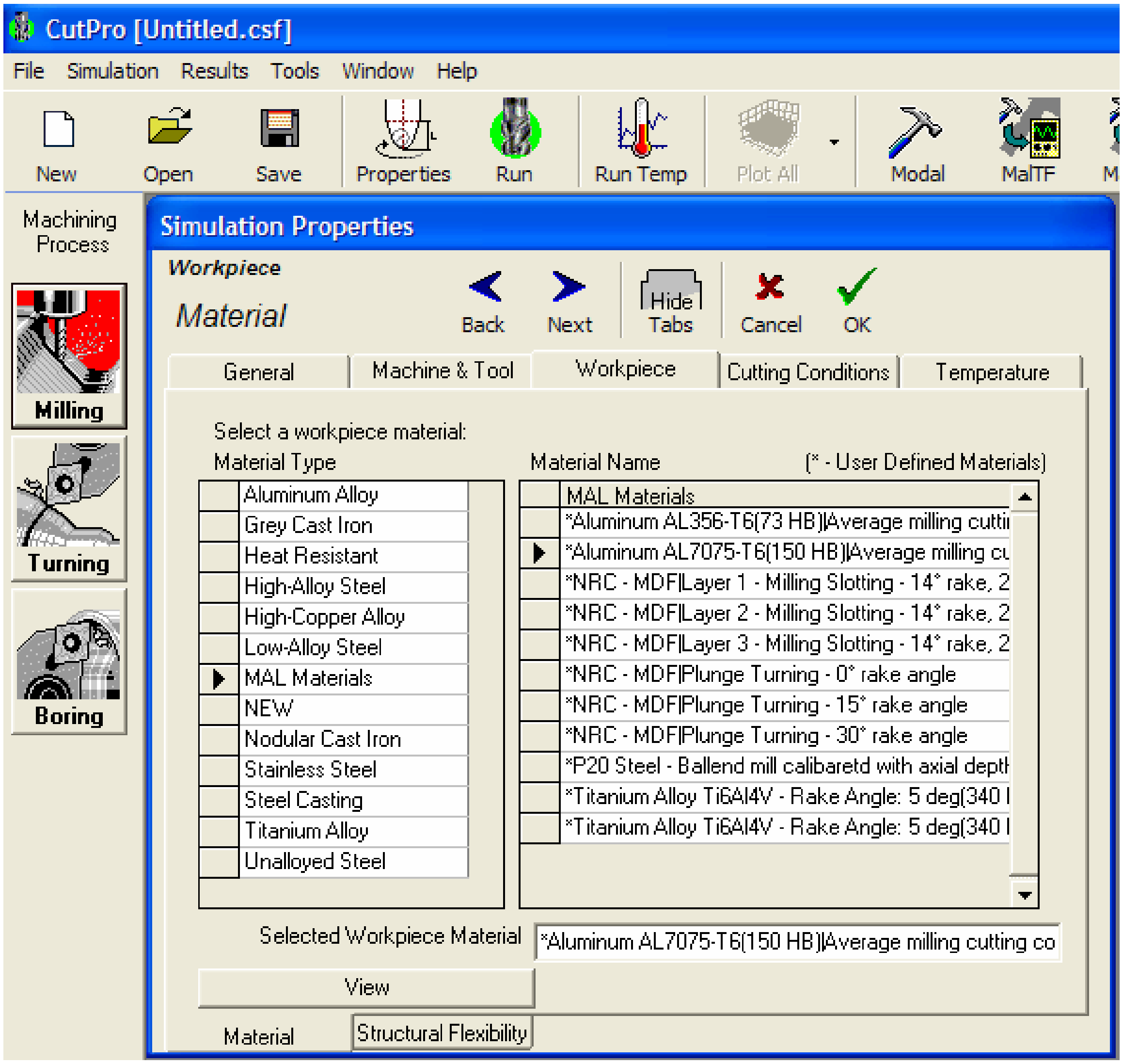


Figure 3.1-69: Workpiece / Material tab

The ***Workpiece / Material*** tab allows you to select or define the material of the workpiece.

3.1.6.1 DEFINE A WORKPIECE MATERIAL

In the ***Workpiece / Material*** tab, you can select the workpiece material from the list or define a new material with its specifications such as composition, density, thermal conductivity, specific heat capacity, Young's modulus, hardness, tensile strength, yield strength, shear strength, impact strength, elongation, reduction in area, condition, heat treatment, melting point, thermal expansion and electrical conductivity. Also, when defining a new material, you must specify the force model and the corresponding cutting coefficients for that model:

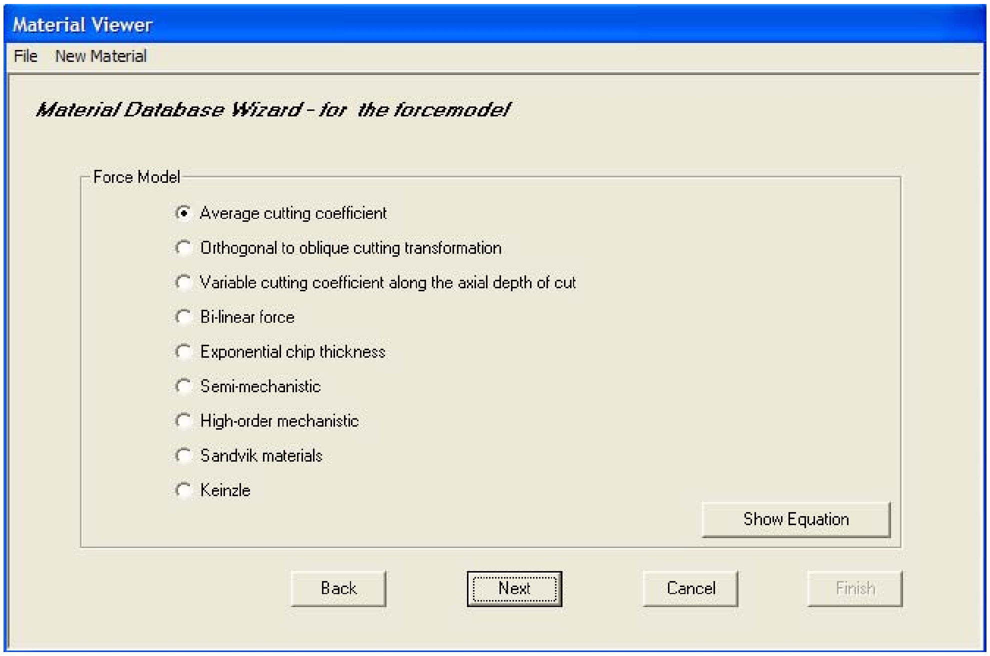


Figure 3.1-70: The Force Model selection window for defining a new workpiece material

There are two different materials in this list defined as ***Fixed Material*** and ***User Defined Material***. You are not allowed to make any modification on ***Fixed Material*** properties but can create your own material (***User Defined Material)*** and enter all specifications of the material manually. User defined materials are denoted with a * preceding their name.

The following functions are available in order to edit materials:

Table 3.1-166: Buttons of Select a workpiece material

New	*Create a new, user-defined material and display it in the **Material Editor** window.*
View/ Edit	*View (fixed materials) or edit (user-defined materials) the specifications of currently selected material in the **Material Editor** window.*
Copy	*Create a copy of the currently selected material and display it in the **Material Editor** window.*
Import	*Import a material from an existing ***.cwm** file*
Delete	*Delete the currently selected material. This button is only enabled for user defined materials.*

If you click on the ***New*** or ***View*** buttons, the following ***Material Editor*** window pops up:

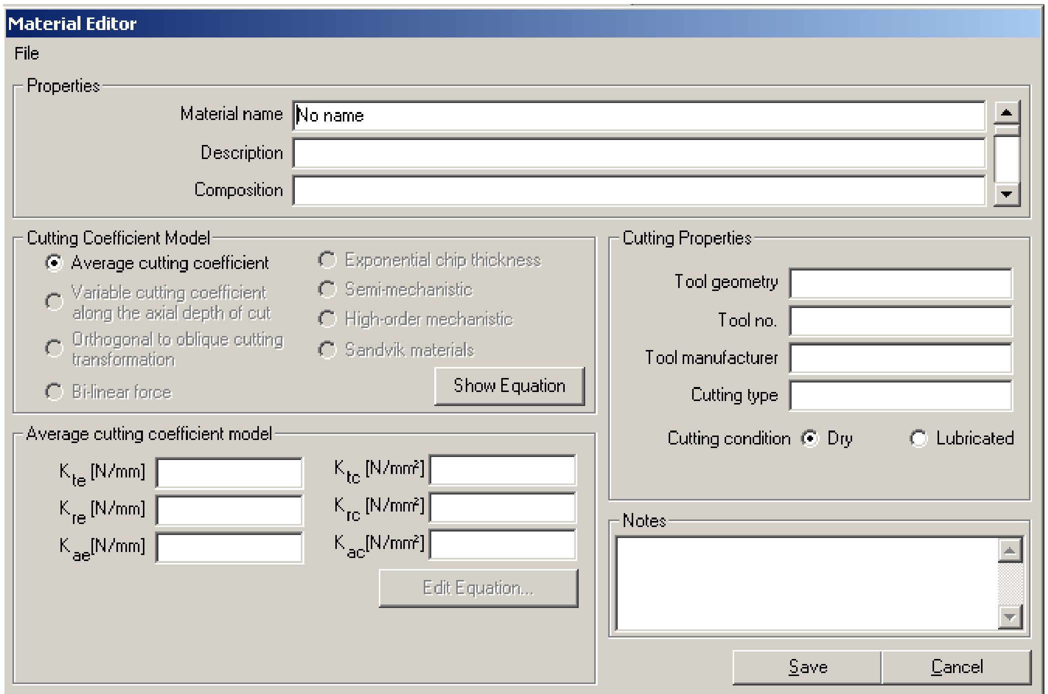


Figure 3.1-71: The Material Editor window for User Defined Materials

You can define and edit only the parameters of ***user defined materials***. The following frames appear in the ***Material Editor*** window:

- Properties
- Cutting coefficient model and its parameters
  - Average cutting coefficient model
  - Variable cutting coefficient model
  - Orthogonal to oblique cutting transformation
  - Bi-linear force model
  - Exponential chip thickness model
  - Semi-mechanistic model
  - High-order force model
  - Sandvik force model
  - Kienzle force model
- Cutting properties
- Notes
- Save / Cancel

▪ *PROPERTIES*

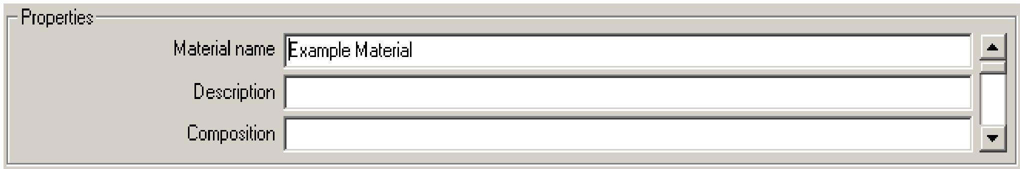


Figure 3.1-72: Properties frame in Material Editor window

Scroll down in ***Properties*** frame to define the specifications of the workpiece material given in the following table:

Table 3.1-177: Specifications of workpiece material

Material name	
Description	
Composition	
Density	*[g/cm^3]*
Thermal conductivity	*[W/mK]*
Specific heat capacity	*[J/kgK]*
Young module	*[N/m^2]*
Hardness	*[HB]*
Tensile strength	*[N/m^2]*
Yield strength	*[N/m^2]*
Shear strength	*[N/m^2]*
Impact strength	*[N/m^2]*
Elongation	*[%]*
Reduction in area	*[%]*
Condition	
Heat treatment	
Melting point	*[°C]*
Thermal expansion	*[10e-6/°C]*
Electrical conductivity	

- ***CUTTING COEFFICIENT MODEL***

In the ***Cutting Coefficient Model*** frame, you see the cutting coefficient model you chose on the ***Workpiece/Material*** tab and define the required parameters for that model. The ***Cutting Coefficient Model*** frame is shown in the following figure:

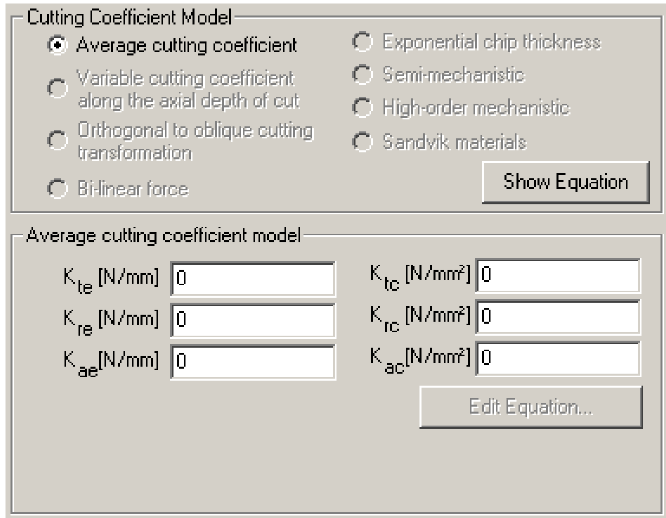


Figure 3.1-73: Cutting Coefficient Model frame for Al7075-T6 (Average Cutting Coefficient model is selected.)

The ***Equation*** window that pops up when you click on ***Show Equation*** button (See Figure 3.1-73) allows you to see both the equations and the definition of the parameters used in the cutting coefficient model:

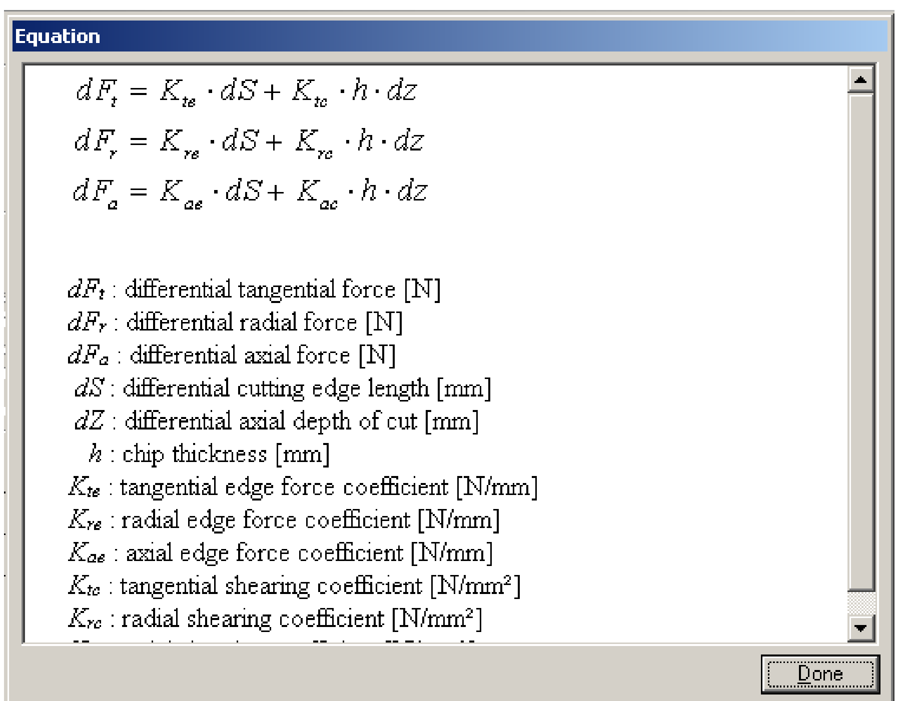


Figure 3.1-74: Equation window of Average Cutting Coefficient model

Click on ***Done*** button in Figure 3.1-74 to close ***Equation*** window.

Equation Editor window which shows up when you click on the ***Edit Equation*** button in **Figure 3.1-73** allows you to define cutting coefficient model parameters by using equations.

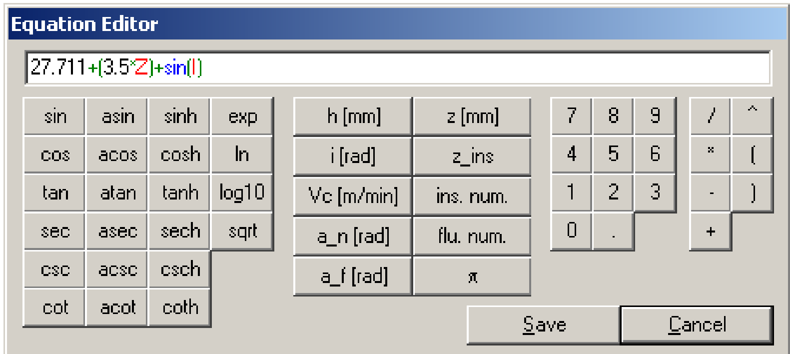


Figure 3.1-75: One of the parameters is represented with an equation in Equation Editor window as an example.

You enter the equations for the cutting coefficient model parameters by clicking on the buttons in the ***Equation Editor*** window. The following mathematical functions are available in ***Equation Editor*** window (See **Figure 3.1-75**):

Table 3.1-188: Mathematical functions in the Equation Editor window

sin	*Sine*
cos	*Cosine*
tan	*Tangent*
sec	*Secant*
csc	*Cosecant*
cot	*Cotangent*
asin	*Arcsine*
acos	*Arccosine*
atan	*Arctangent*
asec	*Arcsecant*
acsc	*Arccosecant*
acot	*Arccotangent*
sinh	*hyperbolic sine*
cosh	*hyperbolic cosine*
tanh	*hyperbolic tangent*
sech	*hyperbolic secant*
csch	*hyperbolic cosecant*
coth	*hyperbolic cotangent*
exp	e^x *-- the inverse of ln; e = 2.71828182845904*
ln	*natural logarithm*
log_{10}	*base 10 logarithm*
sqrt	*square root*

⚠ **All mathematical functions must be followed by an argument written in parentheses.**

The following cutting parameters are available in the ***Equation Editor*** window (See **Figure 3.1-75**):

Table 3.1-19: Cutting parameters in the Equation Editor window

h	*chip thickness [mm]*
z	*depth of cut [mm]*
i	*local helix angle [rad]*
z_ins	*insert depth of cut* *(This option is for inserted cutter)*
Vc	*cutting speed [m/min]*
ins. num.	*insert number* *(This option is for inserted cutter)*
a_n	*rake angle [rad]*
flu. num.	*flute number*
a_f	*relief angle [rad]*
π	*pi = 3.14159265358979*

The following math operators are available in the ***Equation Editor*** window (See **Figure 3.1-75**):

Table 3.1-190: Math operators in the Equation Editor window

+	*Addition*
-	*Subtraction*
*	*Multiplication*
/	*Division*
^	*Power (e.g., x^a =* x^a *)*
( )	*Parentheses*

⚠ **Note that certain restrictions are placed on valid equations. Whenever you click Save, your equation will be automatically checked for errors. You will not be allowed to save an invalid equation.**

Click on ***Save*** to save changes you made in the equation and close the ***Equation Editor*** window. Click **Cancel** to exit the ***Equation Editor*** window without saving any changes. Note that if you enter the cutting coefficients as an equation, your simulation speed will be more than ten times slower (in any time domain simulations) depending on your equations. If it is not necessary, do not enter an equation for cutting coefficients.

- **_CUTTING PROPERTIES_**

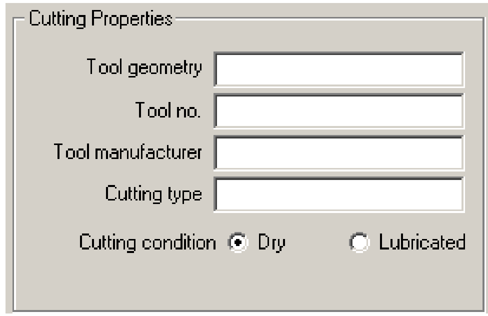


Figure 3.1-76: Cutting Properties frame in the Material Editor window

In the ***Cutting Properties*** frame, you can define the tool geometry, tool number, tool manufacturer, cutting type, and you can select the cutting condition (dry or lubricated).

- **_NOTES_**

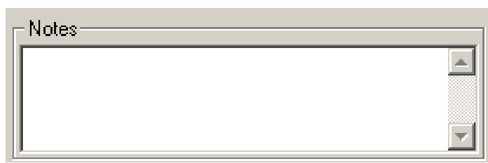


Figure 3.1-77: Notes frame in the Material Editor window

You can write extra information about the material into the text box in ***Notes*** frame.

- **_SAVE/CANCEL_**

Figure 3.1-78: Save and Cancel buttons in the Material Editor window

Press ***Save*** to save changes and exit the ***Material Editor*** window. Press ***Cancel*** to exit ***Material Editor*** window without saving any changes.

3.1.6.2 CUTTING COEFFICIENT MODEL

On the ***Workpiece/Material*** tab (See **Figure 3.1-69**); you can select different cutting coefficient models for your simulation mode:

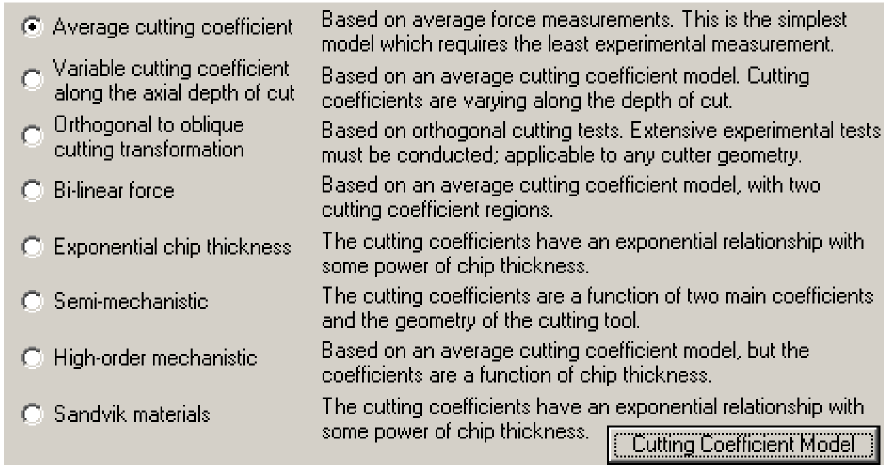


Figure 3.1-79: Cutting Coefficient Model list in Workpiece / Material tab

The following cutting coefficient models are available in CutPro:

- Average cutting coefficient
- Variable cutting coefficient along the axial depth of cut
- Orthogonal to oblique cutting transformation
- Bi-linear force
- Exponential chip thickness
- Semi-mechanistic
- High-order mechanistic
- Sandvik materials

Cutting Coefficient Identification Procedure in CUTPRO

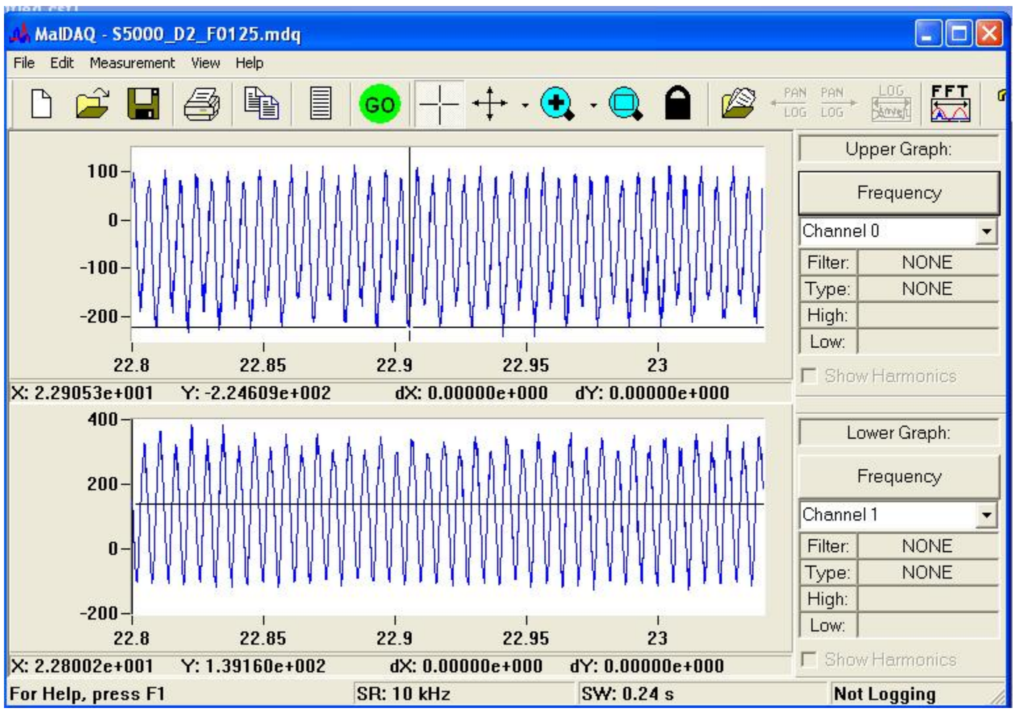
(MAL Inc. March 13, 2006, Vancouver B.C.)

CUTPRO can automatically identify cutting coefficients with its associated option in the general tab of the milling module. You need to conduct a series of milling tests and collect the data in ASCII or MALDAQ (mdq) formats. If you use the "log data" option in MALDAQ, you will need to load the part of the data you are interested in first, and then save the data as a MALDQ (mdq) binary file. It is convenient to name the files as:

S5000_N2_c0050_a5:
Spindle speed: 5000 rpm
Number of teeth: 2
Feed per tooth: 0.0050 mm
Axial depth of cut: a=5 mm

Presently, you need to conduct the cutting tests using a slotting procedure. Make sure that there is no chatter when you conduct the cutting tests, otherwise the dynamometer will not measure the forces correctly due to its limited bandwidth.

Typical cutting force data for a 2 fluted end mill is shown here, which is saved as S5000_D7_f0125.mdq binary file. About 5-6 cutting tests with a feed range starting from 0.05 to 0.075, 0.1, 0.125, 0.150, 0.200 mm/tooth should be sufficient.

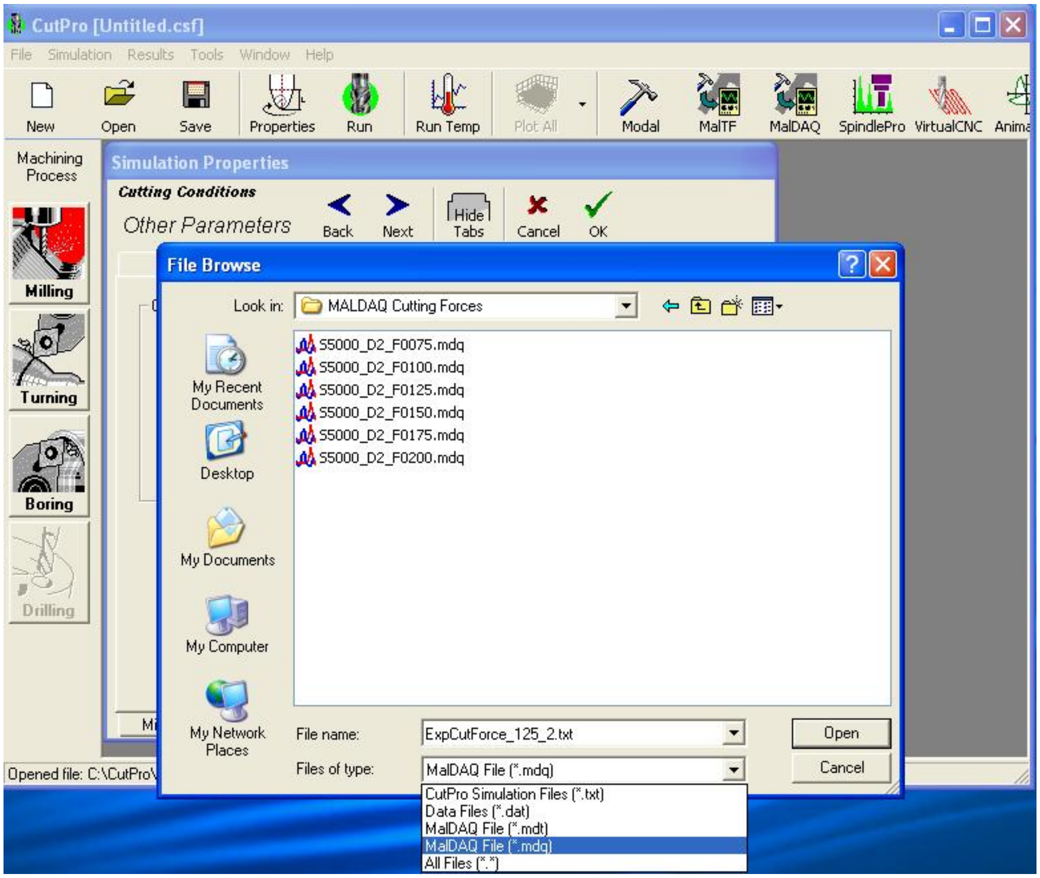


After collecting the cutting force data, please follow the procedure given below:

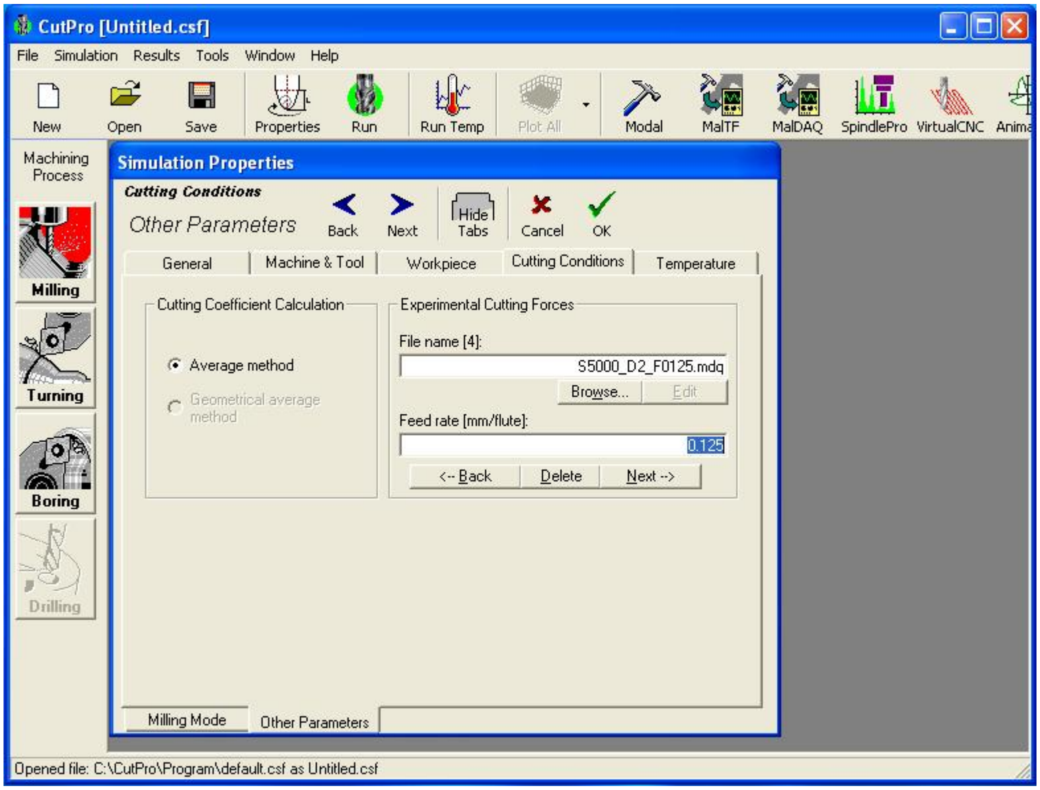
1. Select "Cutting Coefficient Identification" option from "Simulation Properties" window. To upload measured cutting force data, select "Browse" under "Cutting Conditions" tab.

Enter the number of teeth in tool geometry menu, and make sure to click on "rigid" for both cutter and part structure pages. You can identify whether the tool material, but it is not essential. The tool material data is only for your benefit as an information. Select the depth of cut in cutting conditions page. Now you are ready to enter the measurement files when you click next again.

2. Select the force measurement files, which can be text or binary (.mdq) files which can be indicated from the file type as shown below.

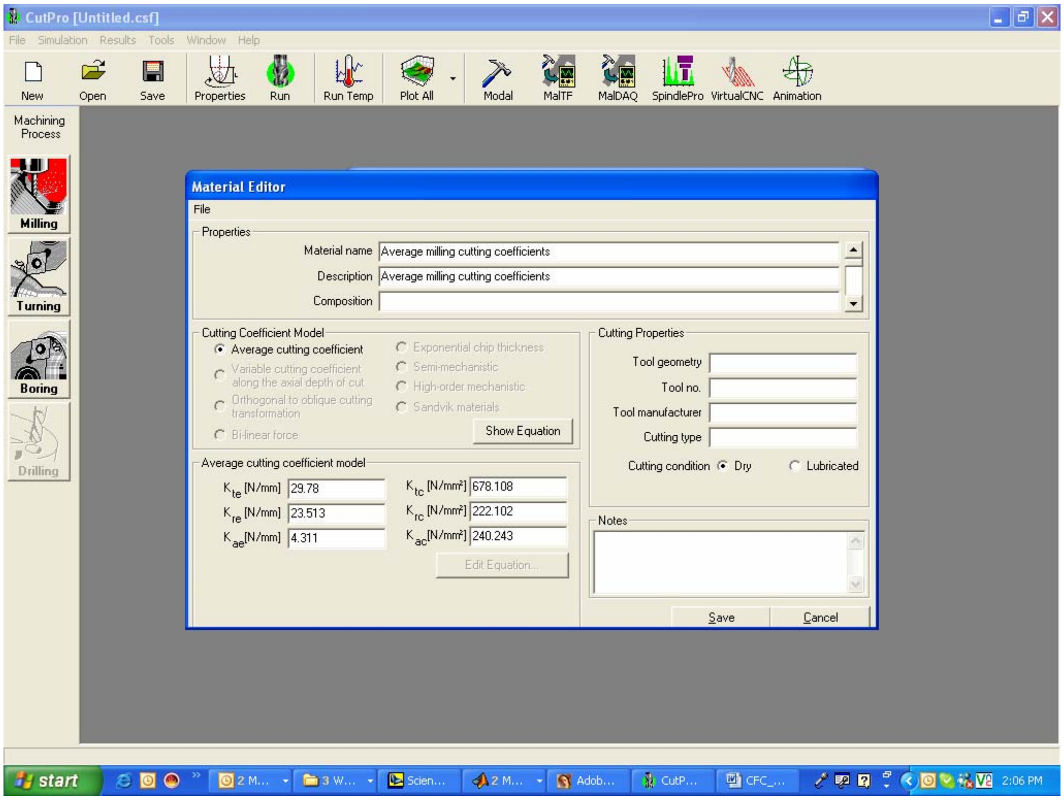


3. Select the correct measurement file, and click "Open" to upload to CutPro.



Make sure to enter the corresponding, correct feed per tooth. Than push "next -→ and select the next file and corresponding feed. Make sure that the files start with the smallest feed and increases without mixing the sequence. Once you finish loading, you need to go back (←-) and check whether all the files and feeds are entered correctly. Click the next button after you complete the file entry.

4. If you click on "OK" and "run", CUTPRO will create a temporary material data. Click on "Plot all", and you will see a graph with average, measured cutting forces. If they form a linear trend, the prediction will be good. Otherwise, the cutting coefficients may be sensitive to the insert geometry and chip load. If you click on Cutting Coefficients button on the graph's bottom menu, you will see the parameters as shown below. You can edit material and other fields as you wish except for the coefficients which are identified by CUTPRO for you. Once you push the save button, you will have user specific (material data in the CUTPRO) which can be accessed only by you.



3.1.6.2.1 AVERAGE CUTTING COEFFICIENT

The ***average cutting coefficient*** model is based on average force measurements. This is the simplest model which requires the least number of experimental measurements. You can use this model for a specific material and cutting tool geometry. In the following figure, you can see the ***Average cutting coefficient*** model frame in ***Material Editor*** window:

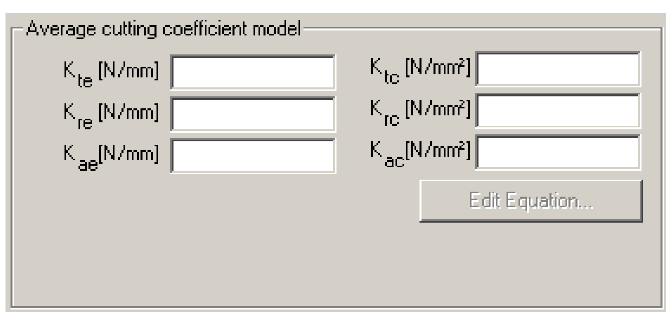


Figure 3.1-80: Average cutting coefficient model frame

The following parameters are used in order to define ***average cutting coefficient*** model:

Table 3.1-201: Parameters for Average Cutting Coefficient model

K_{te}	*Tangential edge force coefficient [N/mm]*
K_{re}	*Radial edge force coefficient [N/mm]*
K_{ae}	*Axial edge force coefficient [N/mm]*
K_{tc}	*Tangential shearing coefficient [N/mm²]*
K_{rc}	*Radial shearing coefficient [N/mm²]*
K_{ac}	*Axial shearing coefficient [N/mm²]*

- ***VARIABLE CUTTING COEFFICIENT ALONG THE AXIAL DEPTH OF CUT***

This force model is based on the **Average Cutting Coefficient** model, except the cutting coefficients vary along the axial depth of cut. In the following figure, you can see the ***Variable cutting coefficient along the axial depth of cut*** model frame in ***Material Editor*** window:

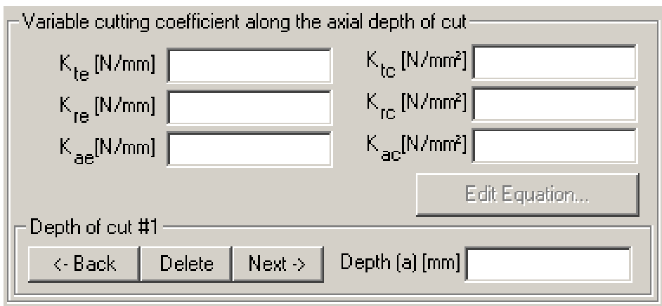


Figure 3.1-81: Variable cutting coefficient along the axial depth of cut model frame in Material Editor window

The following parameters are used in order to define ***variable cutting coefficient along the axial depth of cut*** model:

Table 3.1-212: Parameters for Variable Cutting Coefficient along the Axial Depth of Cut model

Depth (a)	*Depth of cut for which the currently displayed parameters are applicable; up to 18 depths-of-cut may be defined. Use the **Back** and **Next** buttons to move between depths-of-cut.*
Back	*Go to the previous depth of cut*
Delete	*Delete the current depth of cut*
Next	*Go to the next depth of cut*
K_{te}	*Tangential edge force coefficient [N/mm]*
K_{re}	*Radial edge force coefficient [N/mm]*
K_{ae}	*Axial edge force coefficient [N/mm]*
K_{tc}	*Tangential shearing coefficient [N/mm²]*
K_{rc}	*Radial shearing coefficient [N/mm²]*
K_{ac}	*Axial shearing coefficient [N/mm²]*

▪ ORTHOGONAL TO OBLIQUE CUTTING TRANSFORMATION

The force model is based on orthogonal cutting tests. For this model, extensive experimental tests that provide material properties which are applicable to any cutting tool geometry need to be conducted. In the following figure, you can see the ***Orthogonal to oblique cutting transformation*** model frame in the ***Material Editor*** window:

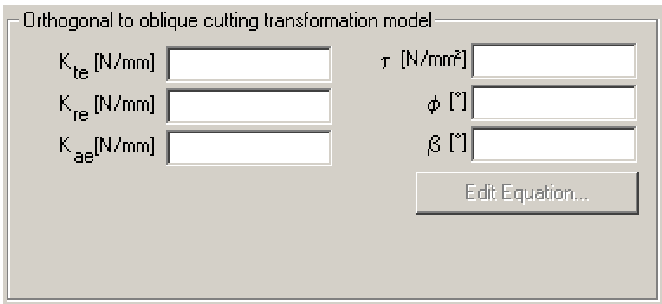


Figure 3.1-82: Orthogonal to oblique cutting transformation model frame in Material Editor window

The following parameters are used in order to define ***orthogonal to oblique cutting*** transformation model:

Table 3.1-223: Parameters for Orthogonal to oblique cutting transformation model

K_{te}	*Tangential edge force coefficient [N/mm]*
K_{re}	*Radial edge force coefficient [N/mm]*
K_{ae}	*Axial edge force coefficient [N/mm]*
τ	*Shear stress [N/mm²]*
ϕ	*Shear angle [°]*
β	*Friction angle [°]*

▪ BI-LINEAR FORCE

This force model is based on the **average cutting coefficient** model, but the ***bi-linear force*** model has two cutting coefficient regions. The first region has edge coefficients for small chip thickness, and the second region has different edge force coefficients after a certain chip thickness limit. In the following figure, you can see the ***Bi-linear force*** model frame in the ***Material Editor*** window:

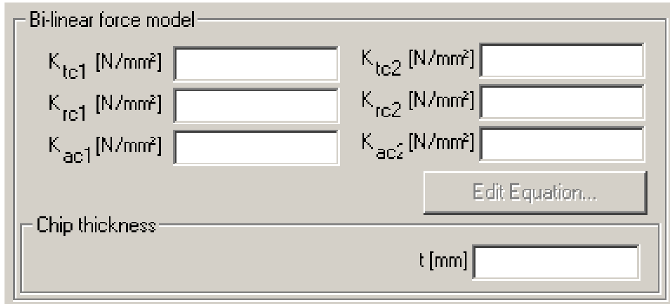


Figure 3.1-83: Bi-linear force model frame in Material Editor window

The following parameters are used in order to define ***bi-linear force*** model:

Table 3.1-234: Parameters for Bi-linear force model

K_{tc1}	*Tangential shearing coefficient (1) [N/mm²]*
K_{rc1}	*Radial shearing coefficient (1) [N/mm²]*
K_{ac1}	*Axial shearing coefficient (1) [N/mm²]*
K_{tc2}	*Tangential shearing coefficient (2) [N/mm²]*
K_{rc2}	*Radial shearing coefficient (2) [N/mm²]*
K_{ac2}	*Axial shearing coefficient (2) [N/mm²]*
t	*Boundary chip thickness, at which parameters (1) change to parameters (2) [mm]*

- ***EXPONENTIAL CHIP THICKNESS***

The cutting coefficients are exponentially related to chip thickness. In the following figure, you can see ***Exponential chip thickness*** model frame in ***Material Editor*** window:

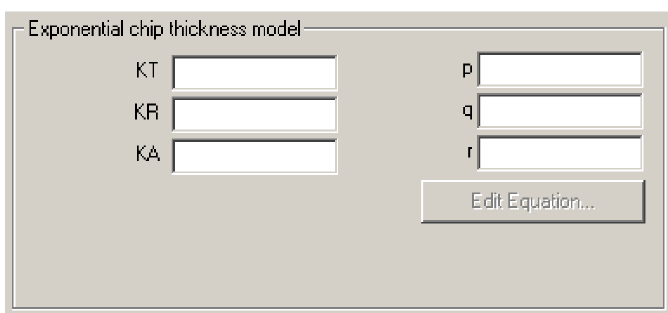


Figure 3.1-84: Exponential chip thickness model frame in Material Editor window

The following parameters are used in order to define ***exponential chip thickness*** model:

Table 3.1-245: Parameters for Exponential chip thickness model

KT	*Tangential shearing coefficient parameter*

KR Radial shearing coefficient parameter
KA Axial shearing coefficient parameter
p Tangential chip thickness order
q Radial chip thickness order
r Axial chip thickness order

SEMI_MECHANISTIC

The cutting coefficients are functions of two main coefficients and the geometry of the tool.

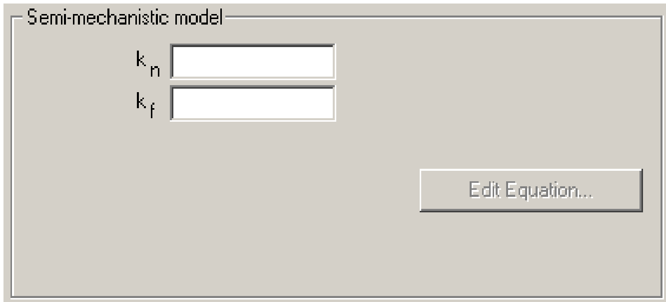


Figure 3.1-85: Semi-mechanistic model frame in Material Editor window

The following parameters are used in order to define the ***semi-mechanistic*** model:

Table 3.1-256: Parameters for Semi-mechanistic model

k_n	*cutting pressure on rake face [N/mm²]*
k_f	*cutting pressure rate on flank face*

- **HIGHER-ORDER MECHANISTIC**

The ***higher-order mechanistic*** model is based on the **average cutting coefficient** model, but the coefficients change based on the polynomial order of chip thickness.

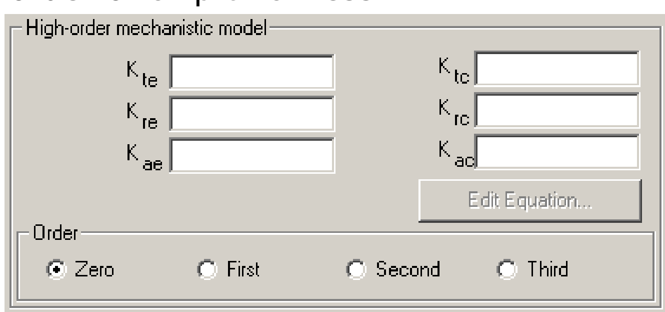


Figure 3.1-86: Higher-order mechanistic model frame in Material Editor window

The following parameters define the high-order mechanistic model:

Table 3.1-267: Parameters for Higher-order mechanistic model

Order	*Zero-, first-, second- or third-order*

K_{te} *Tangential edge force coefficient [N/mm]*
K_{re} *Radial edge force coefficient [N/mm]*
K_{ae} *Axial edge force coefficient [N/mm]*
K_{tc} *Tangential shearing coefficient [N/mm²]*
K_{rc} *Radial shearing coefficient [N/mm²]*
K_{ac} *Axial shearing coefficient [N/mm²]*

After you define the parameters, click on ***Save*** button to save the values you entered, or click on ***Cancel*** button to cancel and close ***Material Editor*** window without saving the parameters.

When you click on ***View*** button in order to see the specifications of the workpiece material, the following ***Material Editor*** window shows up:

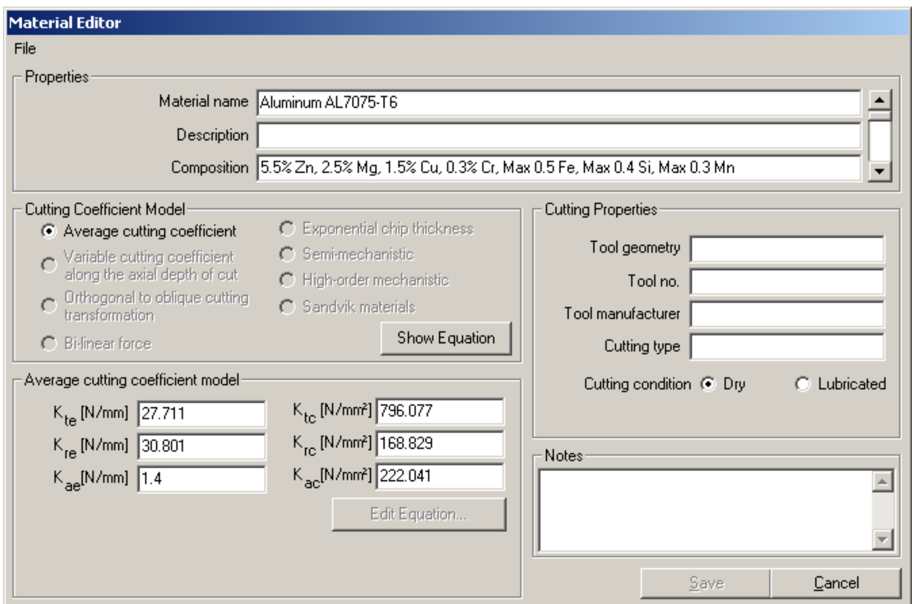


Figure 3.1-87: Material Editor window for Fixed Materials

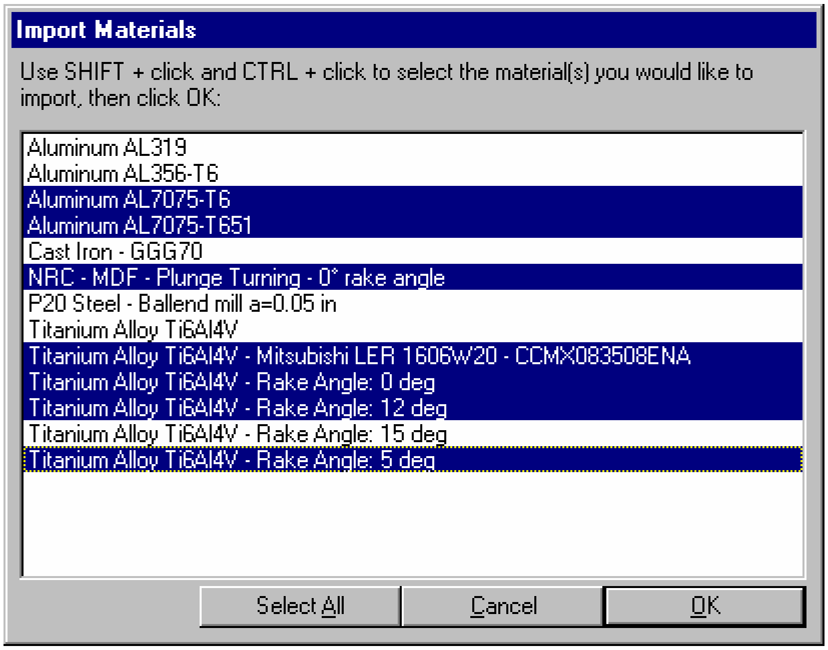


Figure 3.1-88: the Import Materials window. Several materials are selected by clicking with the Ctrl key.

⚠ **If you press Cancel on the Properties window, any changes you have made to the materials will be lost.**

⚠ **Below, you can find short descriptions of material force model listed on this tab.**

You can see the definition of any selected model by clicking ***Show Equation*** button.

Under each model presented above, you will be finding predefined material data. If the material you wish to simulate is not in any material list you can identify the material data by simply doing average cutting coefficient identification. Note that you can also define the material data in any model you wish using ***NEW*** button. When you click NEW button Material Editor Window will show up. You can now enter the equations of cutting coefficients or parameters by using ***Equation Editor***. Note that each force model has its own definition. You can see this by clicking ***Show Equation***. If you wish to add a new material in any model, the equation must meet the definition of the model specified in ***Equation*** window.

⚠ **Note: You can put in additional information regarding the test conditions, under which you developed the data, material's technical specifications and etc.**

3.1.7 WORKPIECE/STRUCTURAL FLEXIBILITY TAB

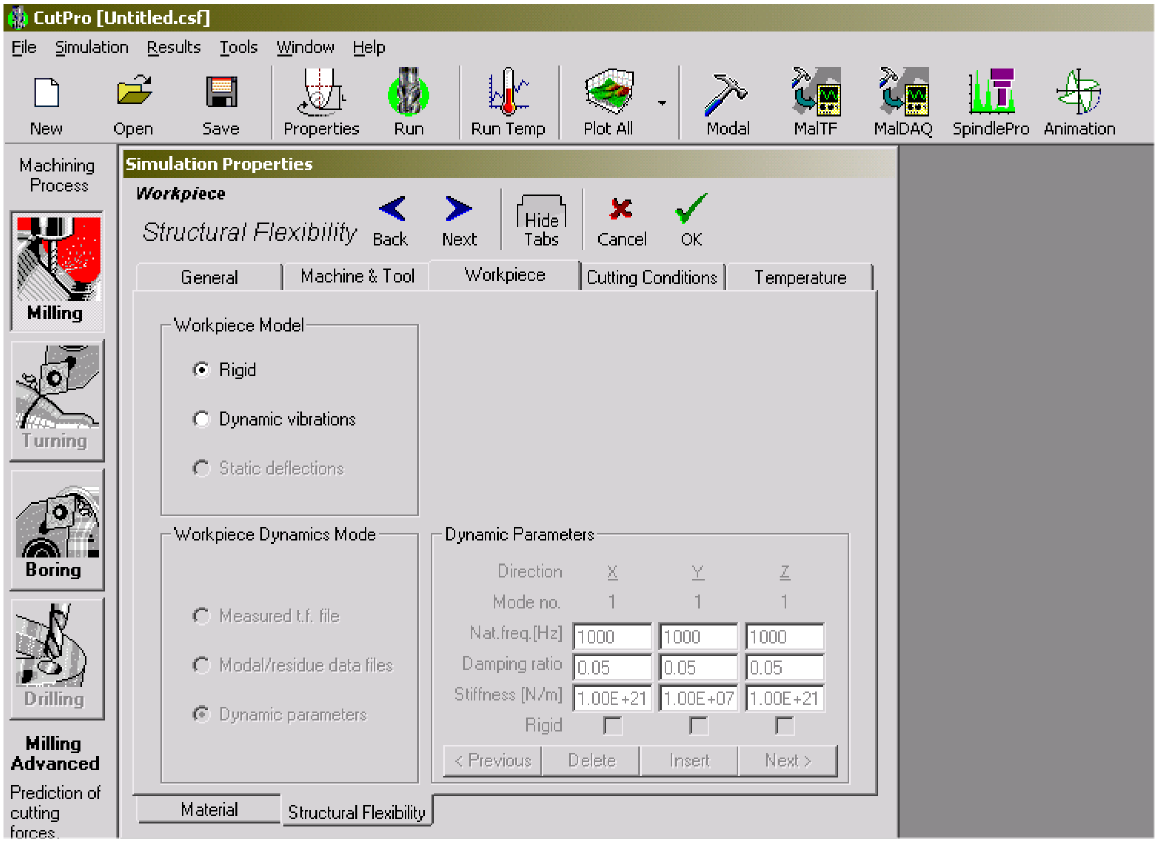


Figure 3.1-89: The Workpiece/Structural Flexibility tab

This tab is the same as the one on Section 3.1.5 MACHINE & TOOL/STRUCTURAL FLEXIBILITY TAB on page 89.

3.1.8 CUTTING CONDITIONS/MILLING MODE TAB

You can define milling modes on this tab. Depending on the tool type you specify on ***MACHINE & TOOL/CUTTER TYPE TAB*** the parameters on this tab could be different. In the following you will be finding the parameters for each tool type. The different tool types are ***Cylindrical Endmil***l, ***Ball Endmill***, ***General Endmil***l, and ***Indexable Cutter***.

3.1.8.1 CYLINDRICAL ENDMILL

The following modes are available for cylindrical endmill.

- Down milling
- Up milling
- Slotting

- Face milling

For each mode you define cutting parameters (i.e. Feed Rate [mm/flute], Spindle speed [rpm], Axial Depth of Cut [mm] and etc.) as well as radial width of cut. Note that some parameters are linked to each other and calculated automatically based on the others, such as Spindle speed, surface speed and Material removal rate.

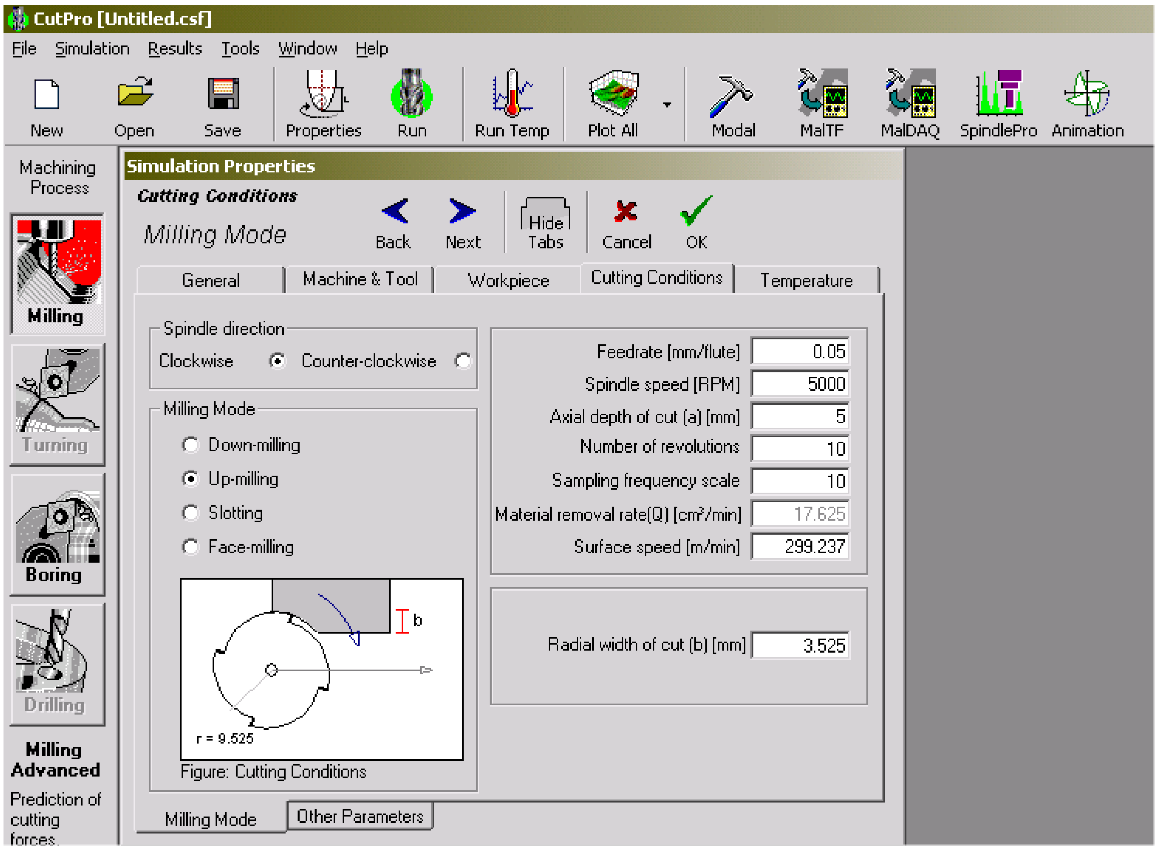


Figure 3.1-90: The Cutting Conditions/Milling Mode tab

- Enter the feed rate of the cutting operation as **[mm/tooth]**.

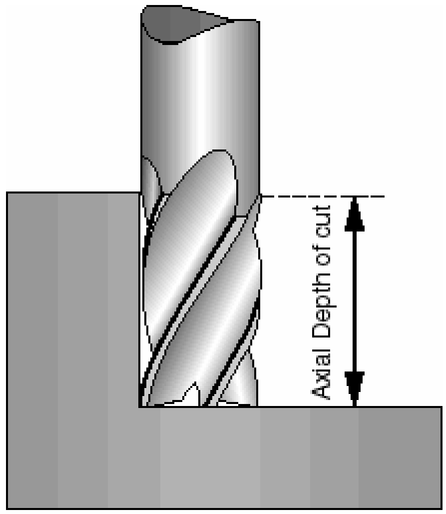
  If the feed rate is in **[mm/min]**, use the following equation to convert,

$$(\text{feedrate}[\text{mm/tooth}]) = \frac{(\text{feedrate}[\text{mm/min}])}{(\text{numberof flute}) * (\text{spindlespeed}[\text{rev/min}])}$$

If you have a non-uniform pitch cutter, your feed rate will be calculated as follows,

$$\left(\text{feedrate}[\text{mm/tooth}]\right) = \frac{\left(\text{entered feedrate}[\text{mm/tooth}]\right) * \left(\text{number of flute}\right) * \left(\text{pitch angle}[\text{degree}]\right)}{360}$$

- Enter the Spindle Speed in RPM. Available only for certain simulations.
- Enter the Axial Depth of Cut.



- Enter the number of revolutions. Available only for certain simulations.
- Enter the sampling frequency scale. Available only for certain simulations.
- Enter the Material Surface Removal rate and Surface Speed. Available only for certain simulations.
- Enter the value of radial width of cut based on the following milling mode description starting from Section 3.1.8.

3.1.8.1.1 DOWN-MILLING

Radial width of cut	*Distance from the top of the workpiece to the lower edge of the cutter. Must be a positive value.*

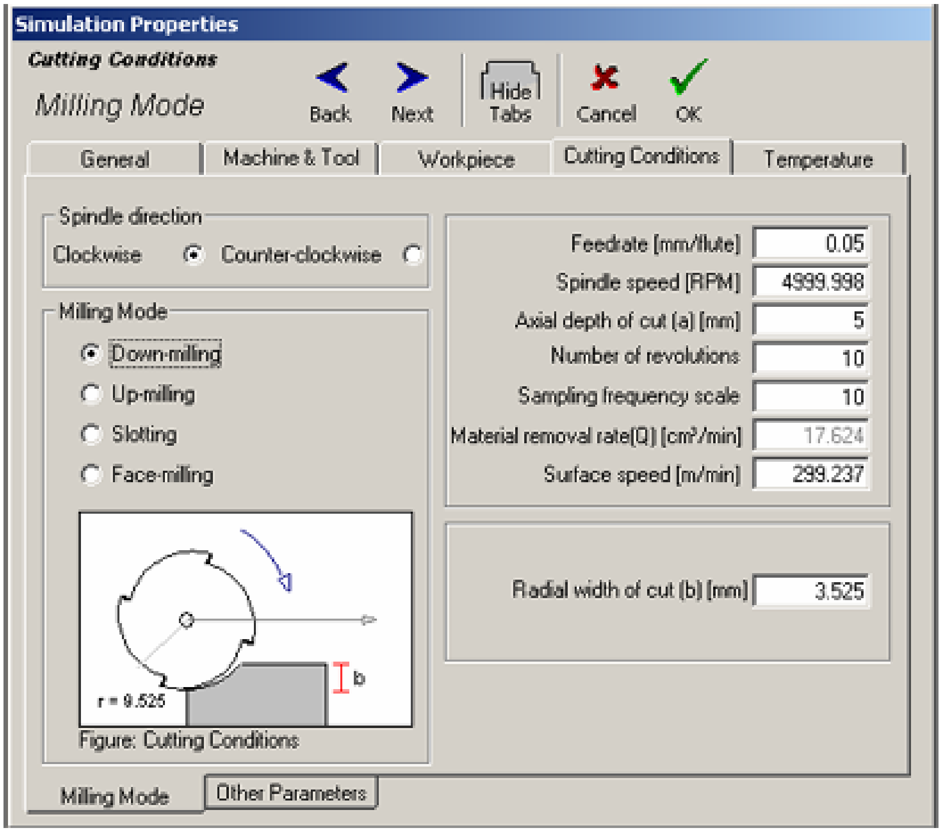


Figure 3.1-91: The Cutting Conditions/Milling Mode tab. Down-milling is selected in this figure.

3.1.8.1.2 UP-MILLING

Radial width of cut	*Distance from the bottom of the workpiece to the upper edge of the cutter. Must be a positive value.*

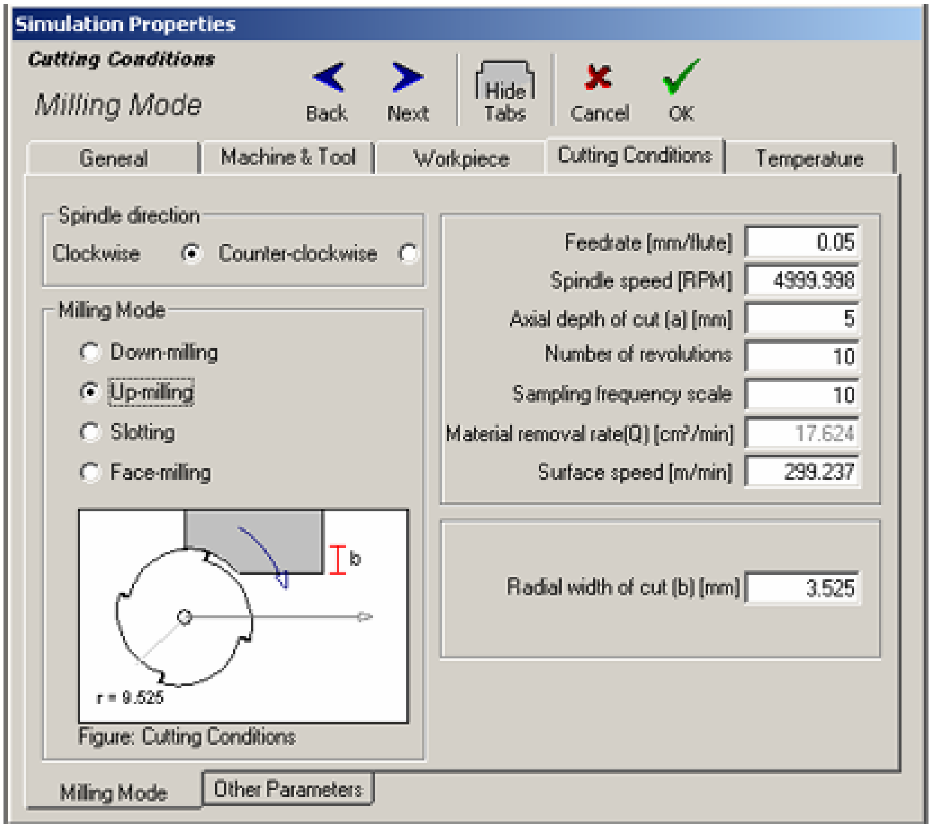


Figure 3.1-92: The Cutting Conditions/Milling Mode tab. Up-milling is selected in this figure.

3.1.8.1.3 SLOTTING

As the tool has full contact with the workpiece for this milling mode ***Radial width of cut*** is equal to the diameter of the tool and text box for radial width of cut is not available.

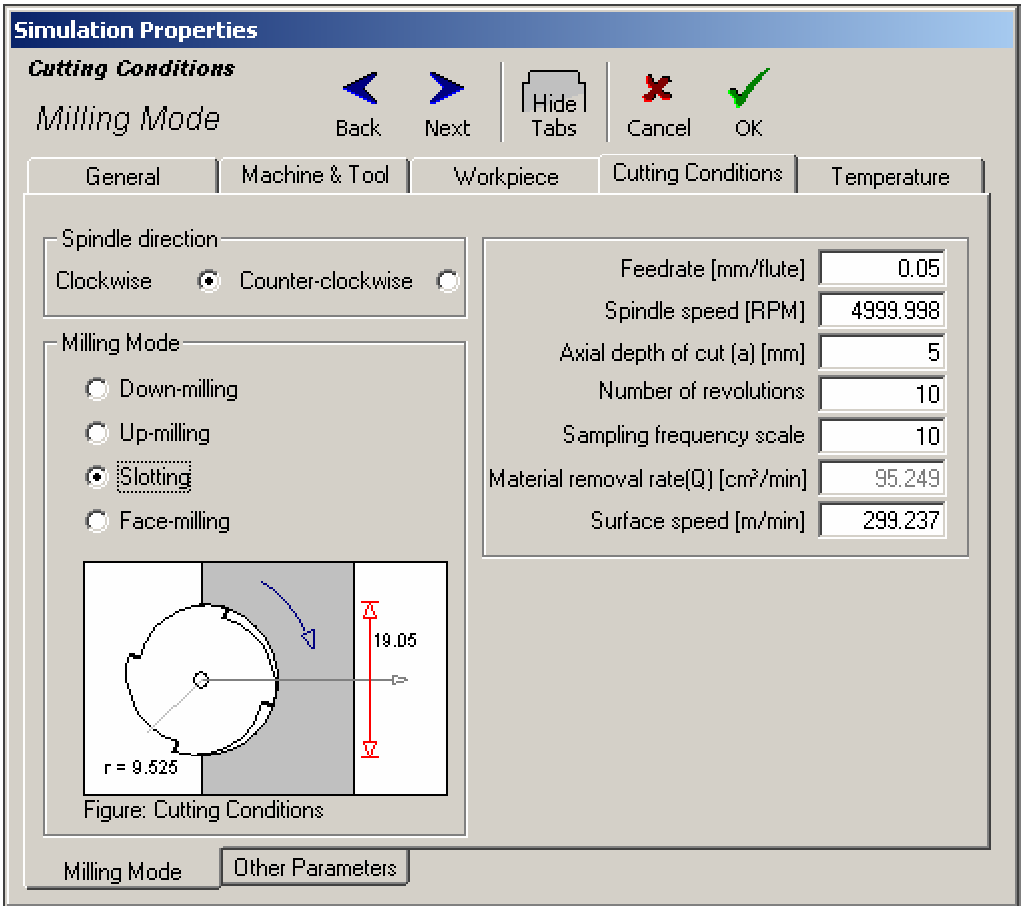


Figure 3.1-93: The Cutting Conditions/Milling Mode tab. Slotting is selected in this figure.

3.1.8.1.4 FACE-MILLING

You have two options to define the width of cut for this mode. You can either enter ***Entrance*** and ***Exit*** angle of the process or enter the value of b_1 and b_2, which are the distance of the tool center to two ends of workpiece, leading the width of cut with the following equation. These parameters are displayed on the side-figure when you click inside of the text boxes.

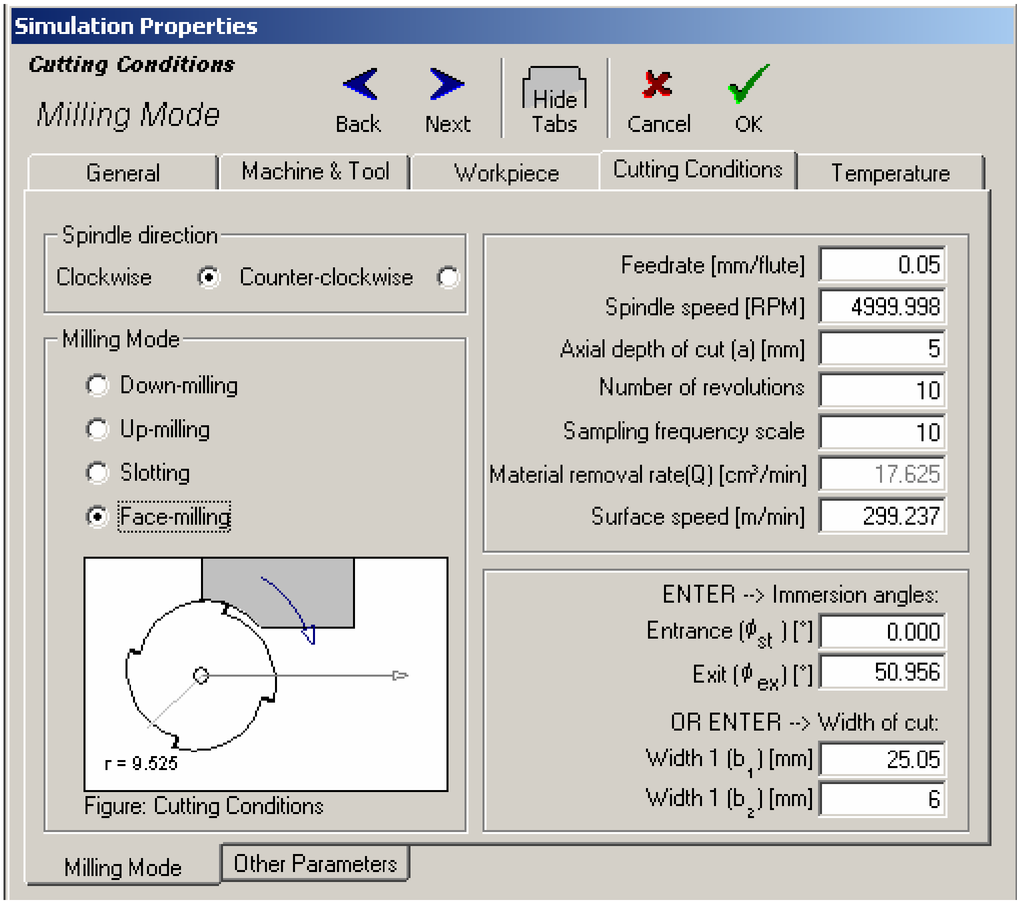


Figure 3.1-94: The Cutting Conditions/Milling Mode tab. Face-milling is selected in this figure.

3.1.8.2 BALL ENDMILL

The cutting parameters are the same for this tool as the regular cylindrical one. However, there is no selection for milling mode and the width of cut is defined through ***Workpiece width(w)*** and ***Y-Offset (y)***.

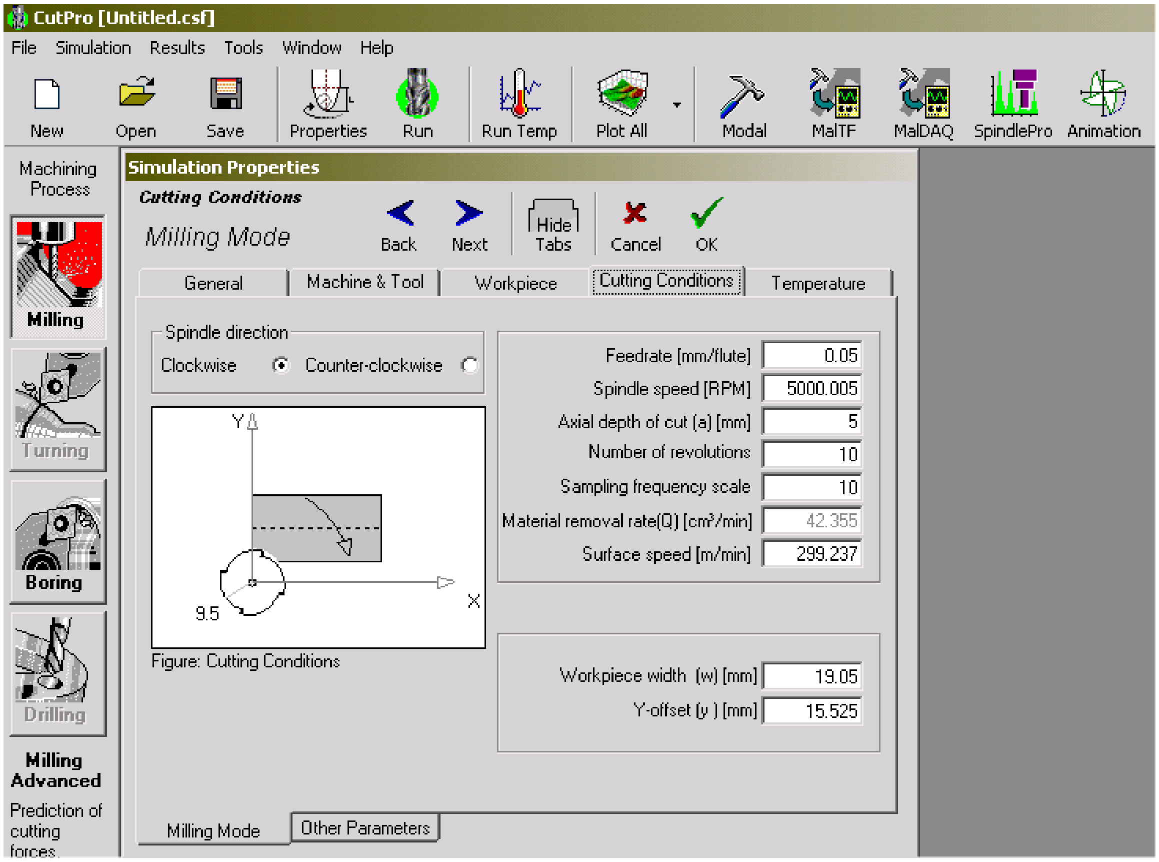


Figure 3.1-95: Cutting Conditions / Milling Mode tab

The relation between the width of cut and w and y can be shown as follows.

- If $y \geq R$

$$WOC = {}^{w}\!/_{2} + R - y$$

-If $y < R$

$$WOC = w$$

where *R* and *WOC* are the radius of the tool and width of cut respectively.

3.1.8.3 GENERAL ENDMILL

Parameters are the same as in Ball Endmill.

3.1.8.4 INDEXABLE CUTTER

Parameters are the same as in Ball Endmill.

3.1.9 CUTTING CONDITIONS/OTHER PARAMETERS TAB

The cutting conditions parameters in this section vary depending on the simulation mode selected (*under the General Tab*). Refer to the pages on a specific simulation mode for details.

3.1.9.1 SIMULATION MODES

3.1.9.1.1 SINGLE TIME DOMAIN

For this simulation mode there is no other parameter to be defined.

3.1.9.1.2 STABILITY LOBES IN TIME DOMAIN

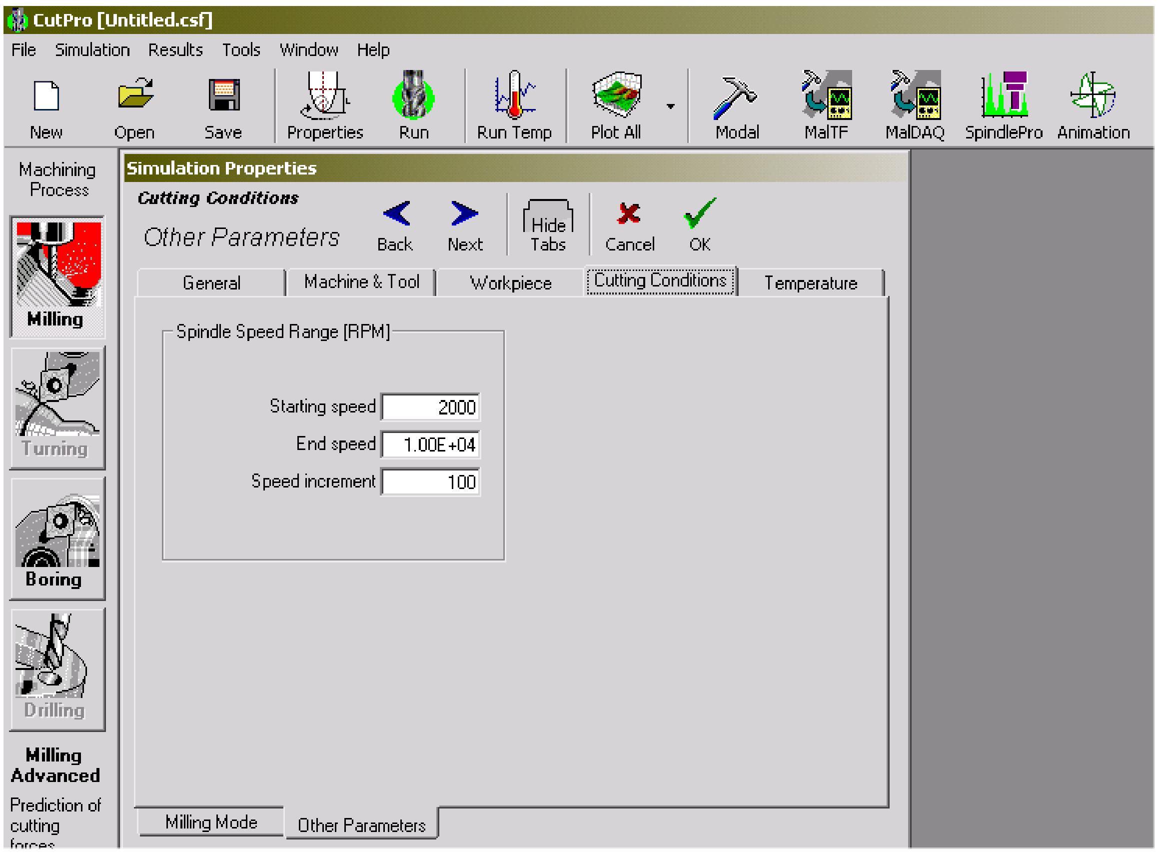


Figure 3.1-96: Cutting Conditions/Other Parameters tab in Stability Lobes in Single Time Domain simulation mode

For this simulation mode you will define Spindle Speed Range for the time domain simulation on this tab. You can see the brief definition of these parameters in the following.

Starting Speed	*This is the spindle speed you wish to start your time domain simulation*
End Speed	*This is the spindle speed you wish to end your*

	time domain simulation
Speed Increment	*This is the spindle speed increment at which the simulation is executed.*

⚠ **Note that depending on the selected speed range and speed increment the simulation time may vary.**

3.1.9.1.3 SINGLE ANALYTICAL STABILITY LOBES

For this simulation mode there is no other parameter to be defined.

3.1.9.1.4 MULTIPLE ANALYTICAL STABILITY LOBES

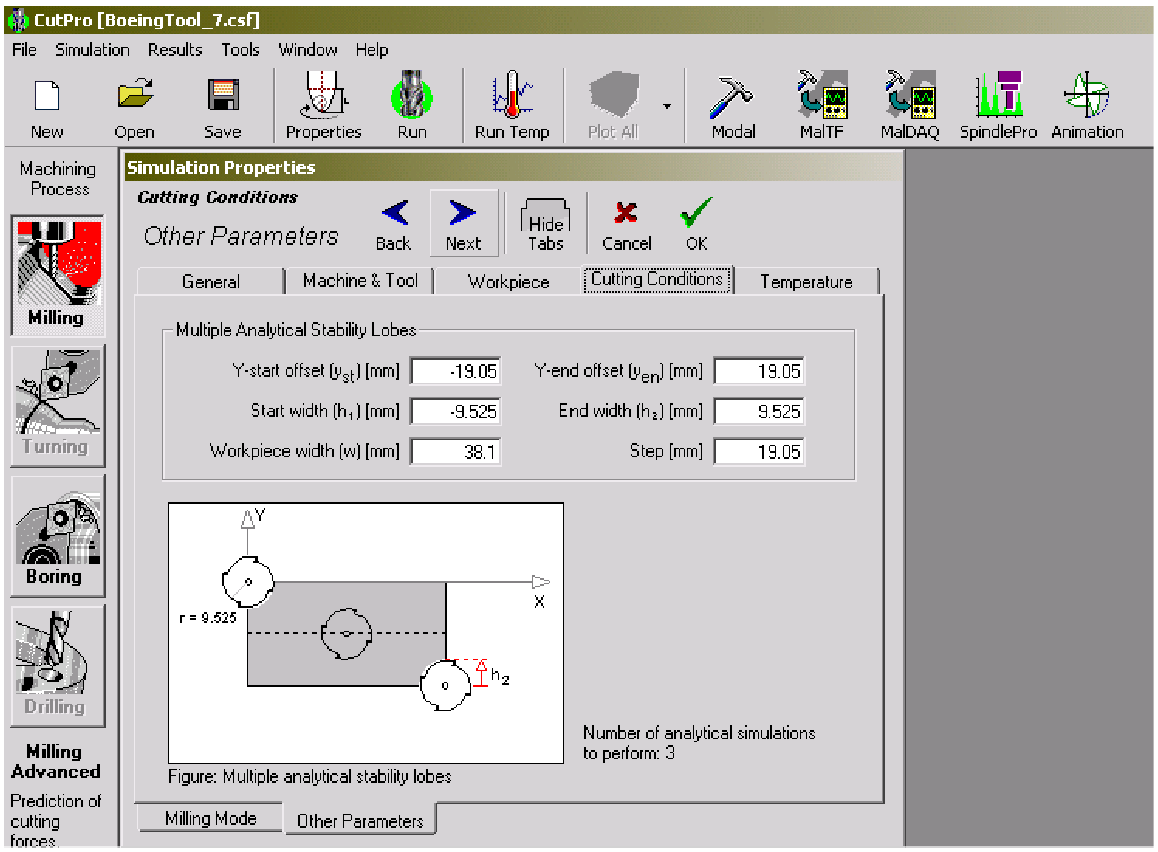


Figure 3.1-97: Cutting Conditions/Other Parameters tab for Multiple Analytical Stability Lobes simulation mode

For this simulation mode you will define simulation steps on this tab. You can see the brief definition of these parameters, which have to be defined, in the following.

Y-start offset (y_{st})	*Defines the starting position of the tool, as measured from the center of the cutter to*

	the center of the workpiece. A negative value positions the tool above the middle of the workpiece; a positive value positions the tool below the middle of the workpiece.
Start width (h_1)	*Alternatively defines the starting position of the tool. If positive, the value is the distance from bottom of the workpiece to the top edge of the cutter; if negative, the value is the distance from the top of the workpiece to the bottom edge of the cutter.*
Workpiece width (w)	*The width of the workpiece. Changing this value may result in automatic changes in the other parameters.*
Y-end offset (y_{en})	*Defines the ending position of the tool, as **Y-start offset** (above).*
End width (h_2)	*Alternatively defines the ending position of the tool, as **Start width** (above).*
Step	*Defines the vertical distance between steps in the simulation. The total number of steps is determined by **Step** as well as the **difference** between **Y-start offset** and **Y-end offset** by dividing **difference / Step**.*

⚠ **All parameters are subject to certain value restrictions. If you enter an invalid number, you will be asked to change it.**

⚠ **Click on the Show/Hide Simulation button to see a graphical representation of the simulation parameters.**

3.1.9.2 OPTIMIZE VARIABLE PITCH

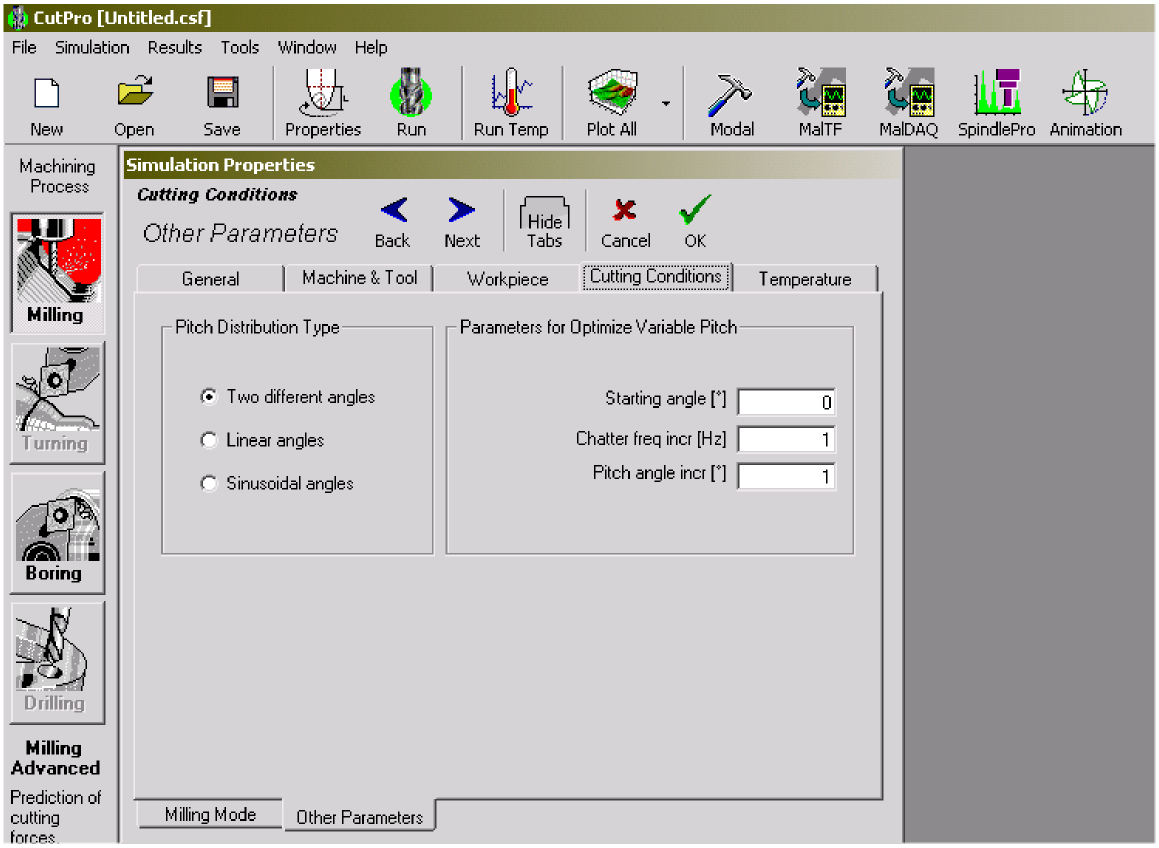


Figure 3.1-98: Cutting Conditions/Other Parameters tab for Optimize Variable Pitch simulation mode

For this simulation mode you will define Pitch Distribution Type and Parameters for Optimize Variable Pitch. You can see the brief definition of these parameters in the following.

Two different angles	*Only two pitch values are used, and are alternated around the cutter (e.g., 30°, 60°, 30°, 60°, etc.)*
Linear angles	*Variation in the pitches is assumed to be linear (e.g., 30°, 45°, 60°, 75°, etc.)*
Sinusoidal angle	*Variation in the pitches is assumed to be sinusoidal.*

Starting angle	The angle at which the simulation starts scanning for the first pitch.
Chatter freq incr.	Increment in chatter frequency.
Pitch angle incr.	Increment in pitch angle.

3.1.9.3 CUTTING COEFFICIENT IDENTIFICATION

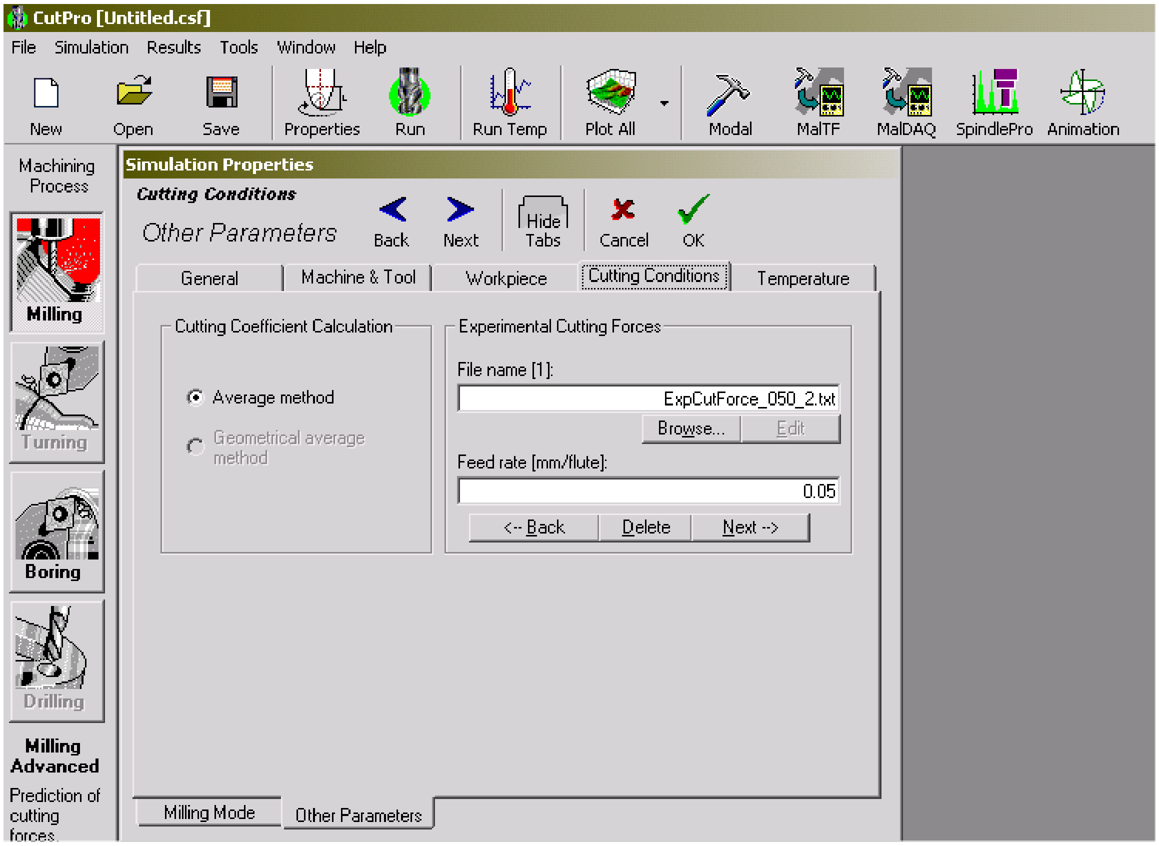


Figure 3.1-99: Cutting Conditions/Other Parameters in Cutting Coefficient Identification simulation mode

For this simulation mode you will load the measurement files one by one specifying the feed rates of each condition. You can see the brief description of the buttons and methods in the following.

Average method	*This is the only cutting coefficients calculation method currently available, based on an average cutting coefficients model (experimental cutting forces from milling).*
Geometrical average method	*This is not currently available.*

File name	*File containing data on experimental cutting forces, at the feed rate specified. Experimental cutting force data file must be in ASCII format as follows,*

	First column is Fx
	Second column is Fy
	Third column is Fz
	The experimental cutting force length should be exact number of revolution (1, 2 or more)
	Unit is Newton
Feed rate	*Feed rate for the current experimental cutting forces file.*
Back	*Go to the previous File name / Feed rate.*
Delete	*Delete the current File name / Feed rate.*
Next	*Go to the next File name / Feed rate.*

3.1.10 TEMPERATURE/PROPERTIES TAB

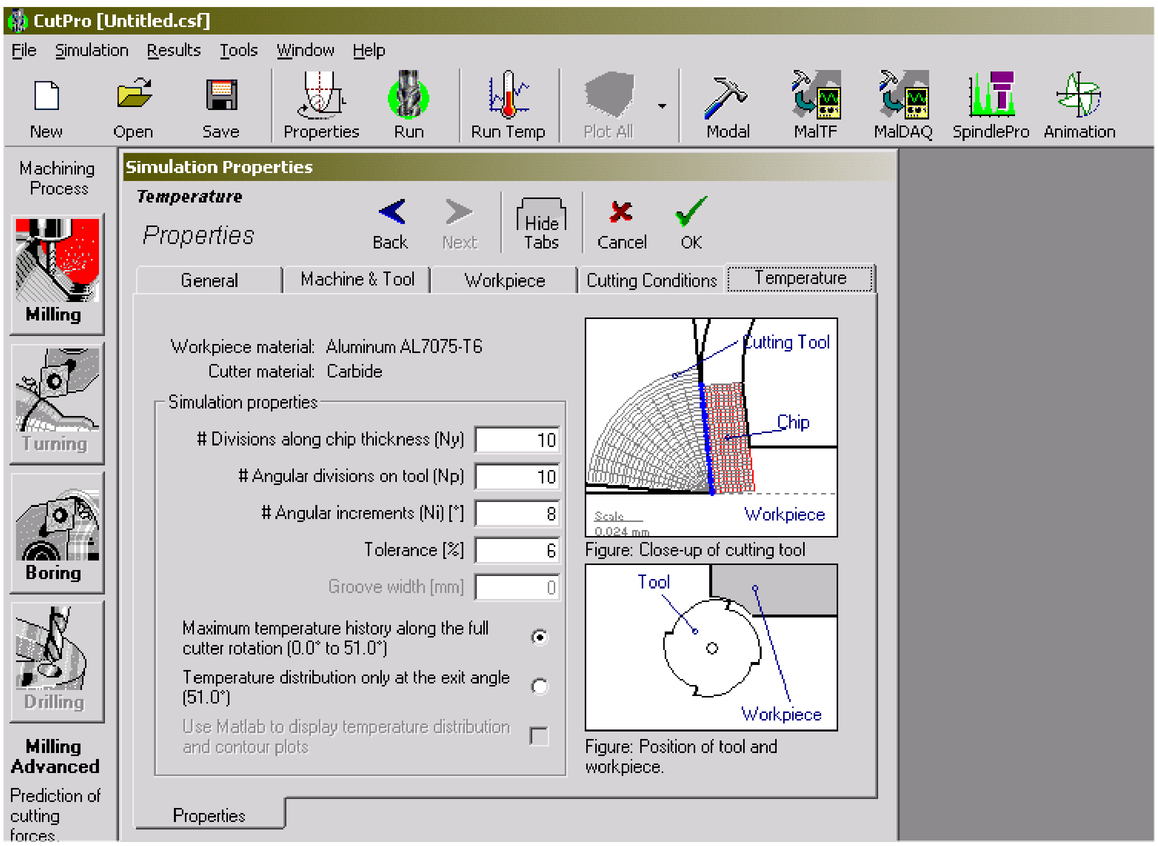


Figure 3.1-100: Temperature / Properties tab

This tab was prepared for only Temperature simulation and is independent of milling and boring simulations. You can find the brief description of the simulation parameters in the following.

# Divisions along chip thickness (Ny)	*The temperature simulation breaks the chip cross-section into a square grid. This defines how many*

	sections there are along the chip thickness; thus, it also determines the number of divisions along the contact length.
# Angular divisions on tool (Np)	*The temperature simulation breaks the cutter cross-section into an angular grid. This defines how many angular sections there are between the rake face and the clearance edge.*
# Angular increments (Ni) [°]	*Applies to milling only. If maximum temperature history along the full cutter rotation (below) is selected, this defines in how many increments the temperature simulation calculates the cutter temperature, along the cutter rotation.*
Tolerance [%]	*The temperature simulation converges the temperature along the rake face with the matching temperature along the contact length of the chip. This defines the maximum allowed difference between these two temperatures.*
Groove width [mm]	*Applies to turning only. This defines the width of a groove, if any, in the workpiece.*
Workpiece diameter [mm]	*Applies to turning only. This defines the diameter of the rotating workpiece.*
Maximum temperature history along the full cutter rotation	*Applies to milling only. If checked, temperature is calculated at a series of increments along the cutter rotation (see above).*
Temperature distribution only at the exit angle	*Applies to milling only. If checked, temperature distribution is calculated for the chip and cutter, and the exit angle only.*
Use MatLab to display temperature distribution and contour plots	*Applies to milling only. If checked, results for tool and chip temperature distribution are enabled. You must have MatLab installed in order to view these*

results.

3.2 PLUNGE MILLING MODULE

3.2.1 GENERAL/SIMULATION MODE TAB

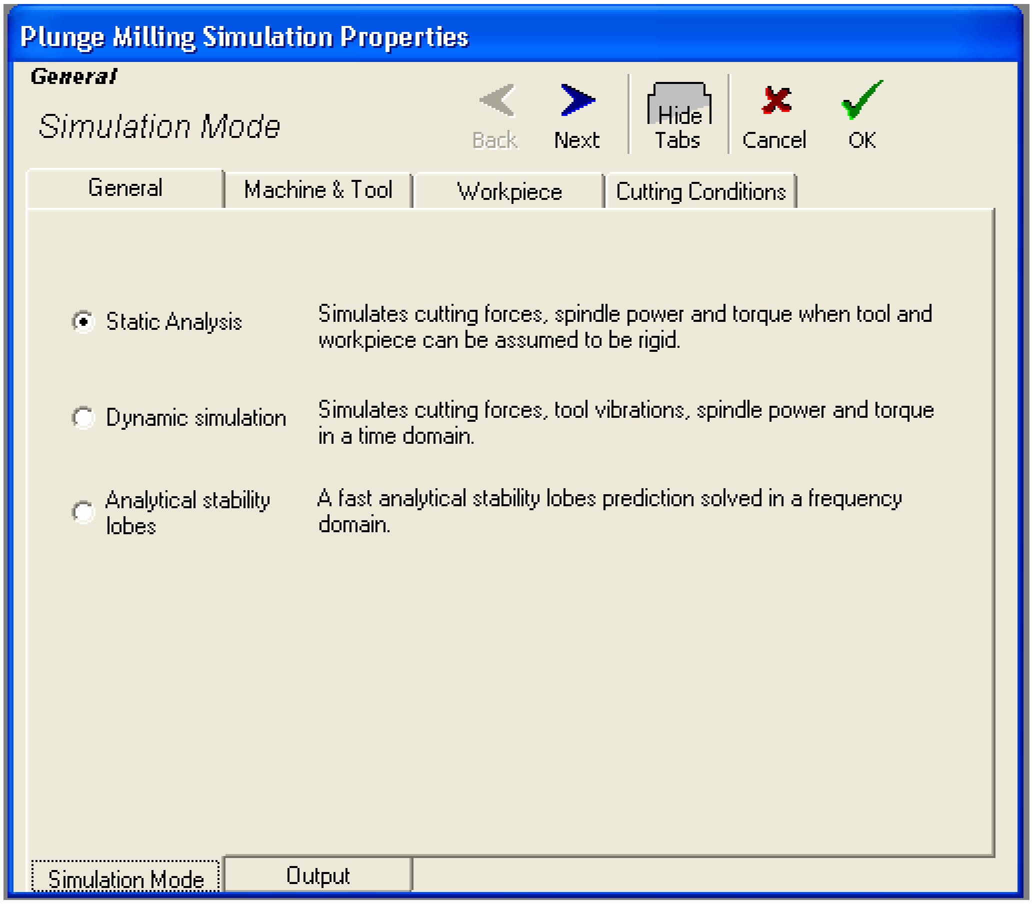


Figure 3.2-1: General/Simulation Mode tab in Plunge Milling module

This tab allows you to choose the simulation mode. There are three simulation modes available: ***Static Analysis***, ***Dynamic Simulation***, and ***Analytical Stability Lobes***.

3.2.2 GENERAL/OUTPUT TAB

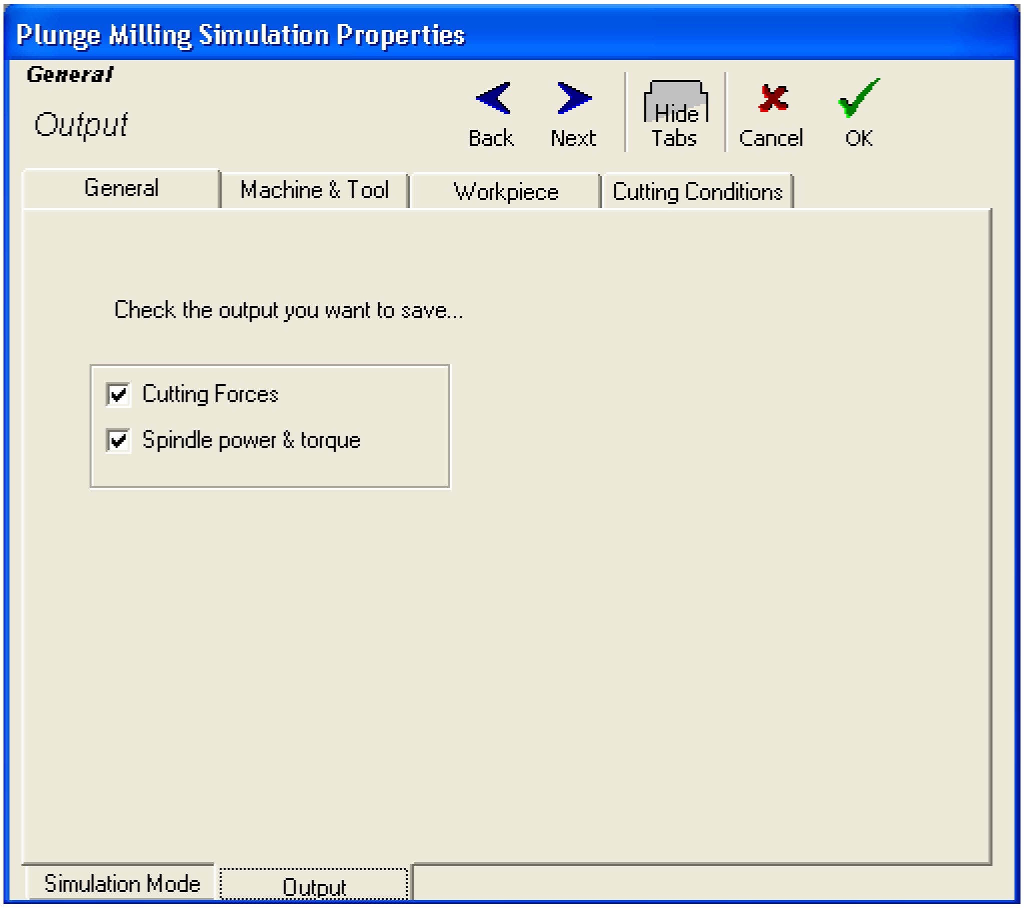


Figure 3.2-2: General/Output tab in Plunge Milling module

This section allows you to specify which results you want CutPro to output in simulation. To include a result in the simulation output, check the box next to it.

3.2.3 MACHINE & TOOL/TOOL TYPE TAB

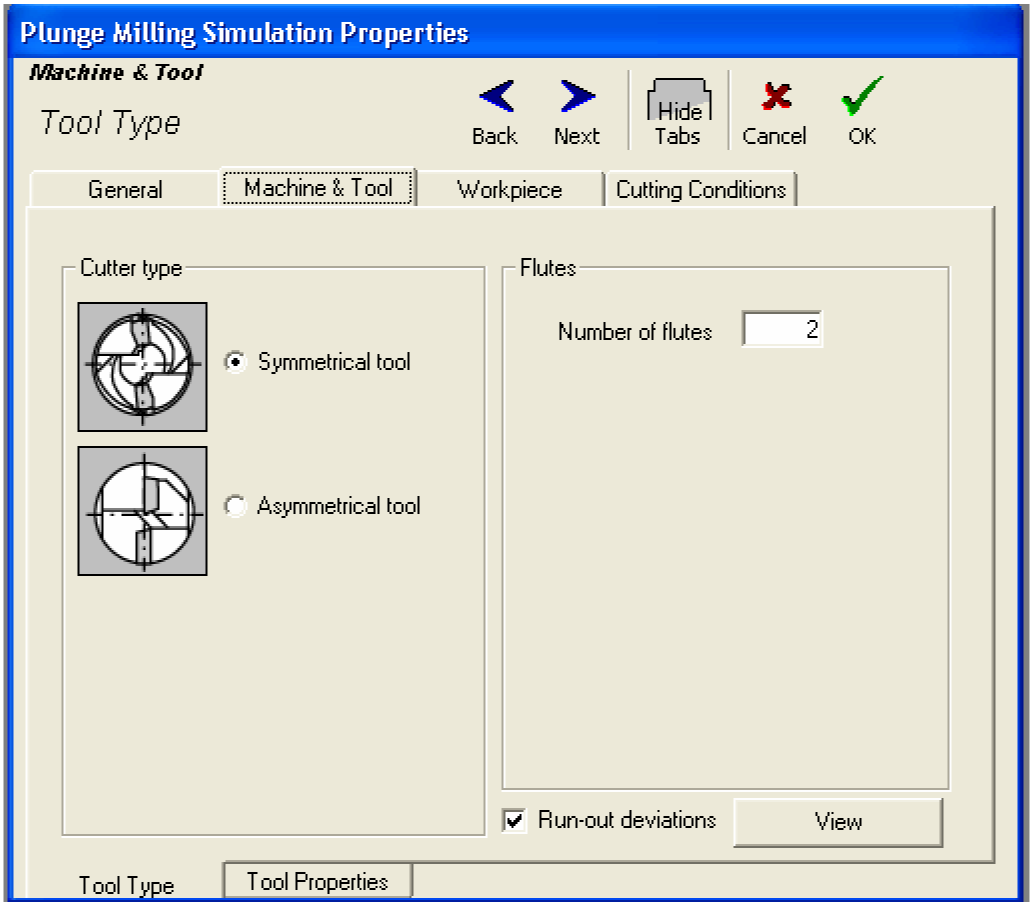


Figure 3.2-3: Machine & Tool / Tool Type tab in Plunge Milling module

This tab allows you to choose the cutter type, to define number of flutes and run-out deviations.

3.2.3.1 TOOL TYPE

There are two options for the tool type: ***Symmetrical tool*** and ***Unsymmetrical tool***. When you choose the tool type, a figure will show general look of the selected tool on the right hand side of the ***Simulation Properties***. The figure will also help you visualize the parameters on the tool when you change them on the ***Tool Properties*** tab.

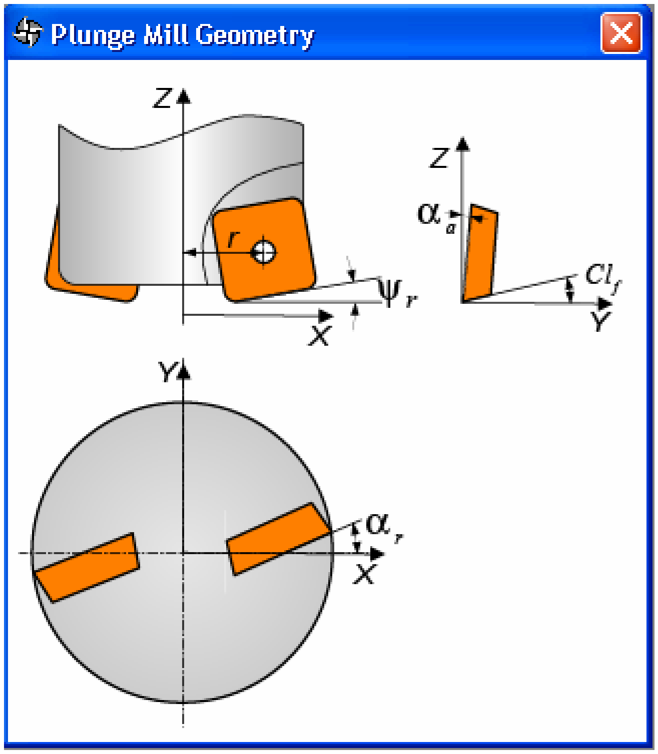


Figure 3.2-4: Symmetrical tool in Plunge Milling module

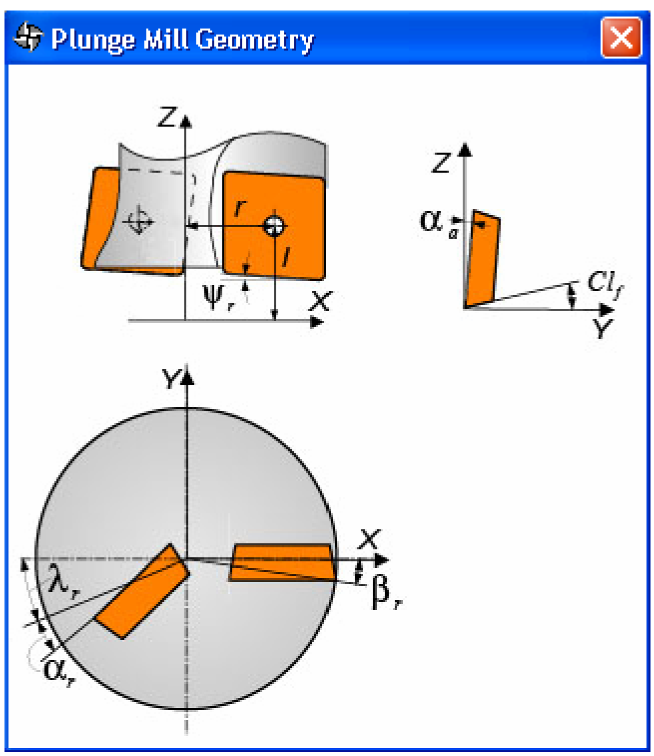
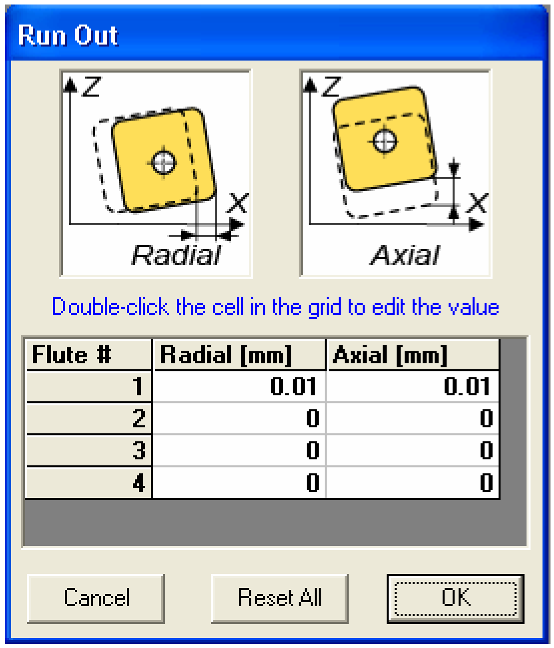


Figure 3.2-5: Unsymmetrical tool in Plunge Milling module

3.2.3.2 RUN-OUT DEVIATIONS OF FLUTES

You can define the radial and axial run-out deviations of each flute. Click the ***View*** button to open the ***Run-out Window***, and in the Run-out window double-click the cell in the grid of which you want to edit the value. You can edit the run-out deviation in the opened edit window.



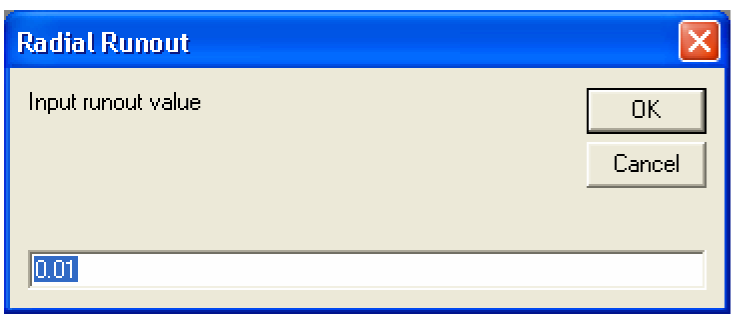


Figure 3.2-6: Run-out edit windows in Plunge Milling module

3.2.4 MACHINE & TOOL/TOOL PROPERTIES TAB

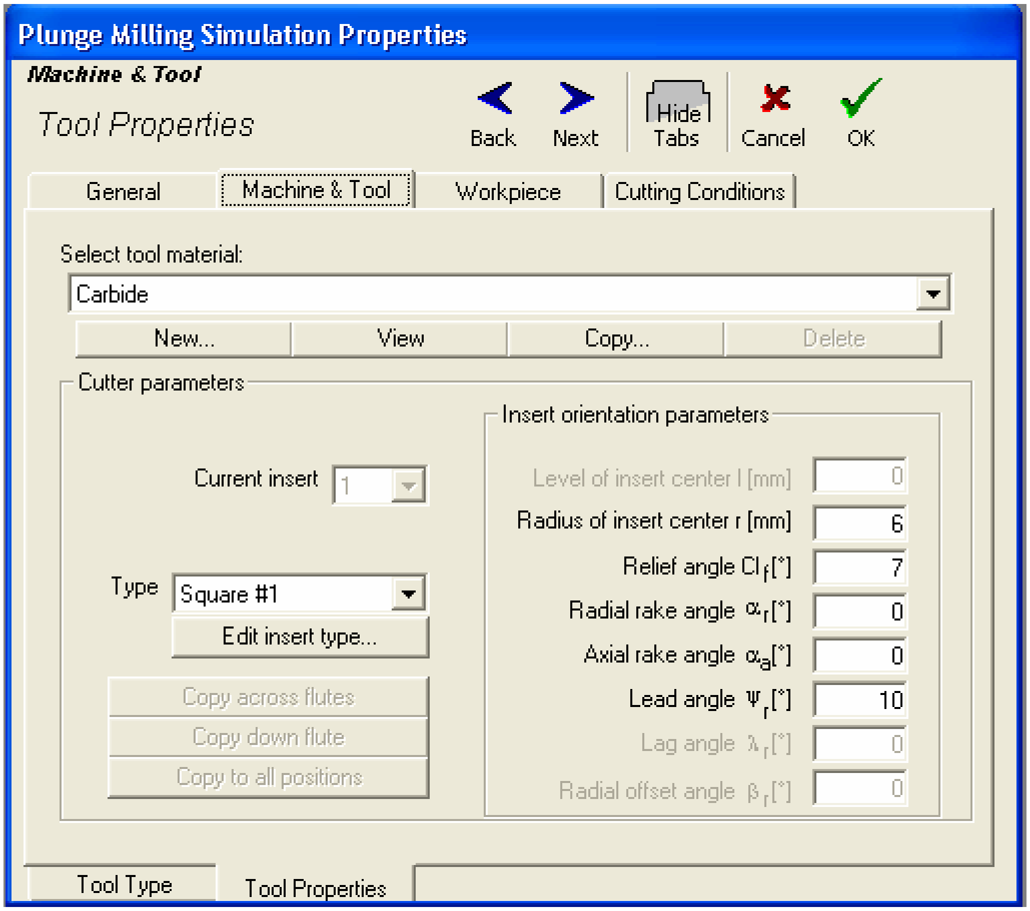


Figure 3.2-7: Machine & Tool/Tool Properties in Plunge Milling

This tab allows you to select or define tool material and enter tool properties. In this tab only the necessary parameters for the selected tool type are enabled.

3.2.4.1 SELECT A CUTTER MATERIAL

For selecting and defining a tool material, refer to ***3.1.4.1 Select a Cutter Material***.

3.2.4.2 TOOL PROPERTIES

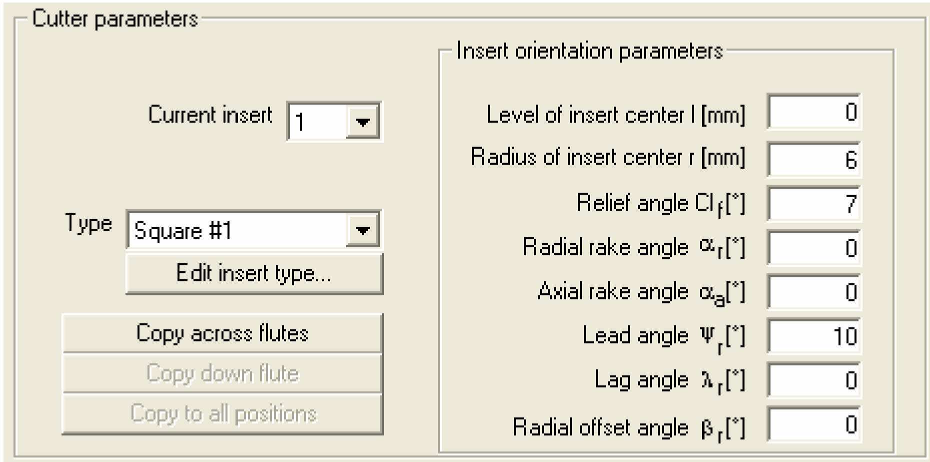


Figure 3.2-8: Tool Properties in Machine & Tool/Tool Properties tab

In the ***Machine & Tool/Tool Properties*** tab, you can define the type of insert and parameters of each flute. You can choose ***No Insert***, ***Square Insert*** or ***Rhombic Insert*** and define geometrical parameters of the insert.

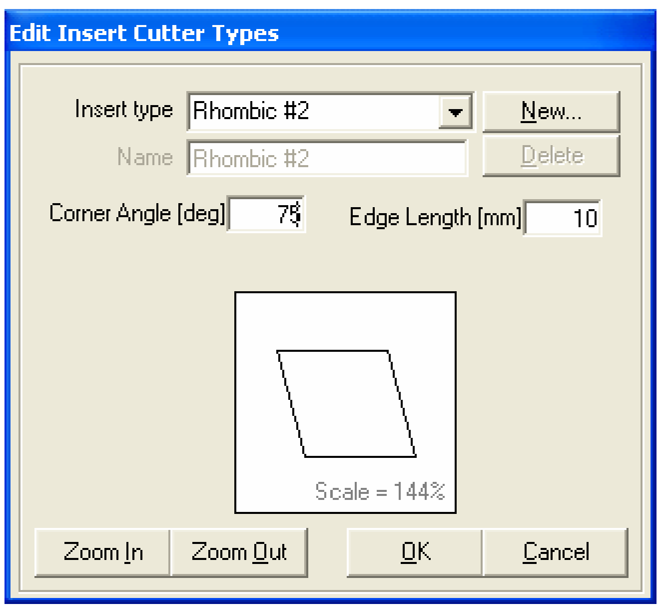


Figure 3.2-9: Edit Insert type for Plunge Milling Module

3.2.5 MACHINE & TOOL/STRUCTURE FLEXIBILITY TAB

The ***Machine & Tool/Structural Flexibility*** tab allows you to enter machine & tool dynamic parameters.

You can model the machine & tool as ***Rigid*** or ***Dynamic vibrations***. For dynamic machine & tool, you need to know the dynamic parameters of the machine & tool. You can enter the natural frequencies, damping ratios and stiffness for up to 6 directions: *X*, *Y*, *Z*, *Θ*, *ZΘ*, ΘZ.

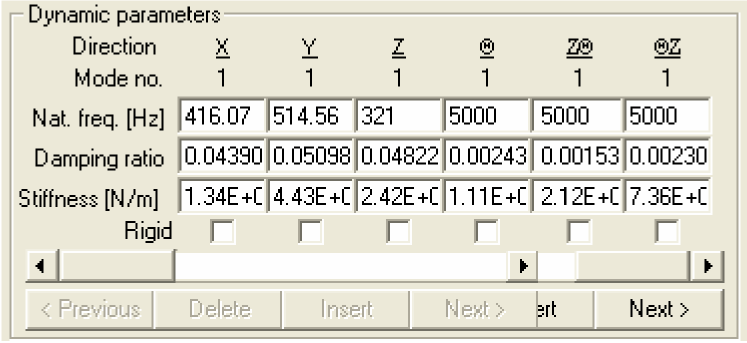


Figure 3.2-10: Machine & Tool Dynamic Parameters

⚠ **If you select the Static Analysis simulation mode, the machine & tool are considered as rigid.**

3.2.6 WORKPIECE TAB

This tab allows to select or define the material of the workpiece. For defining a workpiece material, refer to ***3.1.6.1 Define a Workpiece Material*** in 2½ Axial Milling.

The workpiece is considered as rigid for all simulation modes in plunge milling.

3.2.7 CUTTING CONDITIONS TAB

In the ***Cutting Condition*** tab, you can define the geometry of cut and cutting parameters, which include feedrate, spindle speed, radial depth of cut increment, cutter rotational increment and number of revolutions.

Depending on the simulation mode (static analysis, dynamic simulation, analytical stability lobes) and the type of tool (symmetrical or unsymmetrical) selected, three types of geometry of cut may available: ***Plunge Milling***, ***Plunge Milling with Pilot Hole*** and ***Side Plunge Milling***.

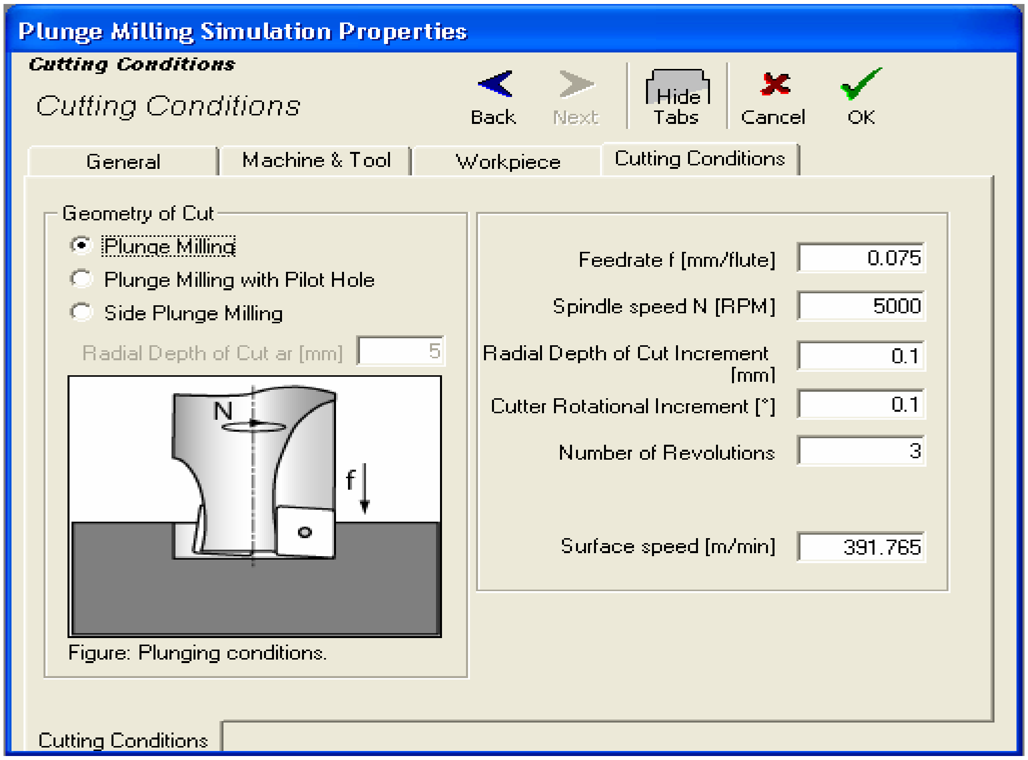


Figure 3.2-11: Geometry of Cut – Plunge Milling

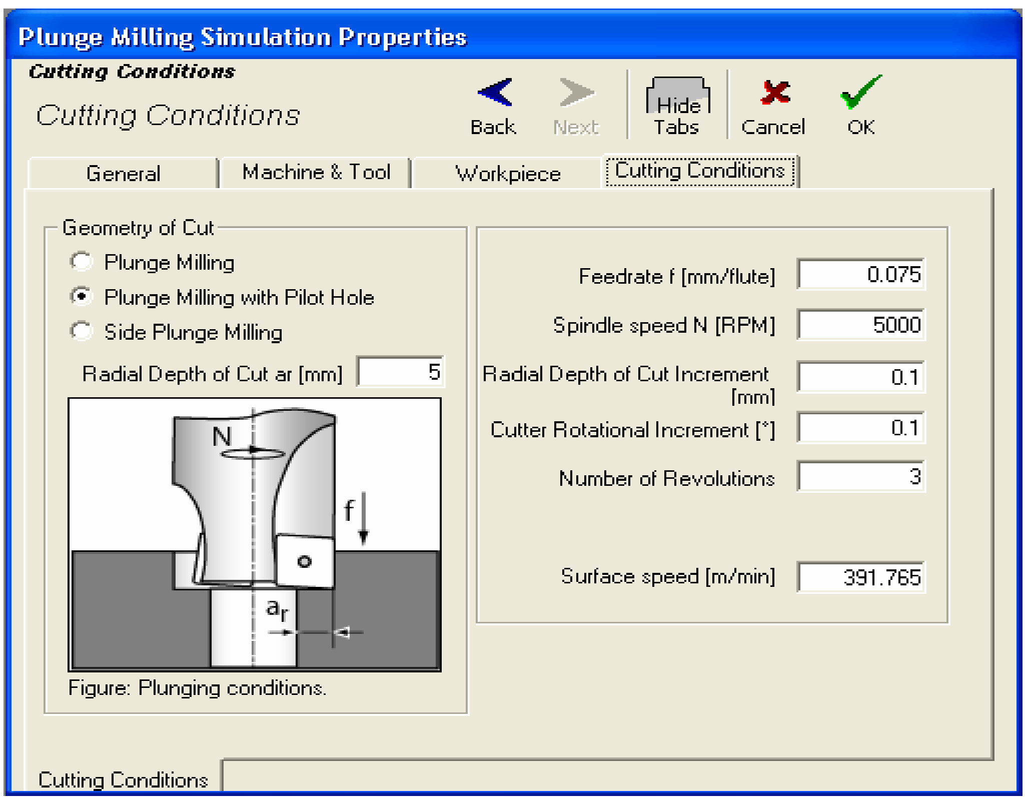


Figure 3.2-12: Geometry of Cut – Plunge Milling with Pilot Hole

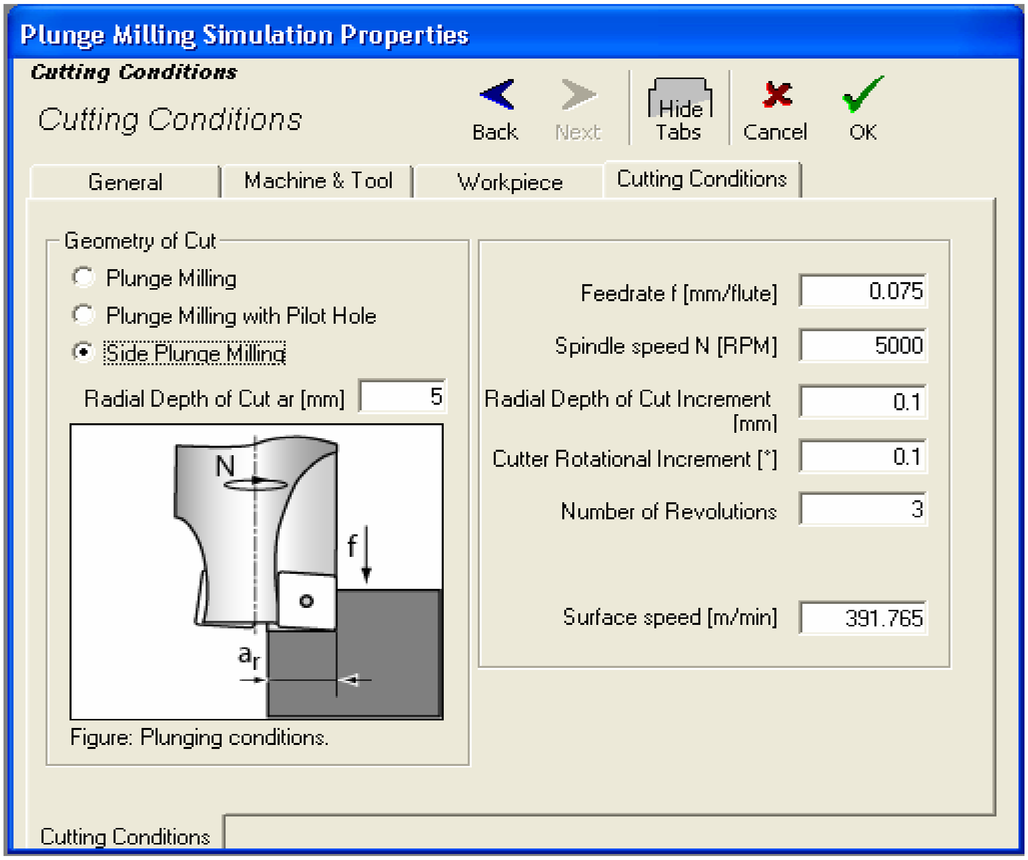


Figure 3.2-13: Geometry of Cut – Side Plunge Milling

3.3 TURNING MODULE

3.3.1 GENERAL/SIMULATION MODE TAB

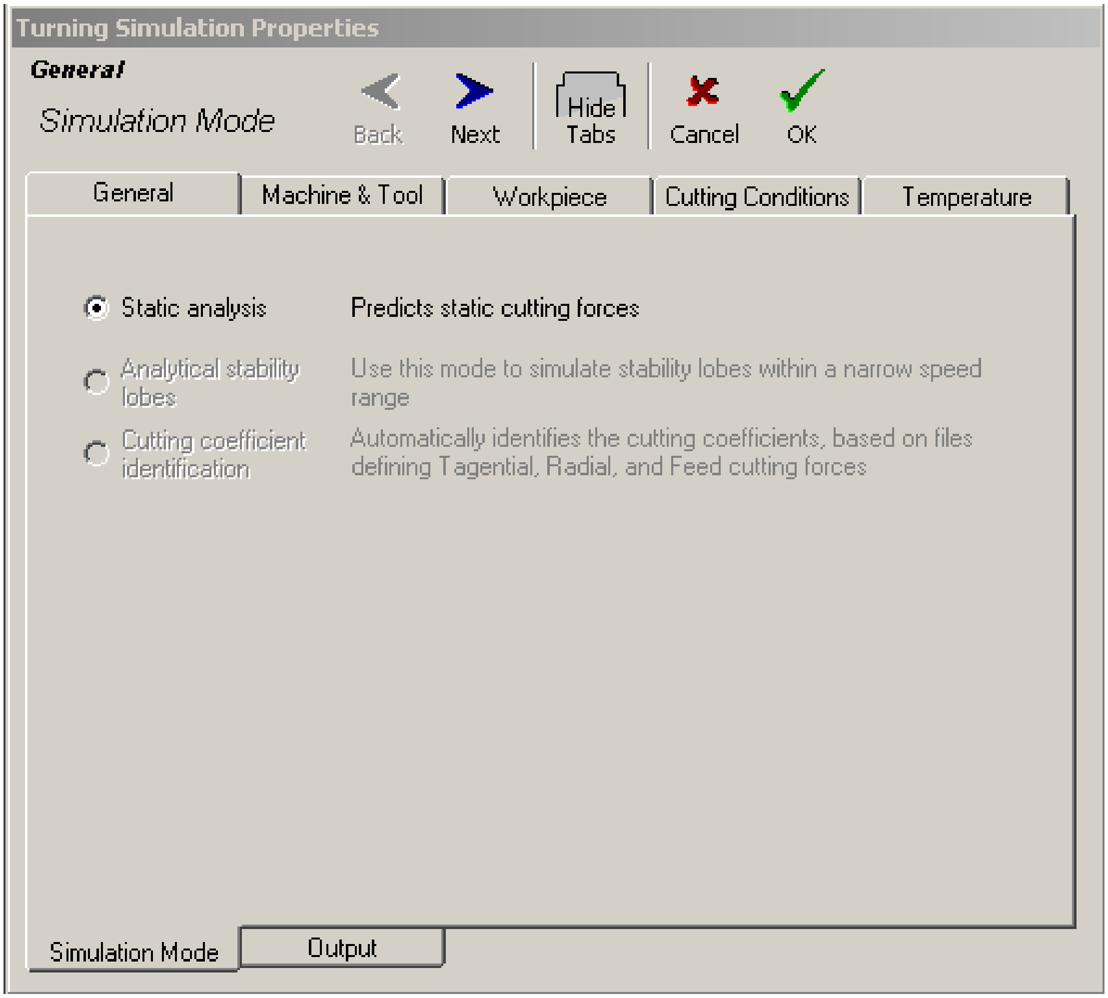


Figure 3.3-1: General/Simulation Mode tab of the Turning module

This tab allows the user to select the simulation mode. Only Static Analysis is available for the time being.

3.3.2 GENERAL/OUTPUT TAB

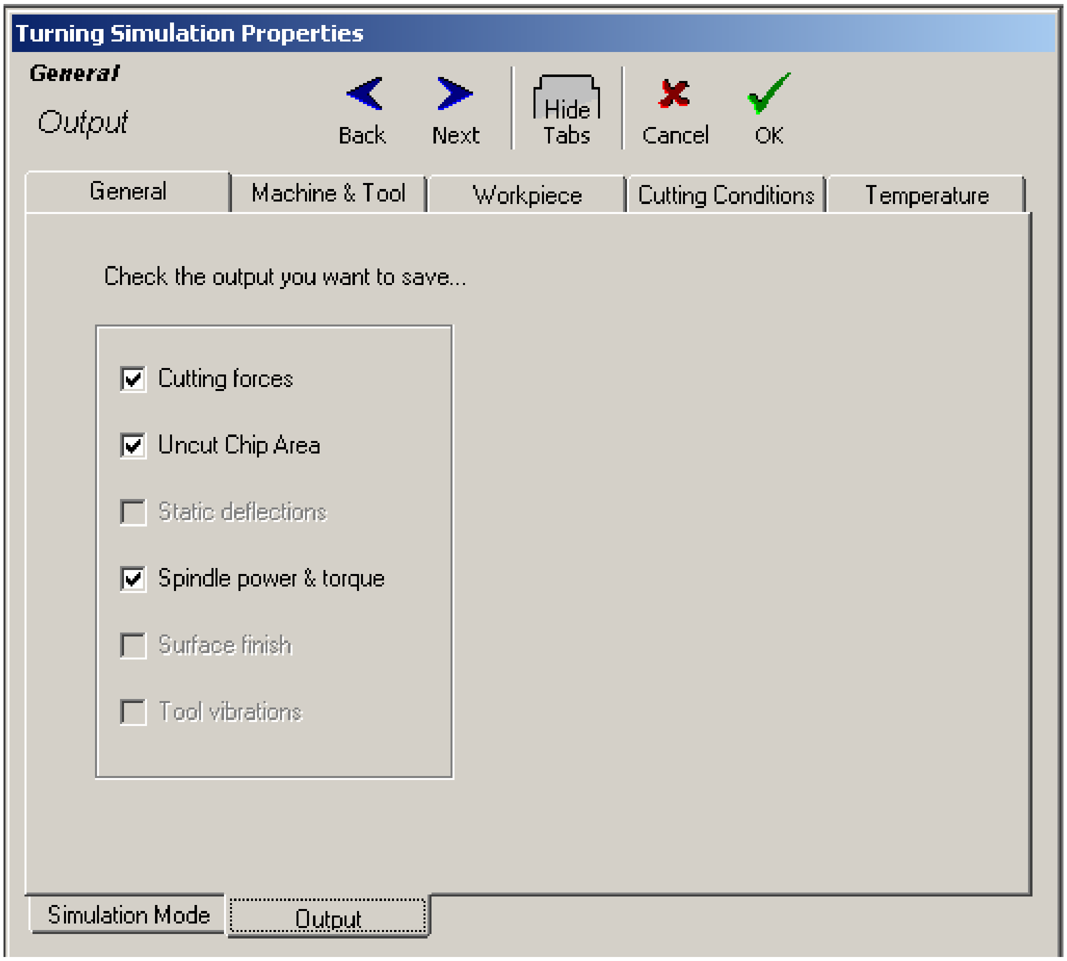


Figure 3.3-2: General/Output tab of the Turning module

This tab allows the user to select the outputs to be made in the simulation. If an item is not selected, its corresponding plot(s) will not be available for viewing and it will not be saved in the simulation file.

3.3.3 MACHINE & TOOL/CUTTER PROPERTIES TAB

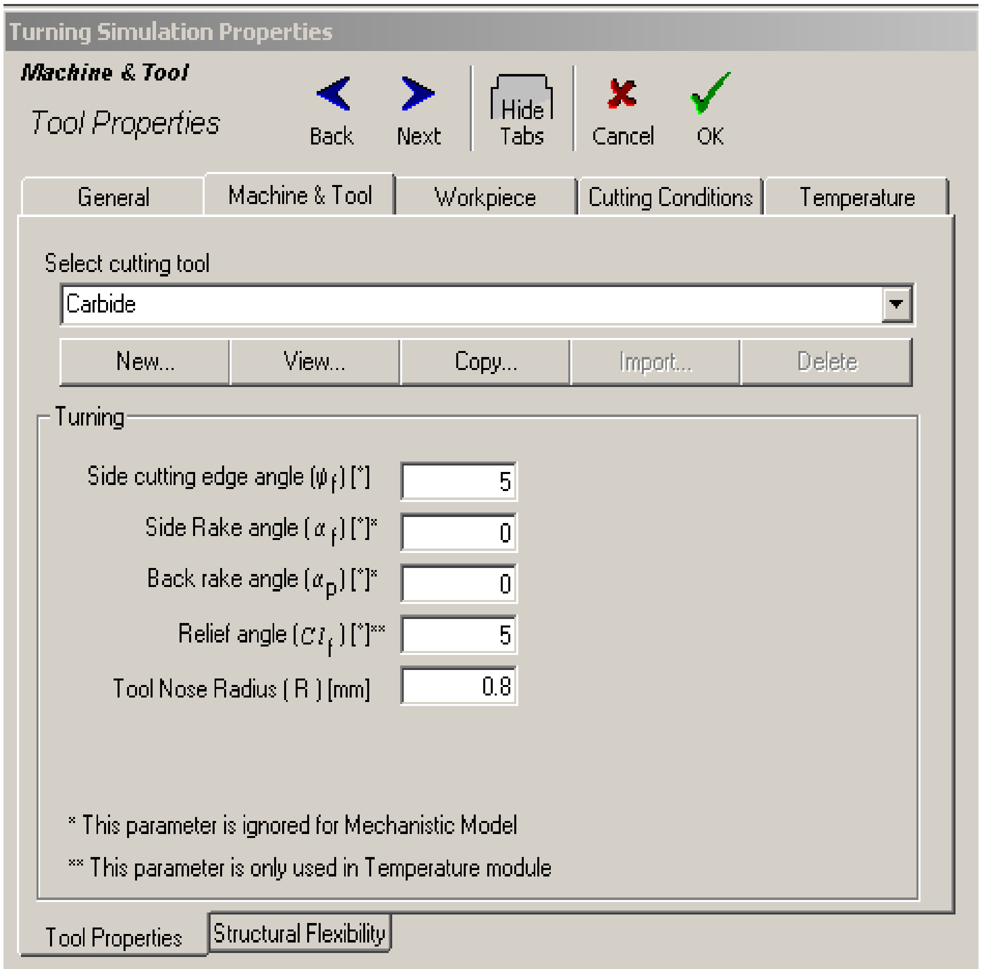


Figure 3.3-3: Machine & Tool/Cutter Properties tab of the Turning Module

This tab allows you to specify the cutter material. This tab is exactly the same as the Cutter Properties tab in the Advanced Milling Module in Section 3.1.4 MACHINE & TOOL/CUTTER PROPERTIES TAB.

3.3.4 MACHINE & TOOL/STRUCTURAL FLEXIBILITY TAB

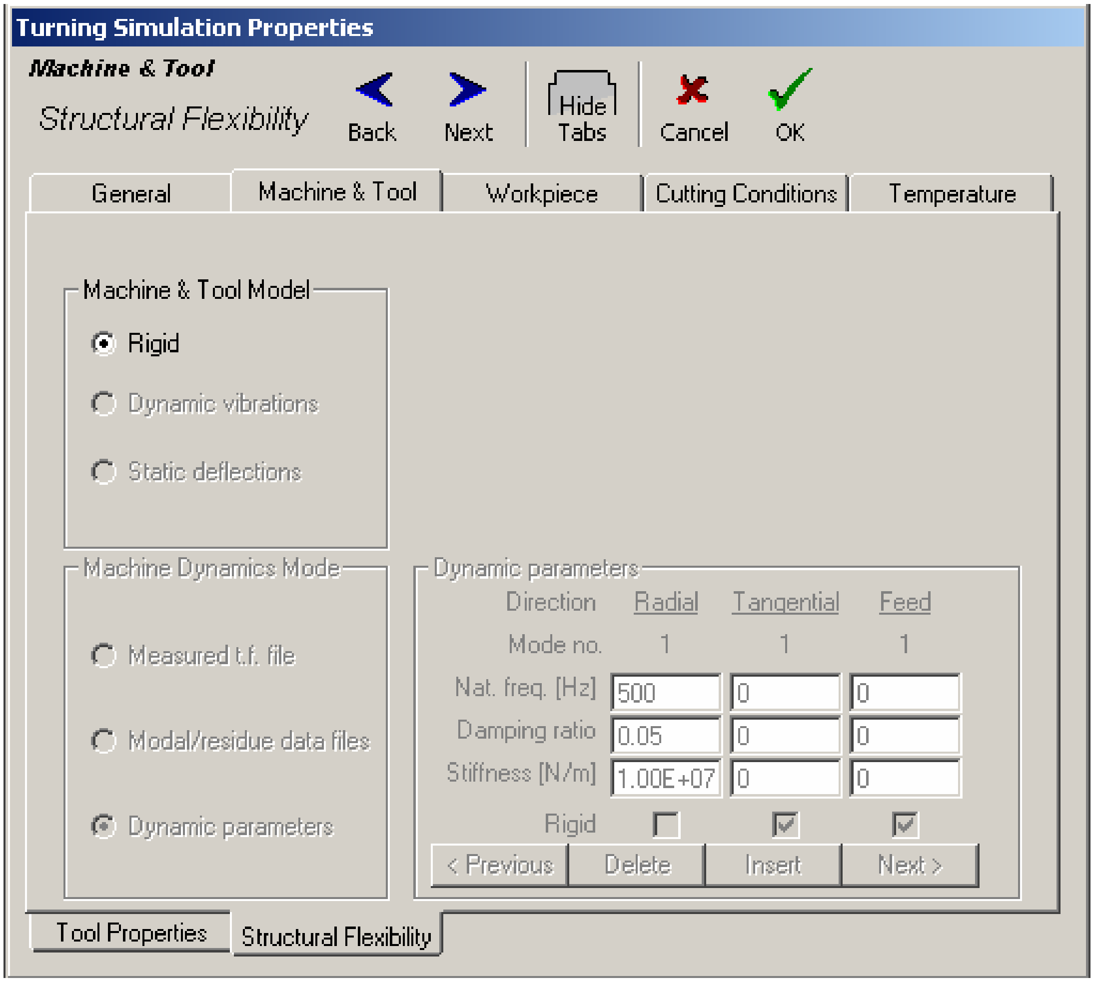


Figure 3.3-4: Machine & Tool / Structural Flexibility tab

This tab allows you to edit the structural flexibility of the machine and tool. Note that this version of CutPro does not yet support the dynamics of the workpiece for turning processes.

3.3.5 WORKPIECE/MATERIAL TAB

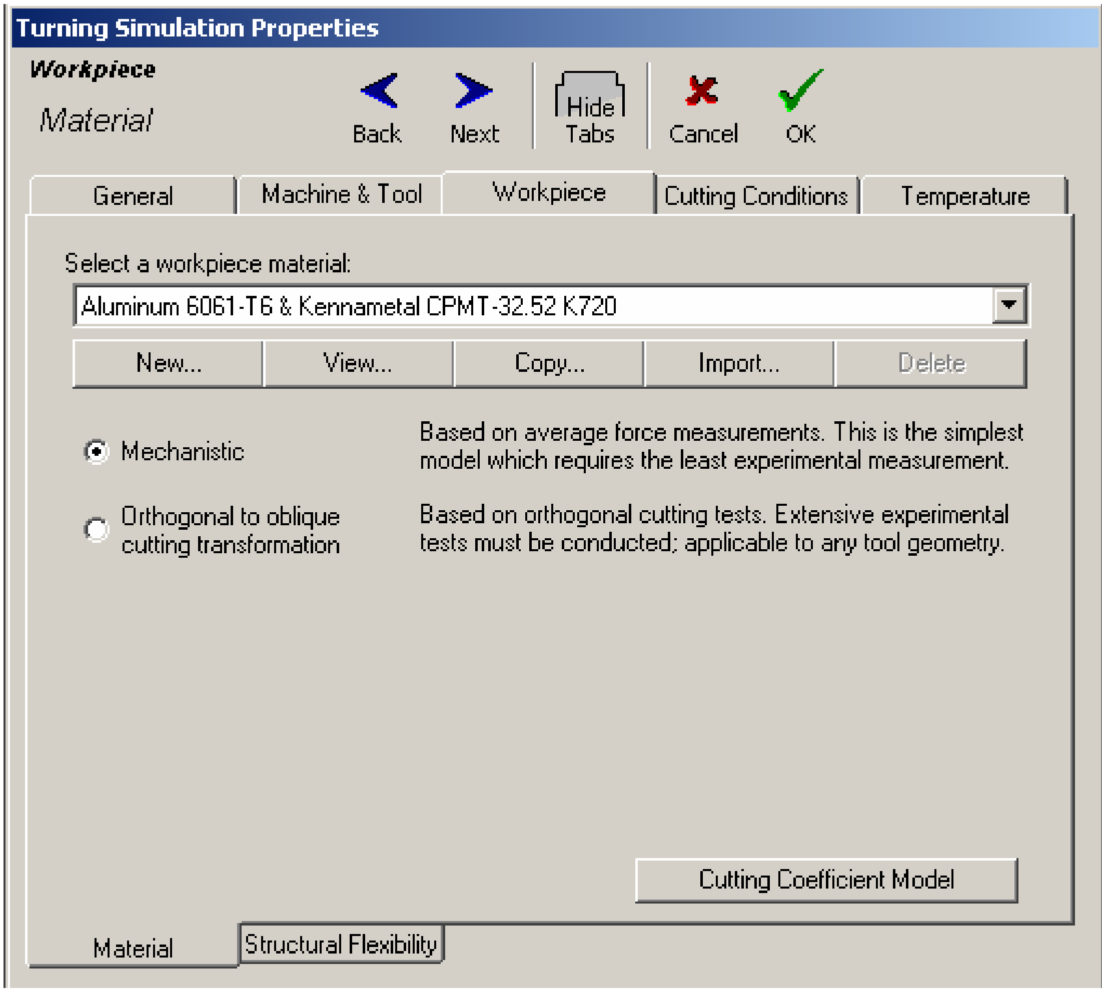


Figure 3.3-5: Workpiece / Material tab of the Turning Module

This tab allows you to specify the material of the workpiece. Please refer to Section 3.1.6 WORKPIECE/MATERIAL TAB (Advanced Milling Module) for detailed description.

3.3.6 WORKPIECE/STRUCTURAL FLEXIBILITY TAB

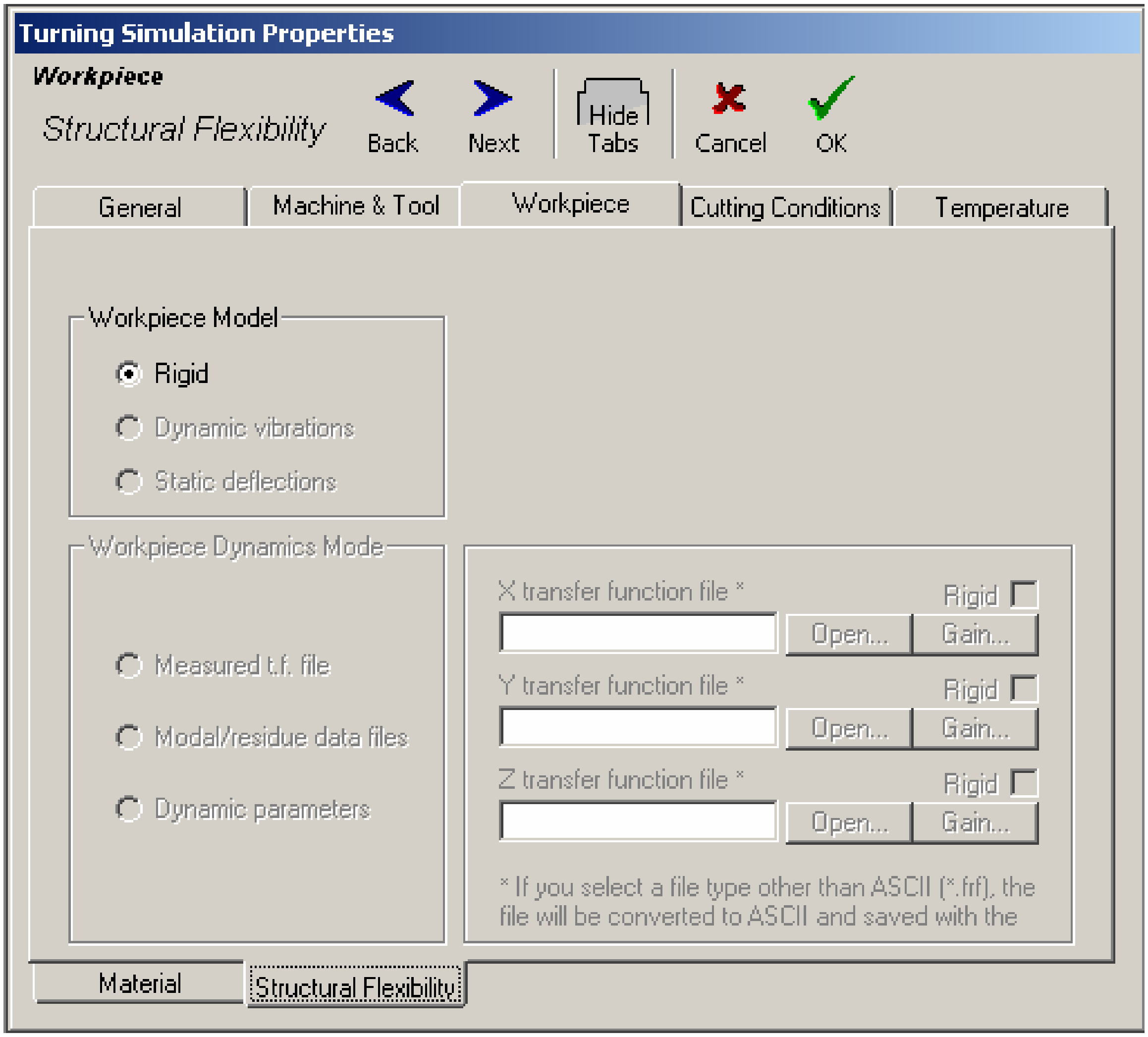


Figure 3.3-6: Workpiece/Structural Flexibility tab

This tab allows you to modify the structural flexibility of the workpiece. Note that this version of CutPro does not yet support the dynamics of the workpiece for turning processes.

3.3.7 CUTTING CONDITIONS TAB

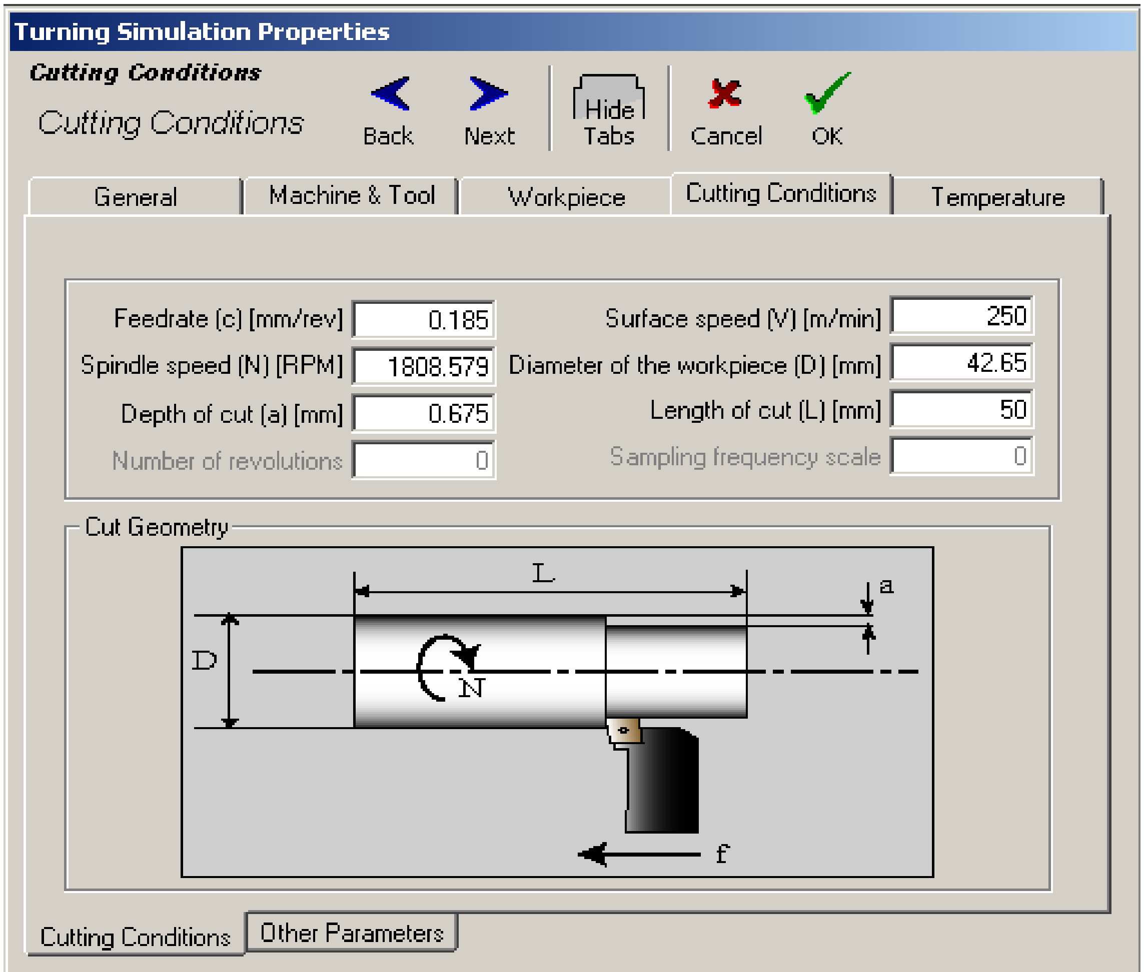


Figure 3.3-7: Cutting Conditions tab of the Turning Module

This tab allows you to enter the cutting conditions: Feed rate, Spindle speed, Depth of cut, and Surface speed.

3.3.8 CUTTING CONDITIONS/OTHER PARAMETERS

There are currently no other parameters that can be defined in this version of CutPro.

3.3.9 TEMPERATURE TAB

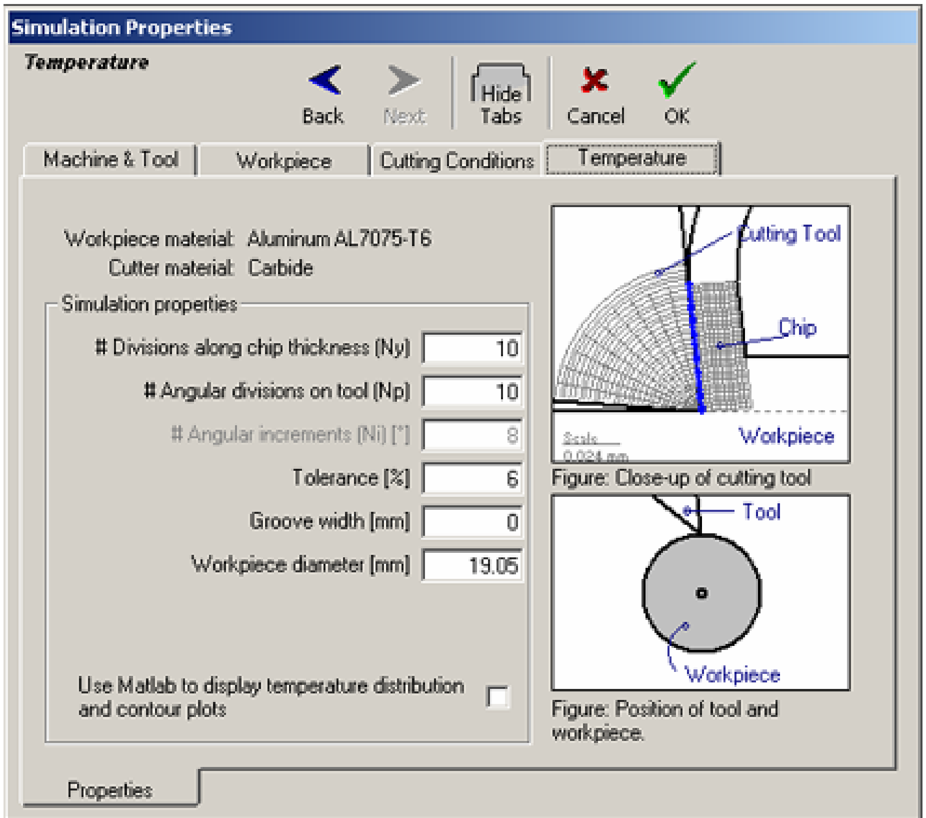


Figure 3.3-8: Temperature/Properties tab of the Turning Module

This tab allows you to change the Simulation properties concerning Temperature. Please refer to Section 3.1.10 TEMPERATURE/PROPERTIES on page 127 for more details about these properties.

3.4 BORING MODULE

3.4.1 GENERAL/SIMULATION MODE TAB

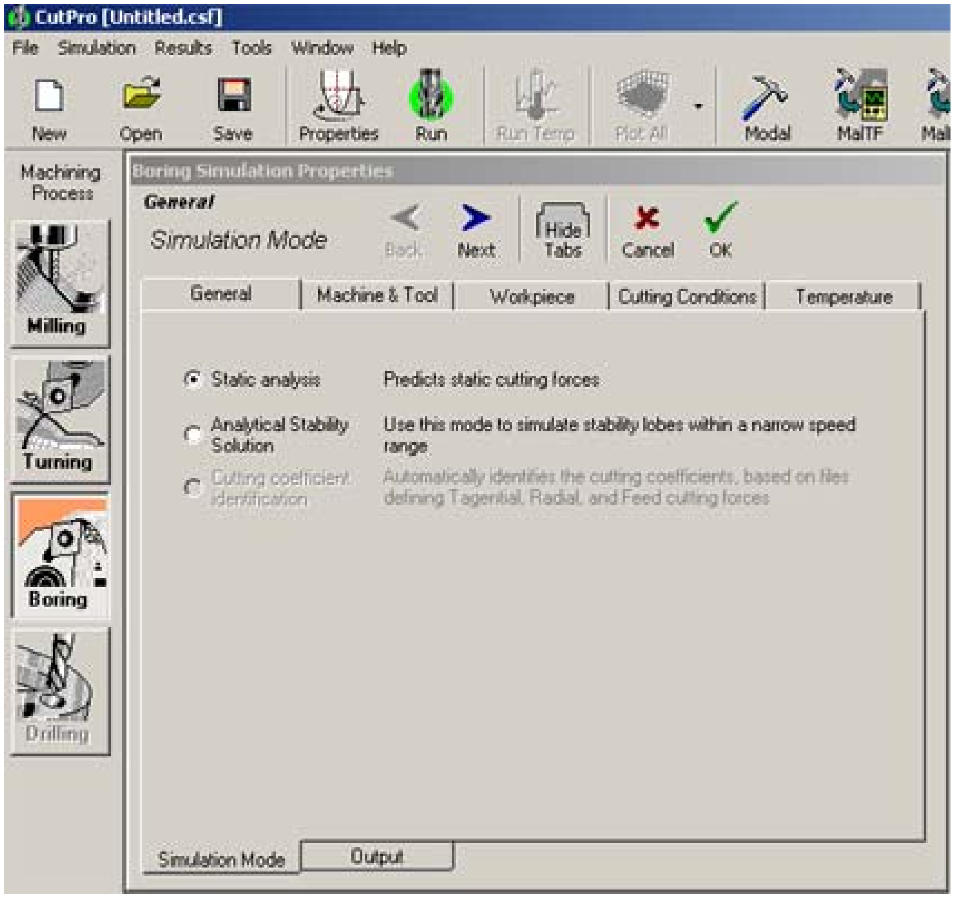


Figure 3.4-1: General/Simulation mode of the Boring Module. Static analysis is selected in this figure.

This tab allows you to choose the simulation mode. There are two simulation modes available, Static Analysis and Analytical stability Solution. The former predicts the cutting forces, uncut chip area, static deflections, spindle power and torque. The latter simulates the stability lobes within a narrow frequency range.

3.4.2 GENERAL/OUTPUT TAB

This section allows you to specify which results you want CutPro to output in simulation. To include a result in the simulation output, check the box next to it.

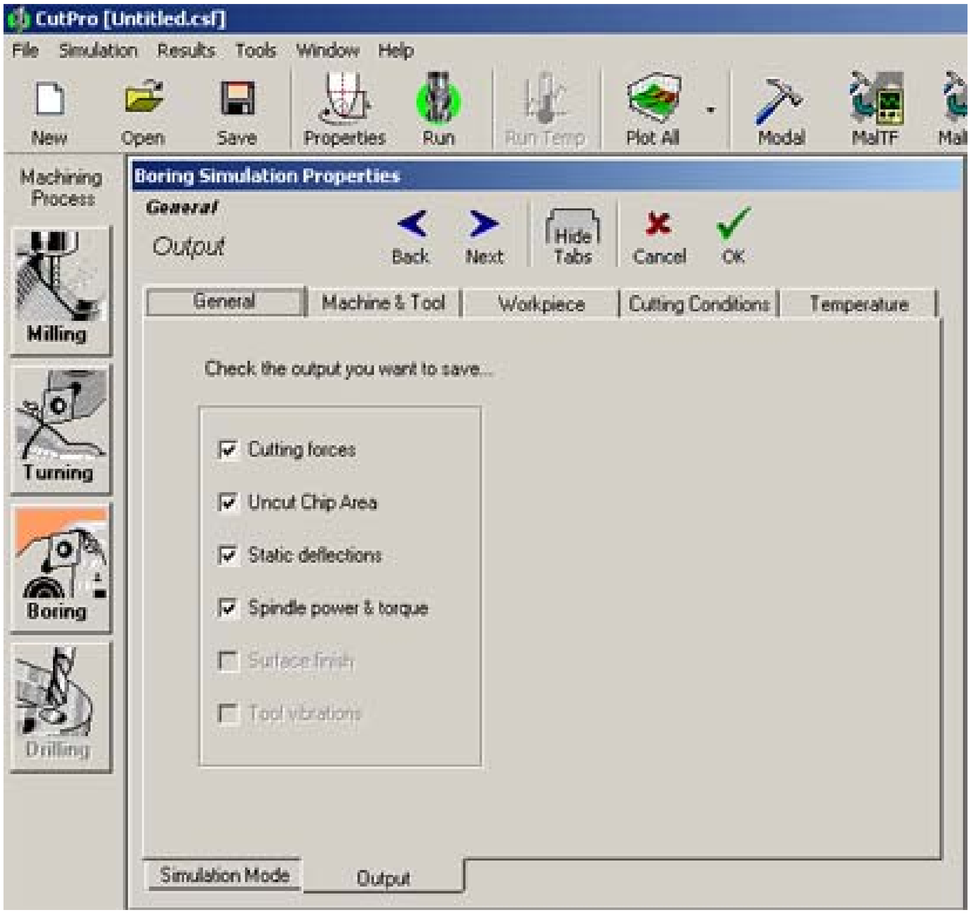


Figure 3.4-2: General / Output tab of the Boring Module

Cutting Forces	*Saves forces in feed, radial, and tangential directions*
Uncut Chip Area	*Saves uncut chip area*
Static deflections	*Saves boring bar radial deflections*
Spindle power & torque	*Saves spindle power and torque*

⚠ **The *Output Tab* is applicable only to the Static Analysis simulation mode.**

3.4.3 MACHINE & TOOL/TOOL PROPERTIES TAB

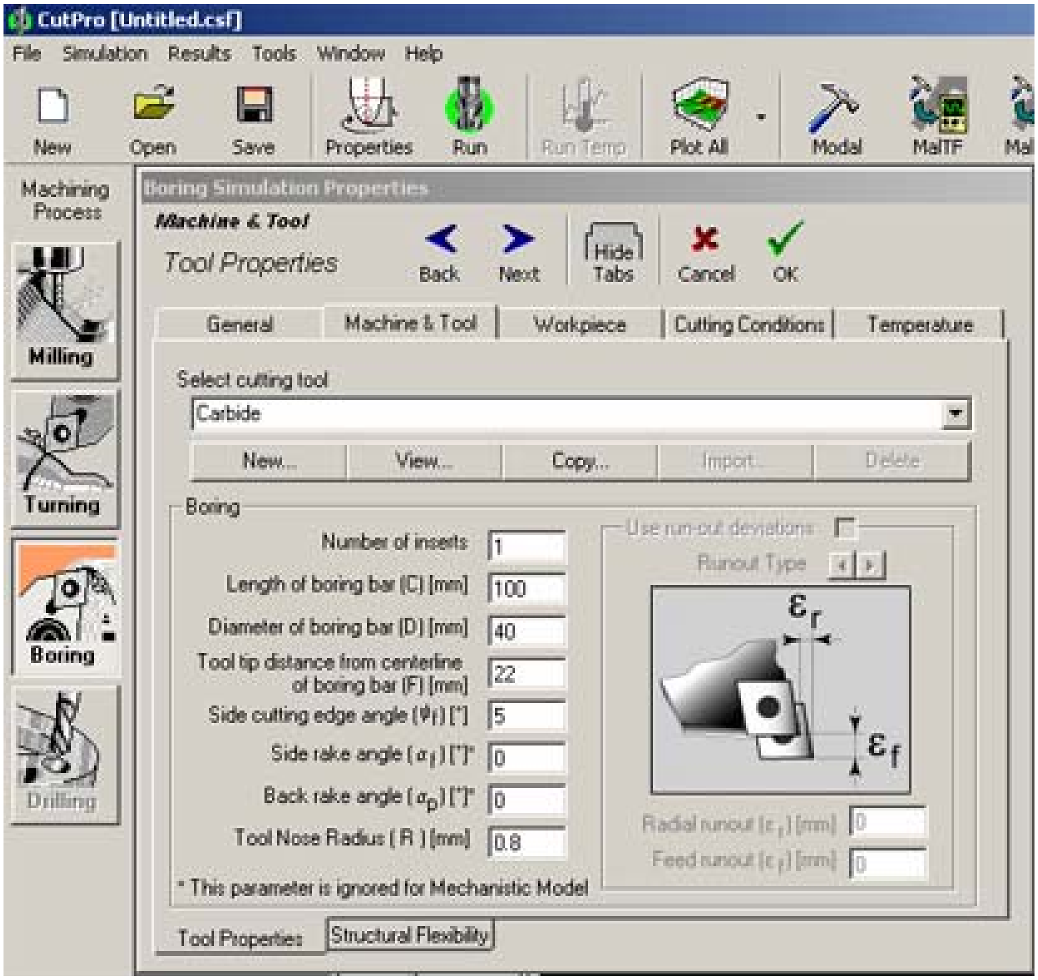


Figure 3.4-3: Machine & Tool / Tool Properties tab

This tab allows you to create and select among different cutting tools to simulate. Some properties are illustrated in the following diagram:

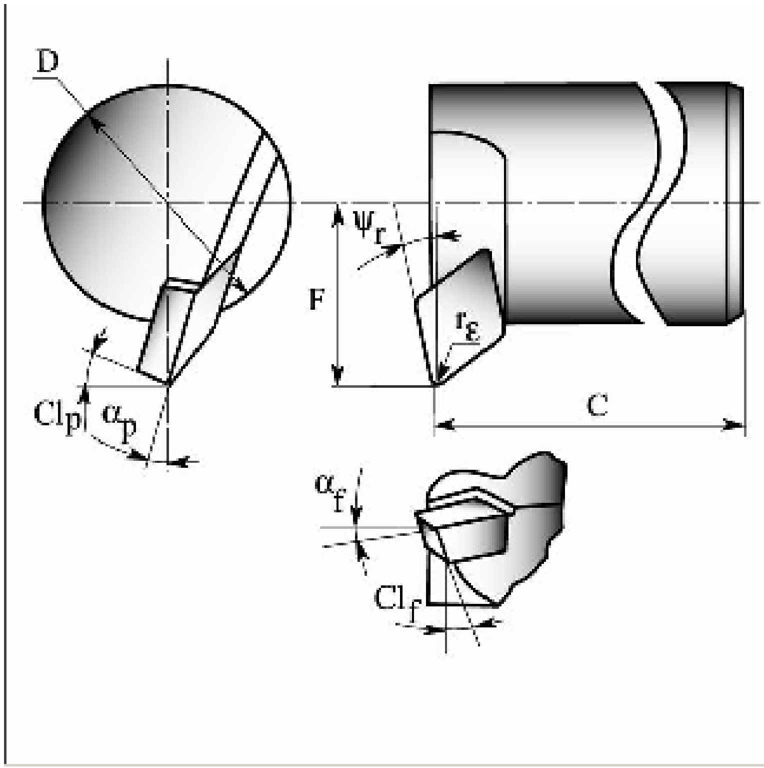
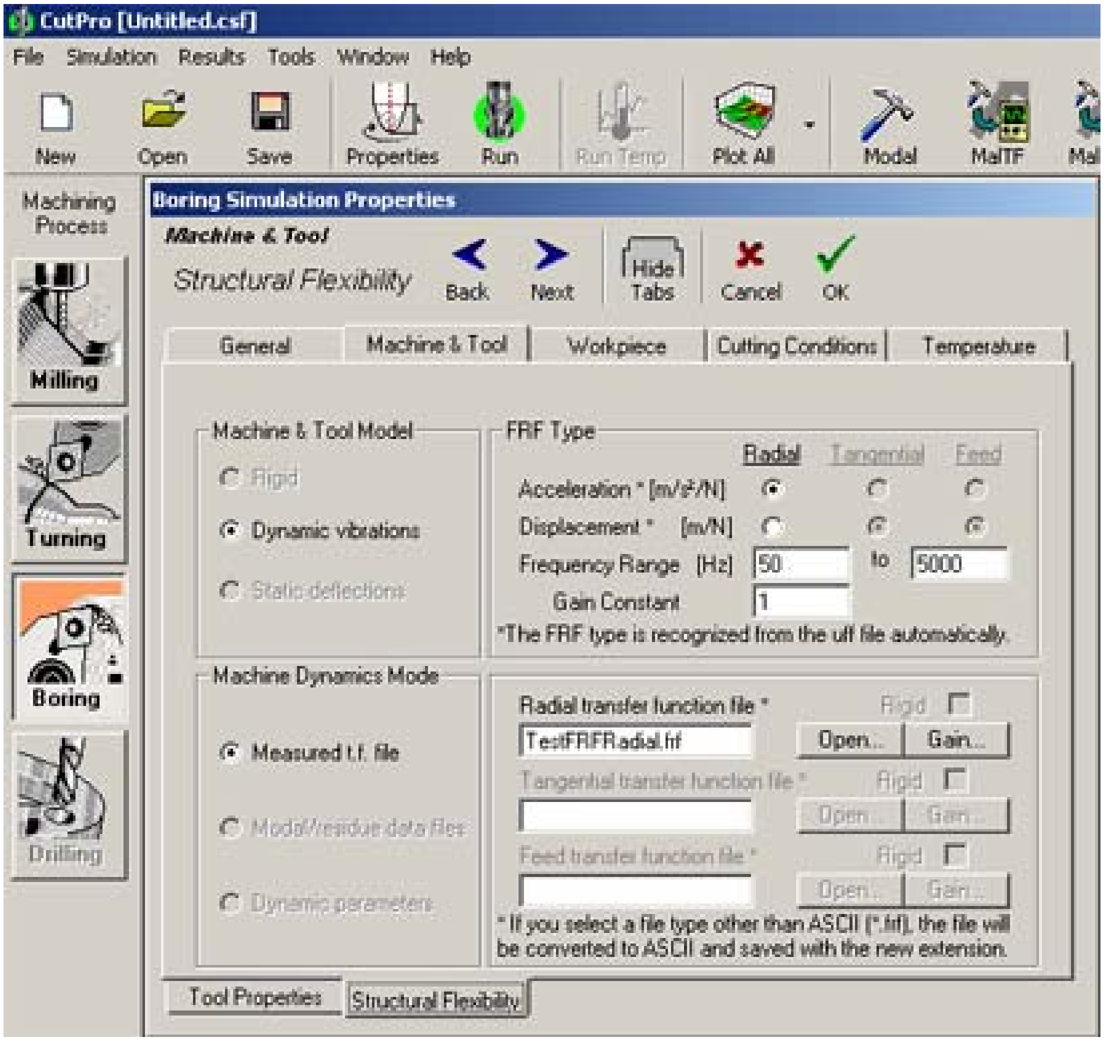


Figure 3.4-4: Geometry of a Boring tool

⚠ **Note: The first four properties listed in the window are not available to the Analytical Stability Simulation.**

3.4.4 MACHINE & TOOL/STRUCTURAL FLEXIBILITY TAB



This tab allows you to input dynamic vibrations of the tool in the radial direction through a measured transfer function file. Click Open to Browse for the desired frf file; the file type can either be Acceleration or Displacement. By pressing Gain, a gain constant can be applied to the selected frf file and a new file with a *_new* extension will be saved by default. For example, TestFRFRadial.frf will be saved under TestFRFRadial_new.frf if a gain constant is applied.

Note: Dynamic vibrations only apply to the radial direction.
Note: Structural Flexibility does not apply to Static Analysis.

3.4.5 WORKPIECE/MATERIAL TAB

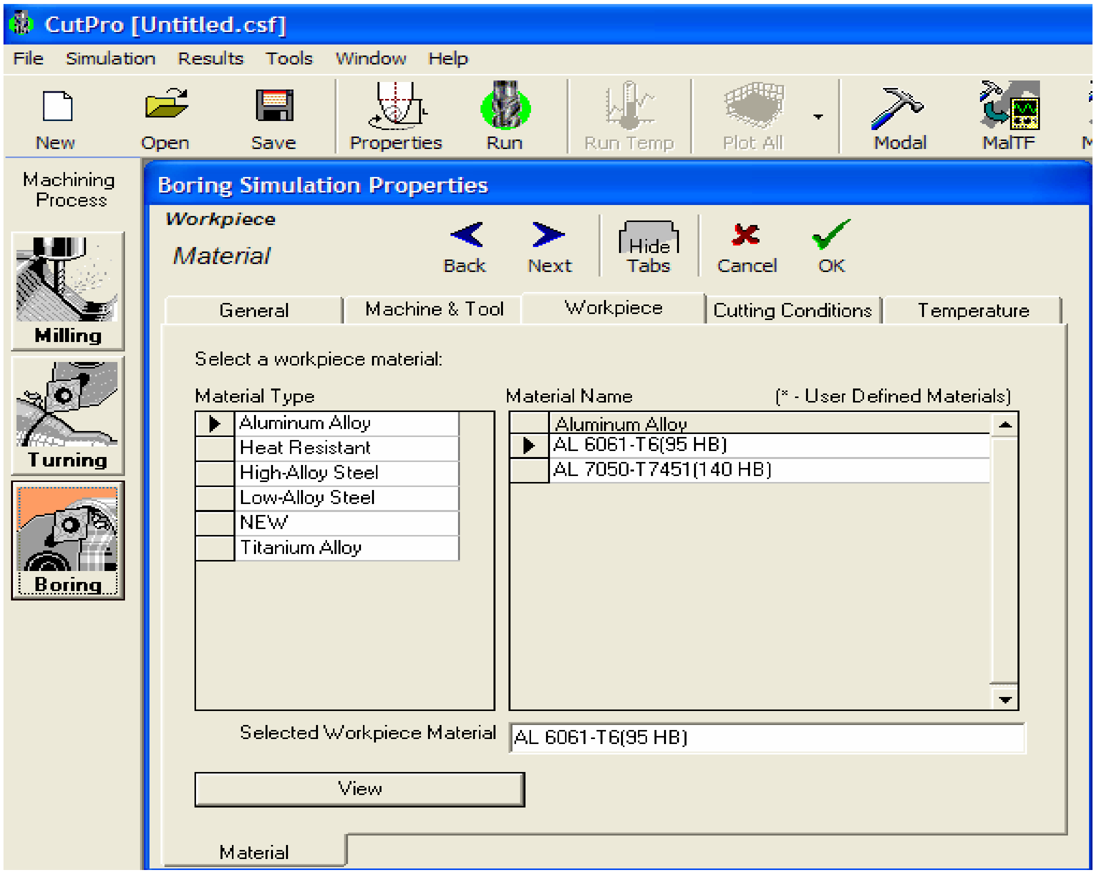


Figure 3.4-5: Workpiece / Material tab in the Boring Module

This tab allows you to select the workpiece material. You may define new materials with different force model simulation modes (Mechanistic or Orthogonal to Oblique Cutting Transformation). Please refer to Section 3.1.6 WORKPIECE/MATERIAL TAB on page 95 for details.

3.4.6 WORKPIECE/STRUCTURAL FLEXIBILITY TAB

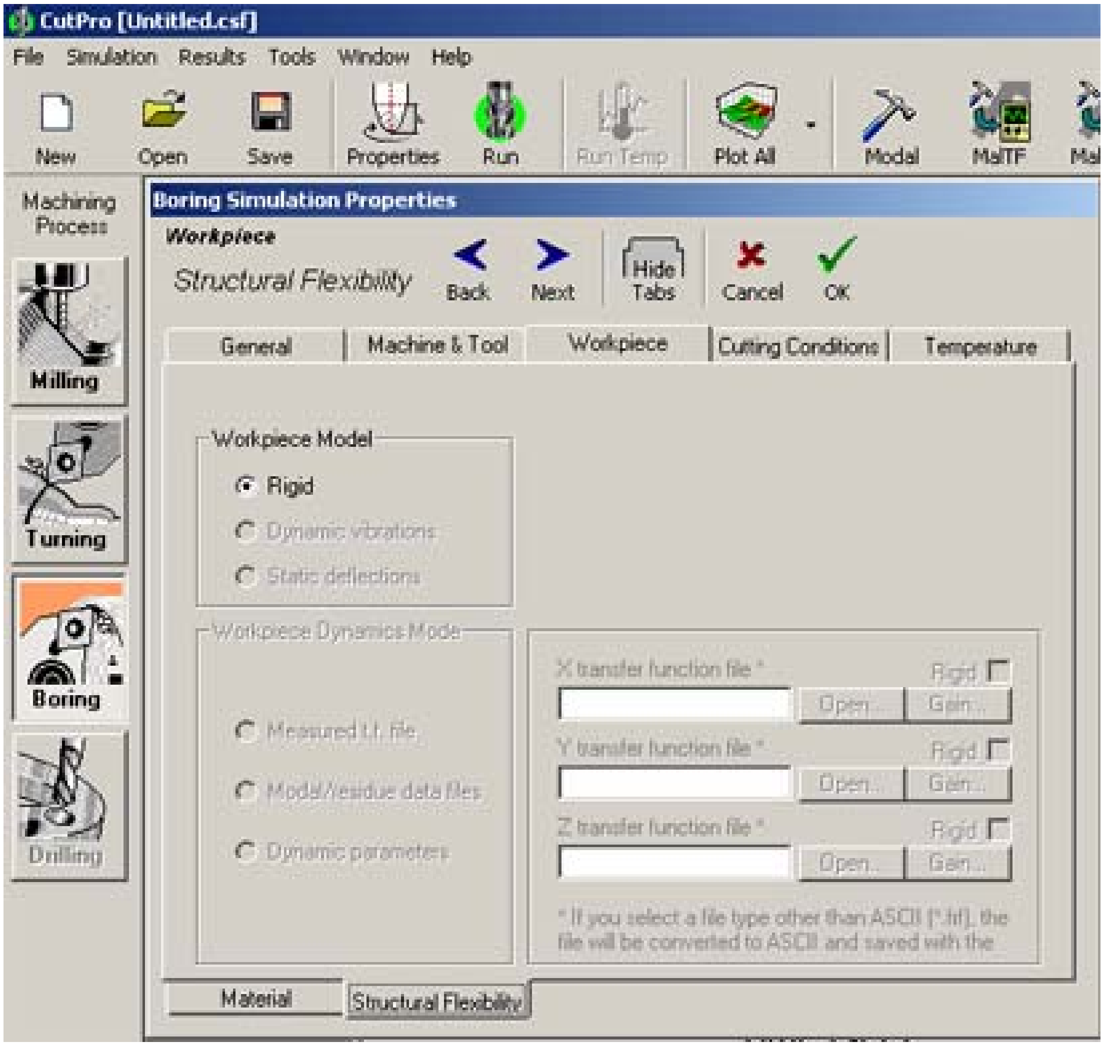


Figure 3.4-6: Workpiece/Structural Flexibility tab in the Boring Module

This tab allows you to modify the structural flexibility of the workpiece. Note that this version of CutPro does not yet support the dynamics of the workpiece for boring processes.

3.4.7 CUTTING CONDITIONS TAB

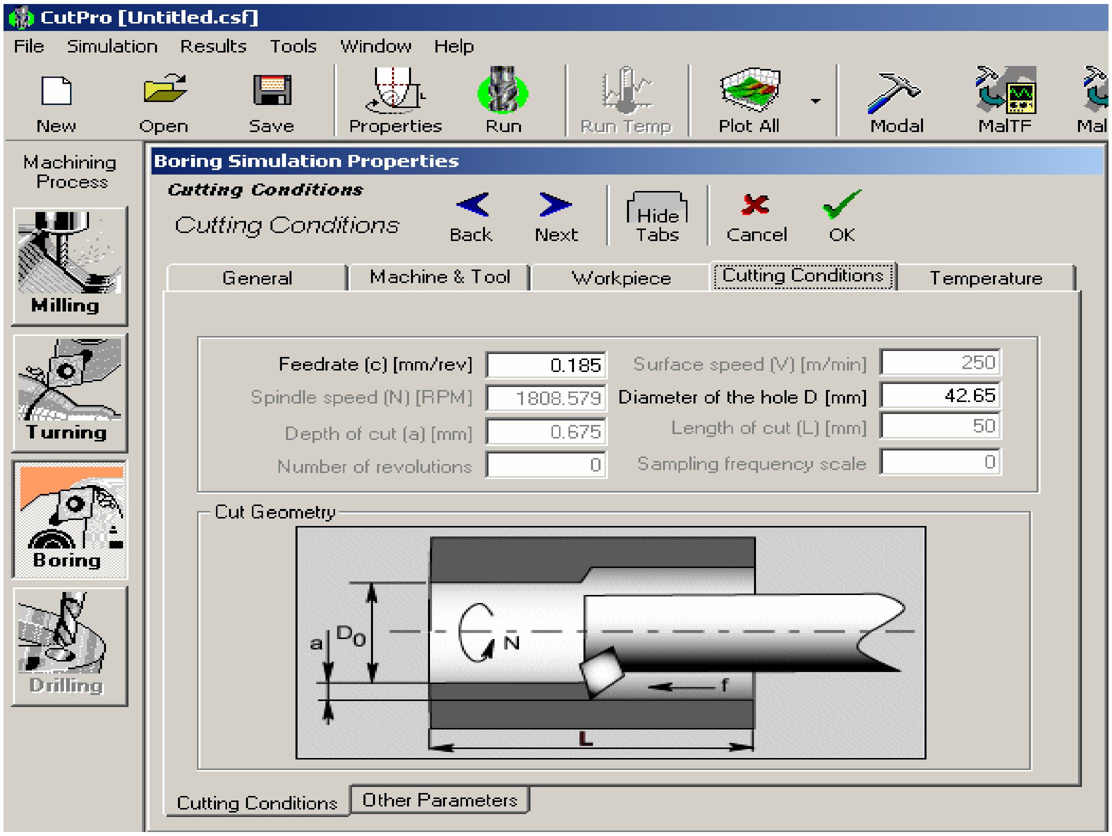


Figure 3.4-7: Cutting Conditions tab

This tab allows you to change the cutting conditions in the boring process, such as feed rate, surface speed, spindle speed, diameter of the hole, etc.

⚠ **Note: Only Feed rate and Diameter of the hole can be modified in Analytical Stability Simulation.**
⚠ **Note: Number of revolutions and sampling frequency scale cannot be modified.**

3.4.8 CUTTING CONDITIONS/OTHER PARAMETERS TAB

There are currently no other parameters that can be modified in this version of CutPro.

3.4.9 TEMPERATURE TAB

Temperature simulation is being developed.

3.5 TEMPERATURE PREDICTION

The importance of temperature prediction for machining processes has been well recognized in the machining research community, primarily due to its effects on tool wear and its constraints on productivity. The rate of wear in particular is greatly dependent on the tool-chip interface temperature. Temperature is a major concern in the machining and production of advanced materials such as titanium and nickel-based alloys. As well as chatter stability, it is perhaps the main limitation in the selection of process parameters such as cutting speed and feed rate. Due to the low thermal conductivity of these materials, most of the heat generated during machining flows into the tool, resulting in severe thermal stresses in addition to mechanical stresses. The thermal stresses accelerate tool fatigue and failures due to fracture, wear or chipping. Furthermore, if the temperature exceeds the crystal binding limits, the tool rapidly wears due to accelerated loss of bindings between the crystals in the tool material.

In the temperature module developed at MAL Inc., the finite difference method is used to predict steady-state tool and chip temperature fields and transient temperature variation in the continuous machining and milling processes. Based on the first law of thermodynamics, heat balance equations are determined in partial differential equation form in Cartesian coordinates for the chip and in the Polar coordinates for the tool. The finite difference method is then used for the solutions of the steady-state tool and chip temperature fields. In the solution procedure, the heat partition between tool and chip is determined recursively. In order to determine the transient temperature variation in the case of interrupted machining such as milling, the chip thickness is discretized along the time. Steady-state chip and tool temperature fields are determined for each of these discretized machining intervals. Based on thermal properties and boundary conditions, time constants are determined for each discrete machining interval. By knowing the steady-state temperature and time constants of the discretized first-order heat transfer system, an algorithm developed at MAL Inc. is used to determine transient temperature variations.

The program outputs include the chip and tool temperature fields, distribution of the rake face temperature, heat partition along the rake face, maximum and average temperature history for continuous cutting, and variation of the maximum temperature along the cutter rotation in the case of milling.

4 RUNNING A SIMULATION

4.1 RUNNING A MACHINING SIMULATION

Follow these steps to define and run a simulation:

- In the main CutPro window, click **New** to create a new simulation, or click **Open** to open an existing one.
- Enter the parameters defining the simulation. See the Properties Window for more information. Click **OK** on the **Properties Window** to save changes and close the window.
- 

Click **Run** to run the simulation. The progress of the simulation is displayed in a **DOS window** (below). When the simulation is done, the DOS window is closed, and the results are loaded automatically. If you want to abort the simulation before its completion, press the **Stop** button.

⚠ **You cannot run any simulations in the DEMO version of CutPro.**

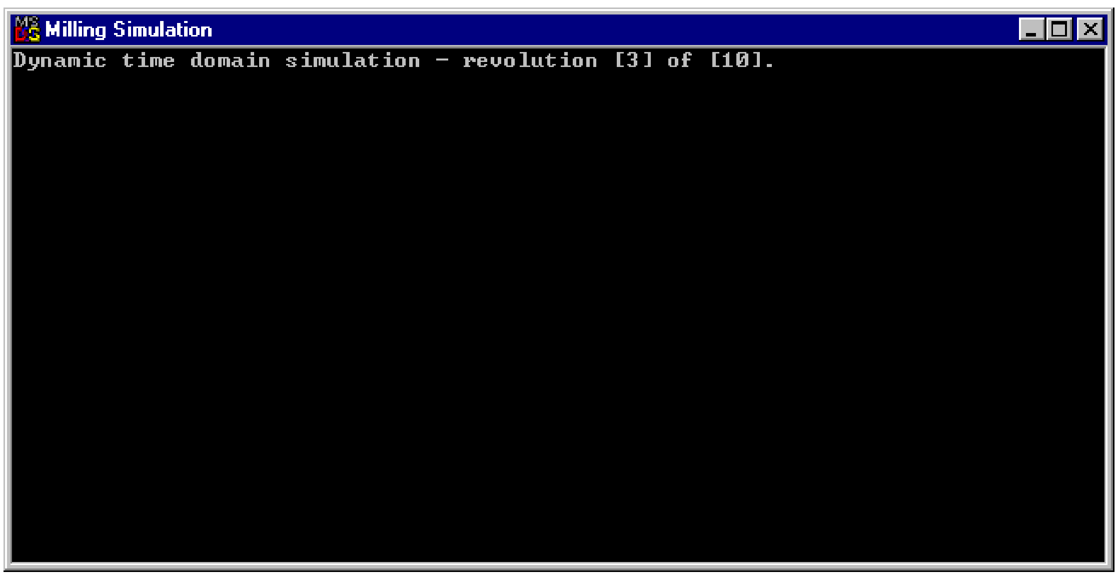
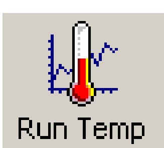


Figure 4.1-1: A DOS window appears when the Run button is pressed

4.2 RUNNING A TEMPERATURE SIMULATION

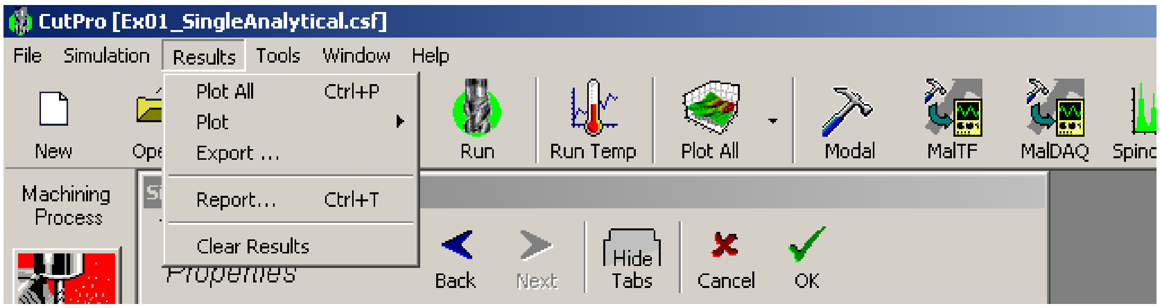


Click **Run Temp** to run the Temperature Simulation. A **DOS window** similar to the window above will be displayed. When the simulation is done, the DOS window is closed and the results are loaded automatically. If you want to abort to simulation before its completion, press the **Stop Temp** button.

Please refer to Chapter 8 – Example Files for examples of simulations.

5 VIEWING RESULTS

Once you have run a simulation, one or more results are produced, depending on what you have selected on the **Output Tab** and the type of simulation you have run. All of the available results are listed under the **Results > Plot** menu.



5.1 VIEWING ALL RESULTS

Select **Results > Plot All**, or clicking **Plot** on the main window toolbar.

5.2 VIEWING INDIVIDUAL RESULTS

Select an individual result under **Results > Plot**. The available output results are as follows. Only certain results will be available, depending on the type of simulation you have run.

5.3 RESULTS WINDOW

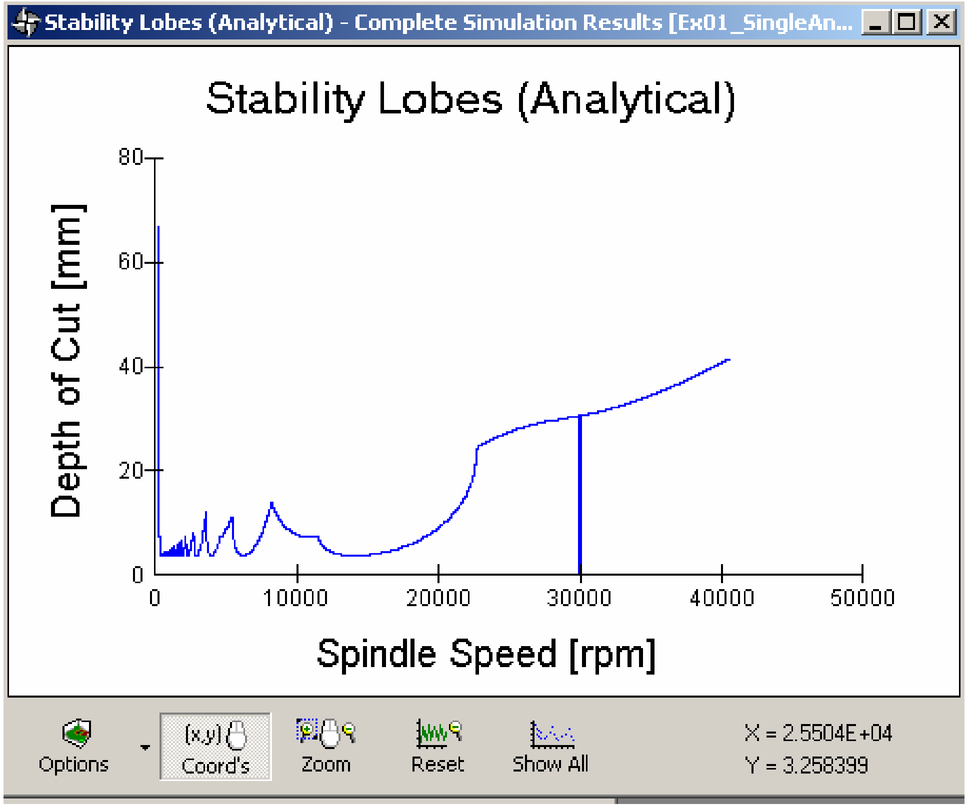
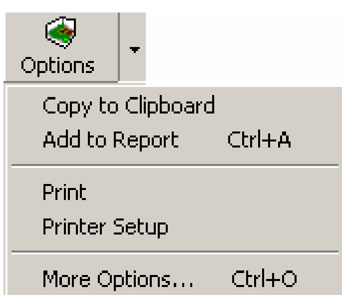


Figure 5.3-1: Sample Analytical Stability Lobes

Five or more toolbar buttons are present on each Result Window.

5.3.1 OPTIONS

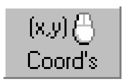


The Options toolbar button provides five options:

Copy to Clipboard	*Copies the graph onto the clipboard as a bitmap; to save as a file, click paste on a picture editing software.*
Add to Report	*Adds the current result to the results Report*
Print	*Prints the graph on the current printer.*

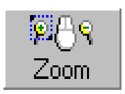
Printer Setup	*Brings up the standard Windows **Printer Setup** window, allowing you to select the current printer and change other options such as paper size.*
More Options	*Displays a tabbed dialog in which you can change the look of the graph. See **Graphppr.hlp**, in the **Help directory** under your main CutPro directory, for more details.*

5.3.2 X-Y COORDINATES



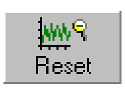
When this button is pressed, you may left-click on the graph to display the coordinates of a specific point.

5.3.3 ZOOM



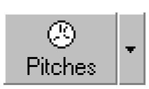
When this button is pressed, you may used the left mouse button to click and drag a zoom rectangular on the graph. Use the right mouse button to go back to the previous view.

5.3.4 RESET



Click this button to reset the graph's axes to their original (ie maximally zoomed out) values.

5.3.5 PITCHES



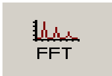
(Optimal Variable Pitch graph only) Click on the graph with the mouse button to see the pitches corresponding to a specified first pitch. If you right-click, a table is displayed on the graph illustrating the pitches. If you left-click, the pitches are added to the Pitches button menu on the toolbar.

5.3.6 CUTTING COEFFICIENTS

(Cutting Coefficient Identification graph only) Click this button to see the cutting coefficients associated with the graph.

You may then save these coefficients as a user-defined workpiece material.

5.3.7 FFT



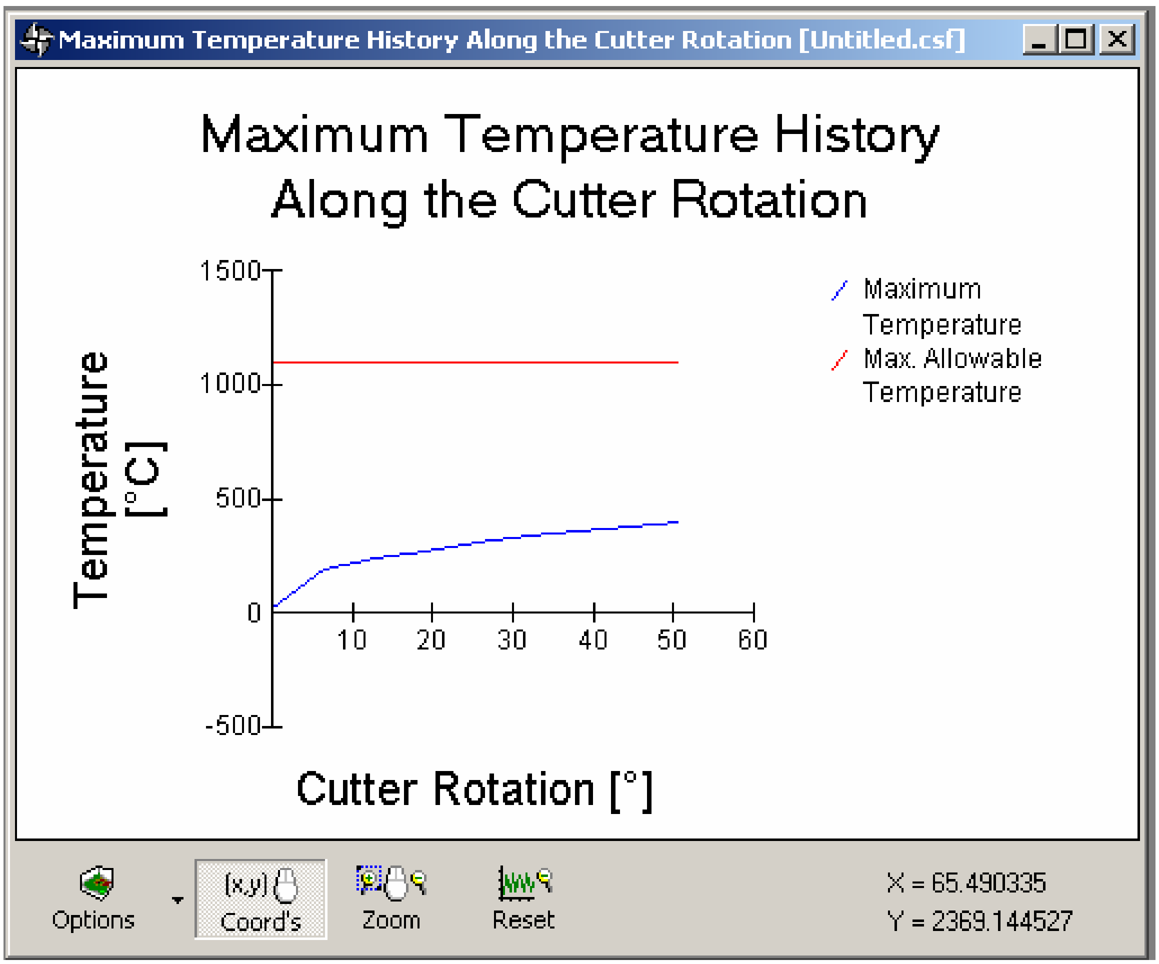
(Single Time Domain graphs only) Click this button to use Fourier Transform to see the graph in frequency domain.

5.4 PLOTS

A particular graph can be plotted individually as described in Section 4.2. Each module has its own set of available plots. The following is a description of each type of plot:

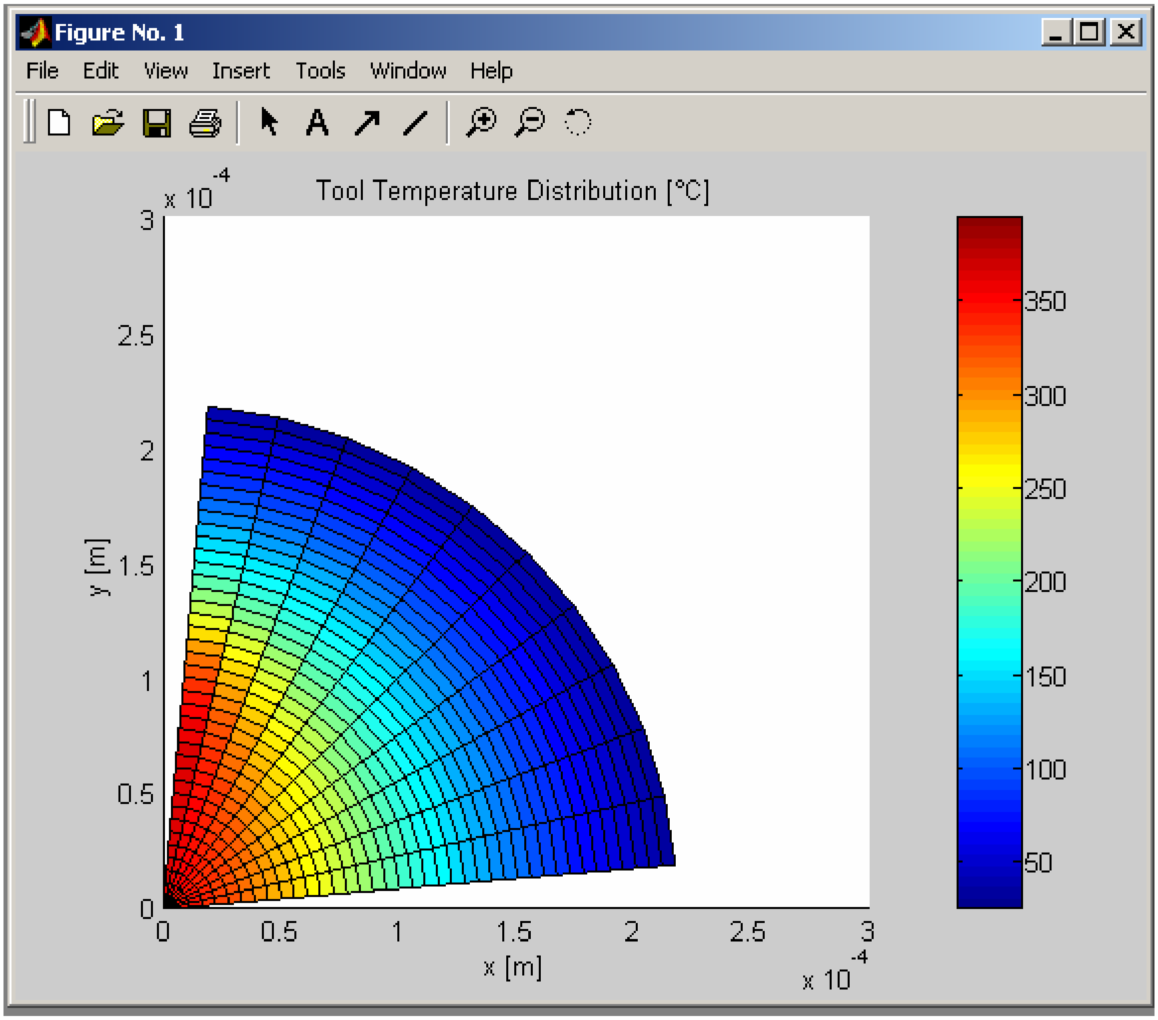
5.4.1 MILLING MODULE PLOTS

5.4.1.1 MAXIMUM TEMPERATURE HISTORY ALONG THE FULL CUTTER ROTATION



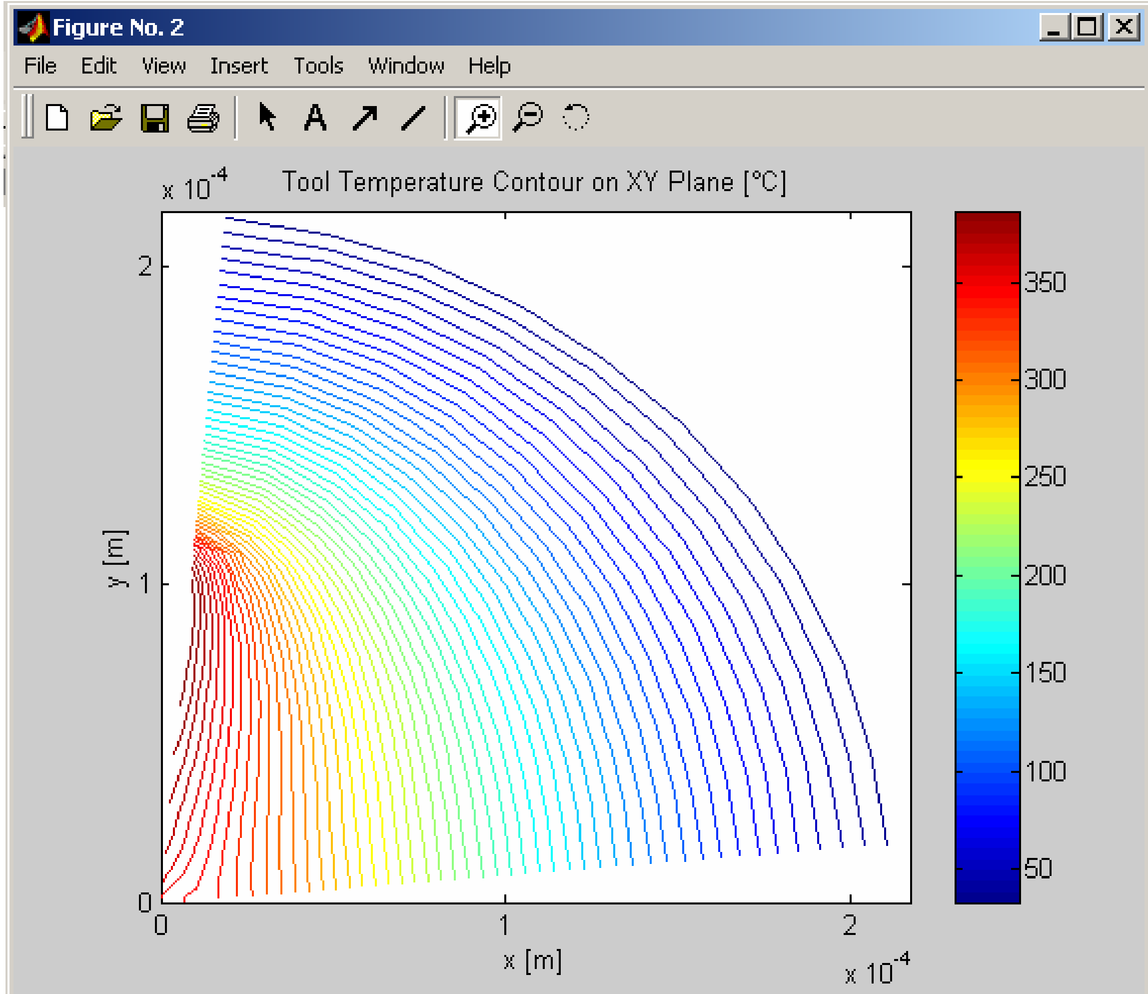
Temperature is calculated at a series of increments along the cutter rotation. Please refer to Section 3.1.10 TEMPERATURE/PROPERTIES for more information regarding Temperature Simulation.

5.4.1.2 TOOL TEMPERATURE DISTRIBUTION



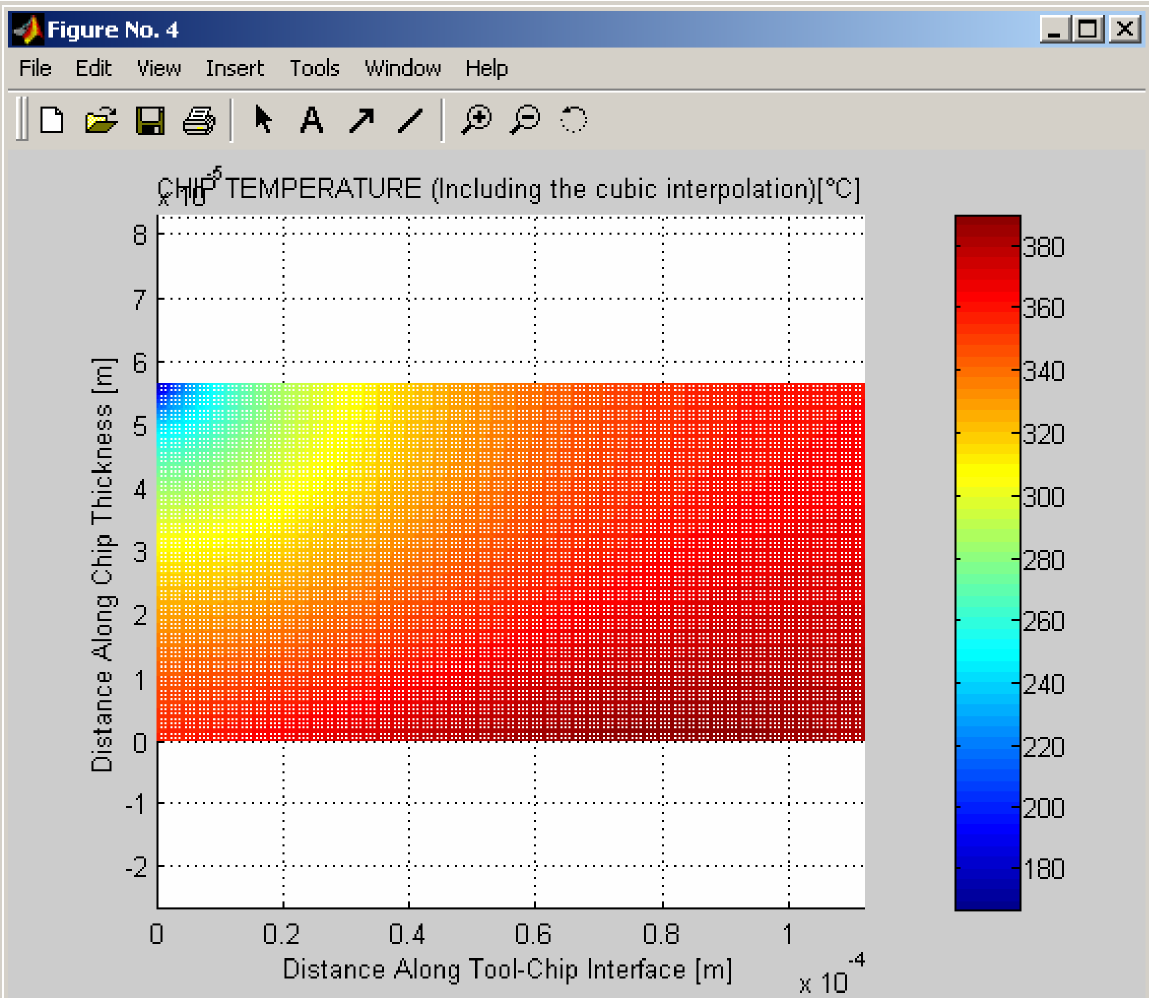
MATLAB is required to run in order to plot the Tool Temperature Distribution. Please refer to Section 3.1.10 TEMPERATURE/PROPERTIES for more information regarding Temperature Simulation

5.4.1.3 TOOL TEMPERATURE CONTOUR ON XY PLANE



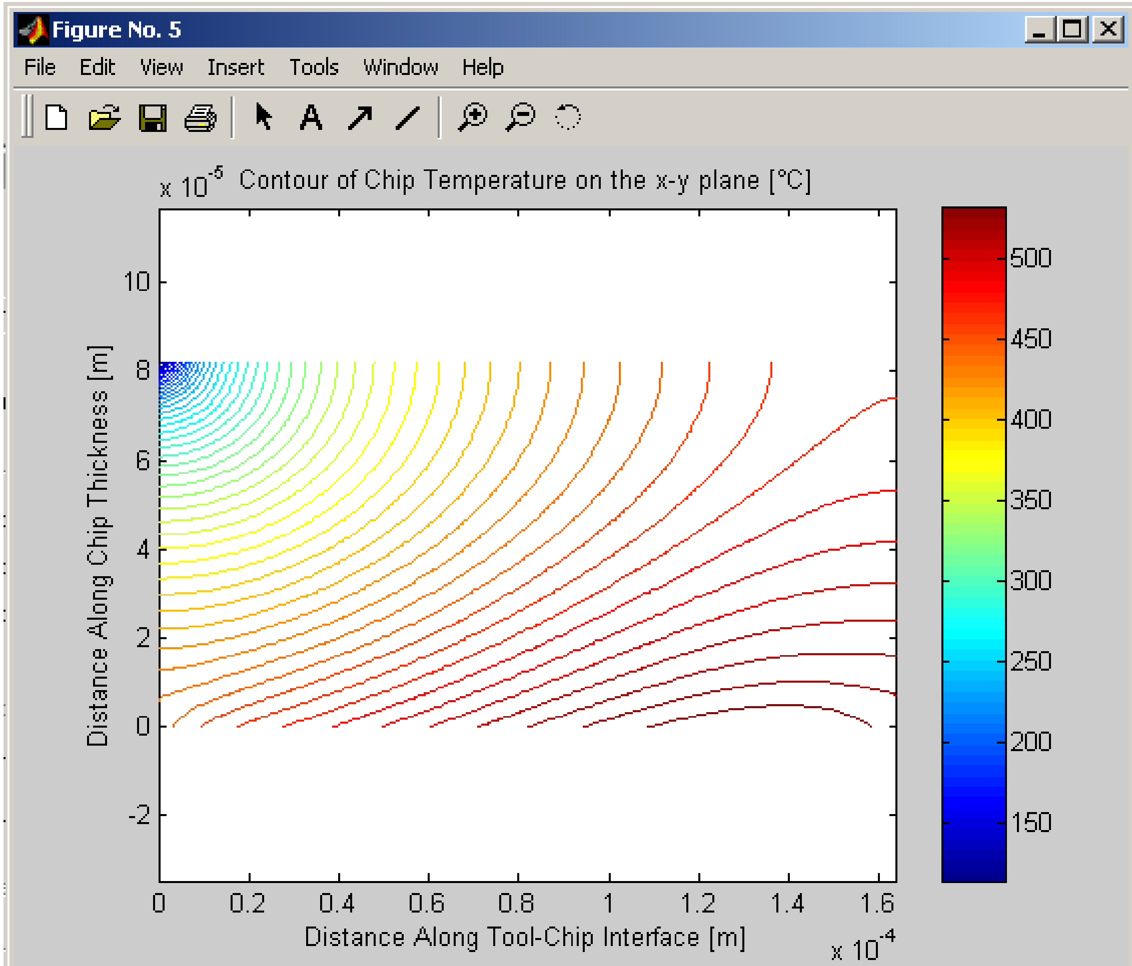
MATLAB is required to run in order to plot the Tool Temperature Contour. Please refer to Section 3.1.10 TEMPERATURE/PROPERTIES for more information regarding Temperature Simulation

5.4.1.4 CHIP TEMPERATURE DISTRIBUTION



MATLAB is required to run in order to plot the Chip Temperature Distribution. Please refer to Section [3.1.10 TEMPERATURE/PROPERTIES] for more information regarding the Temperature Simulation

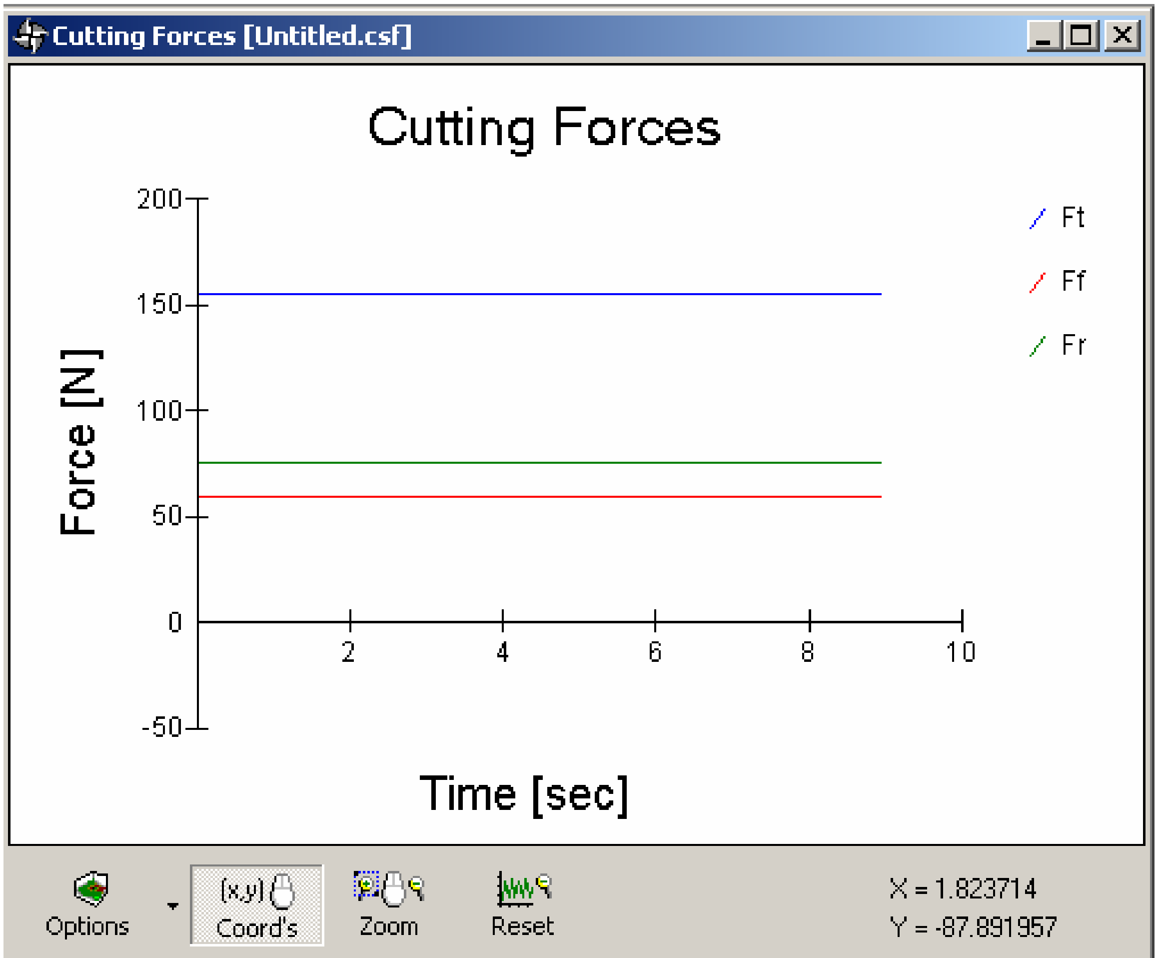
5.4.1.5 CHIP TEMPERATURE CONTOUR



MATLAB is required to run in order to plot the Chip Temperature Contour. Please refer to Section 3.1.10 TEMPERATURE/PROPERTIES for more information regarding the Temperature Simulation

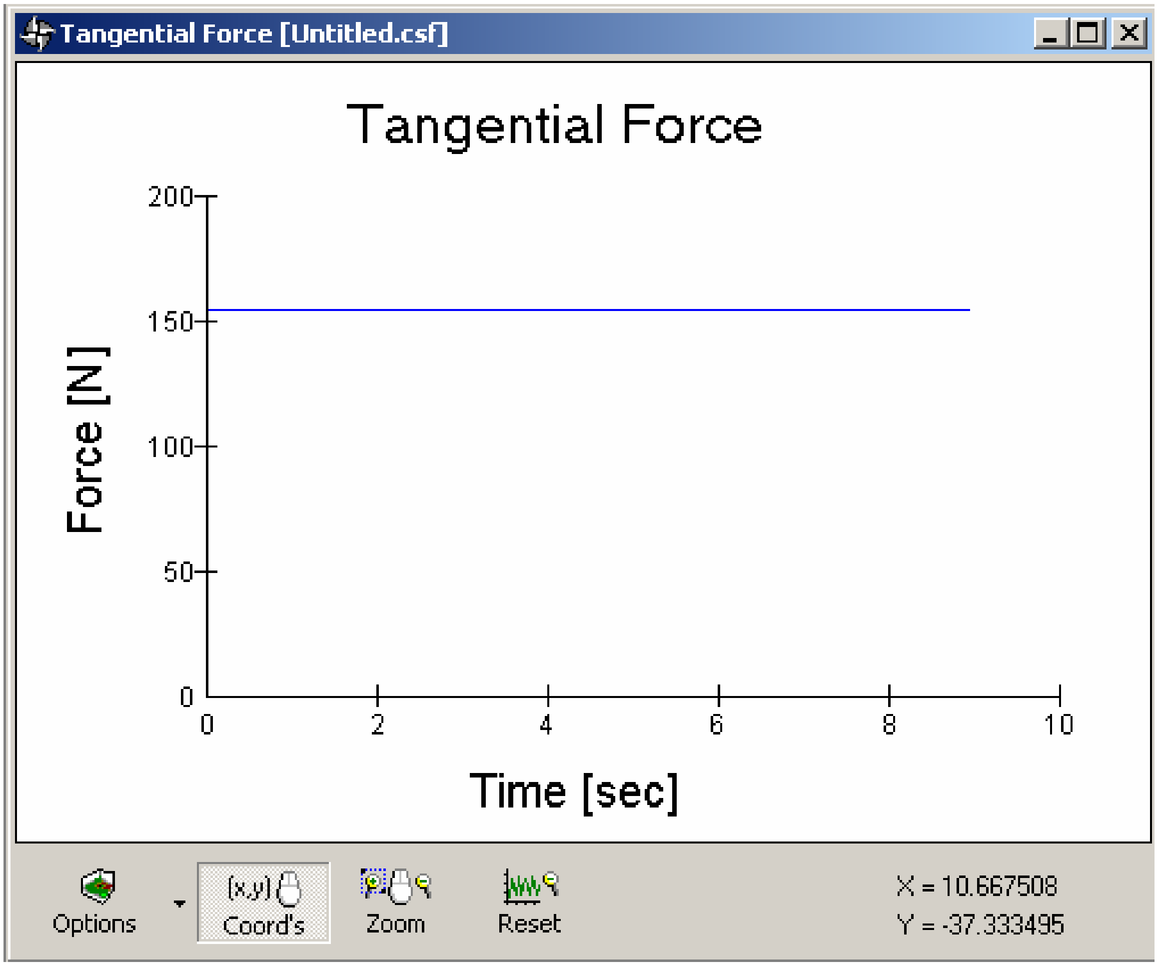
5.4.2 TURNING MODULE PLOTS

5.4.2.1 CUTTING FORCES



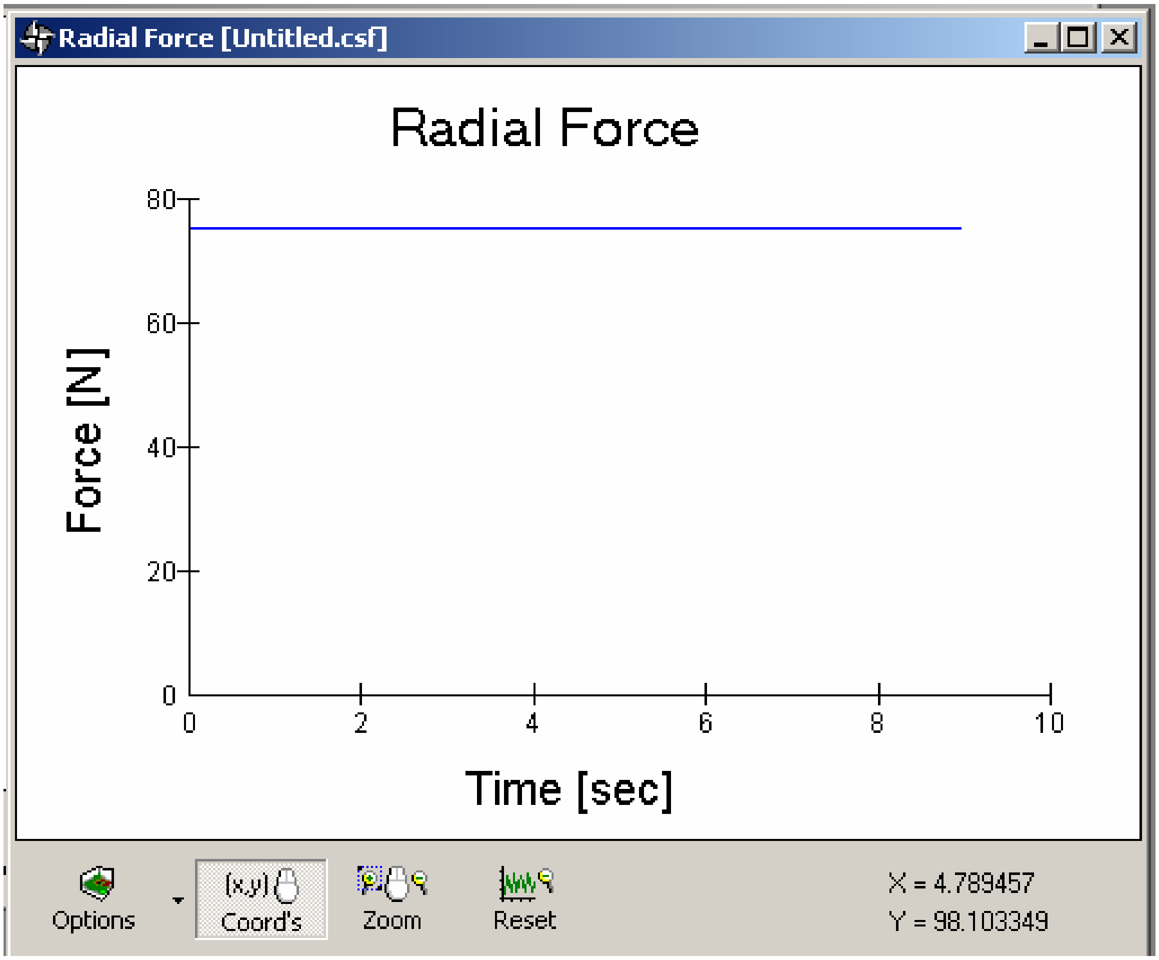
This plot shows the cutting forces in the X, Y, and Z directions in three different colours. Please refer to Figure 2.1-1 in Section 2.1 Milling Module for the axes definitions of X, Y, Z.

5.4.2.2 TANGENTIAL FORCE



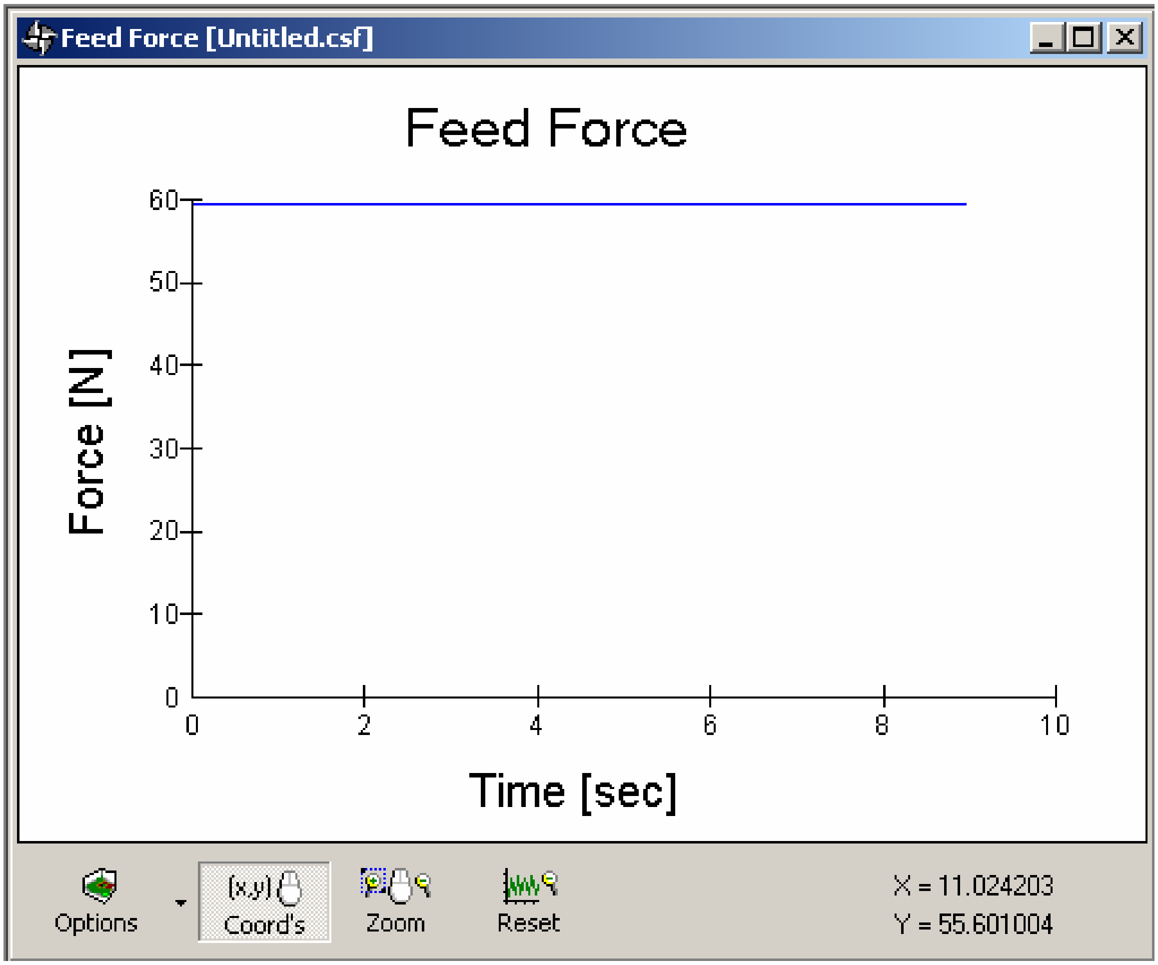
This plot shows the cutting force in the tangential direction.

5.4.2.3 RADIAL FORCE



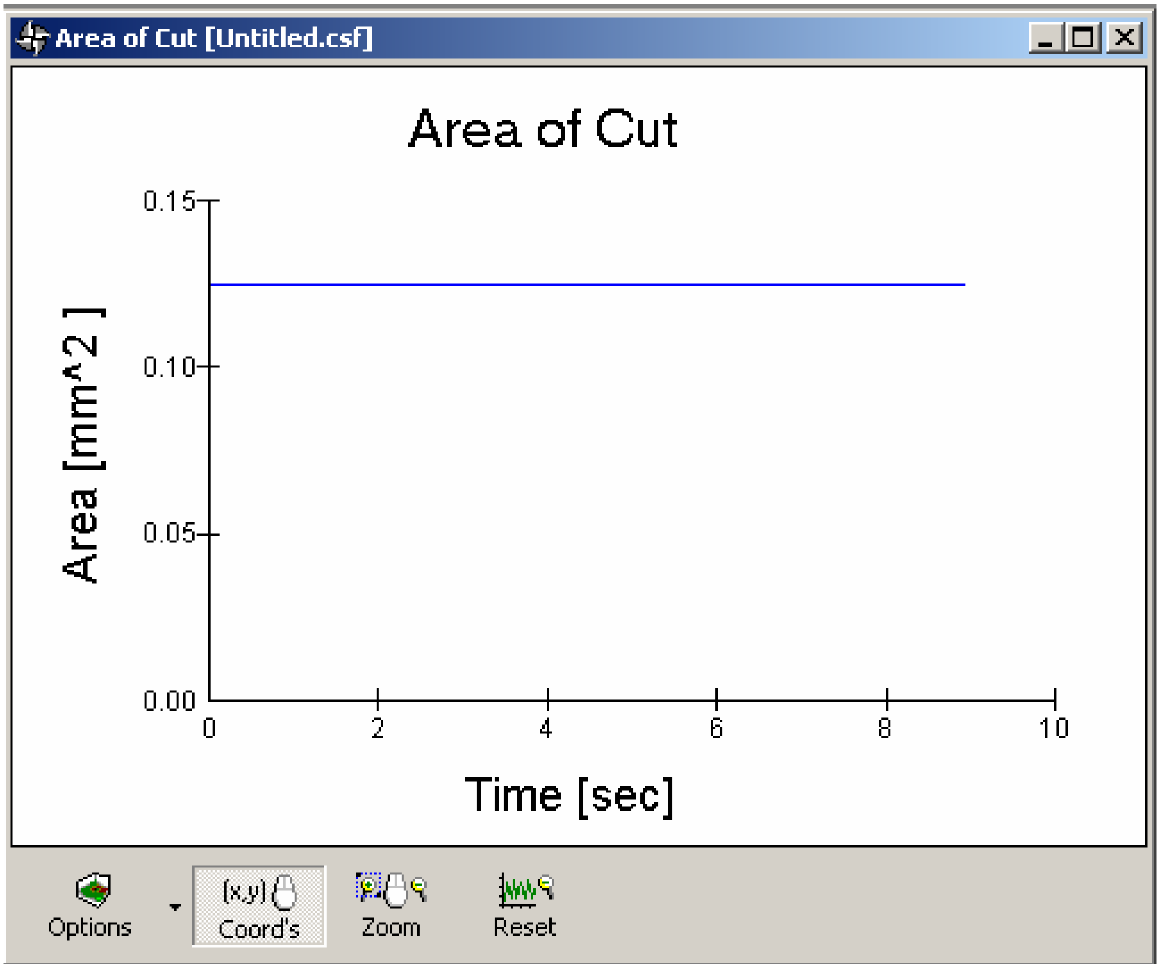
This plot shows the cutting force in the radial direction.

5.4.2.4 FEED FORCE



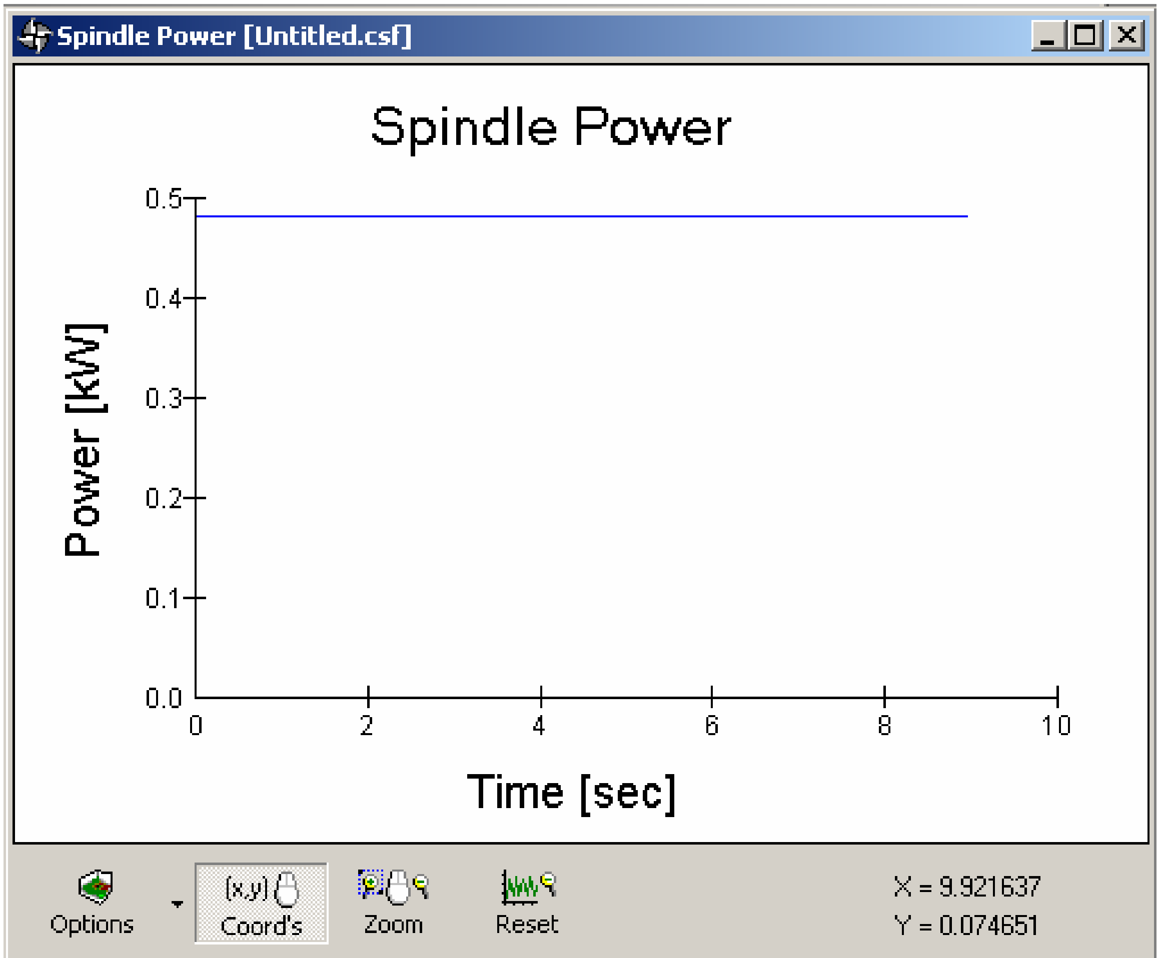
This plot shows the cutting force in the feed direction.

5.4.2.5 AREA OF CUT



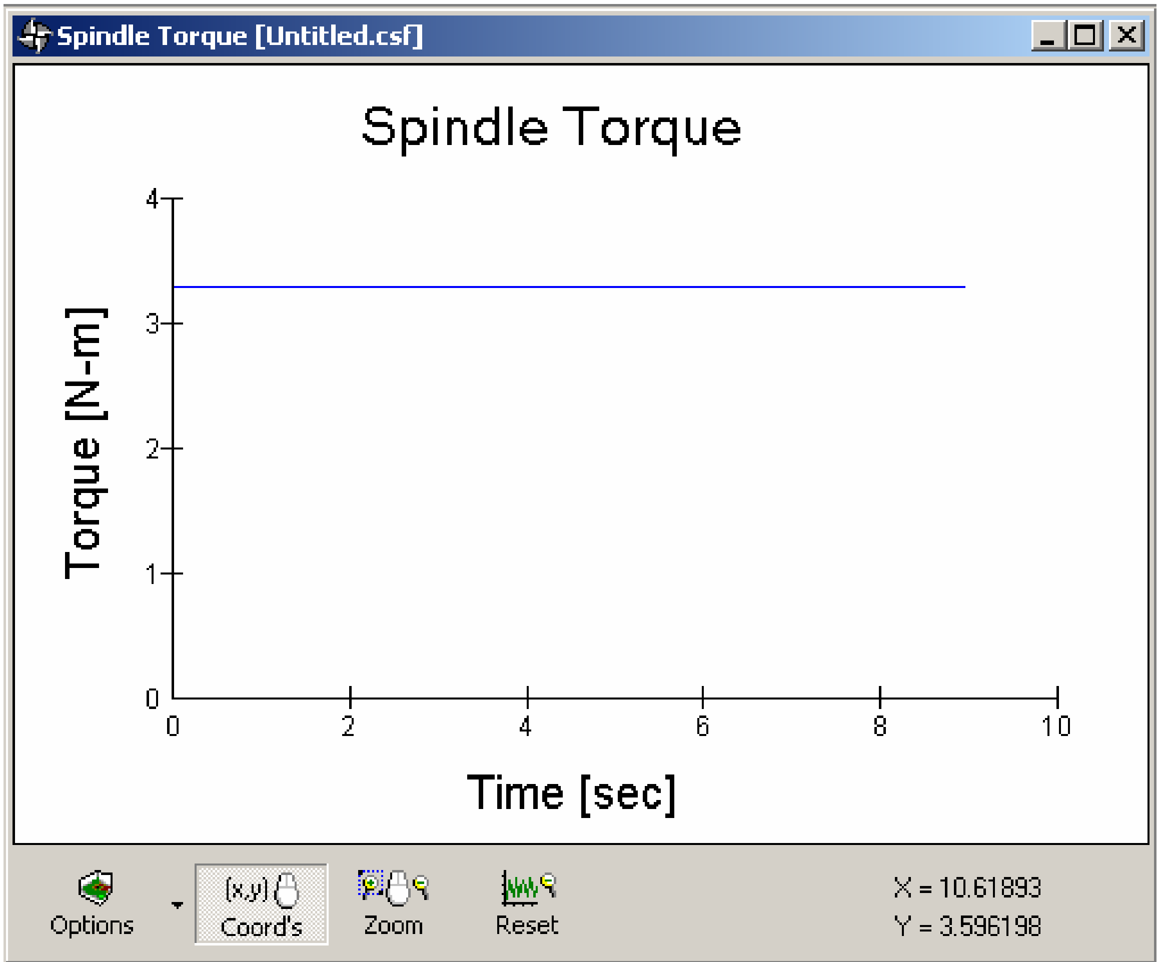
This plot shows the area of cut.

5.4.2.6 SPINDLE POWER



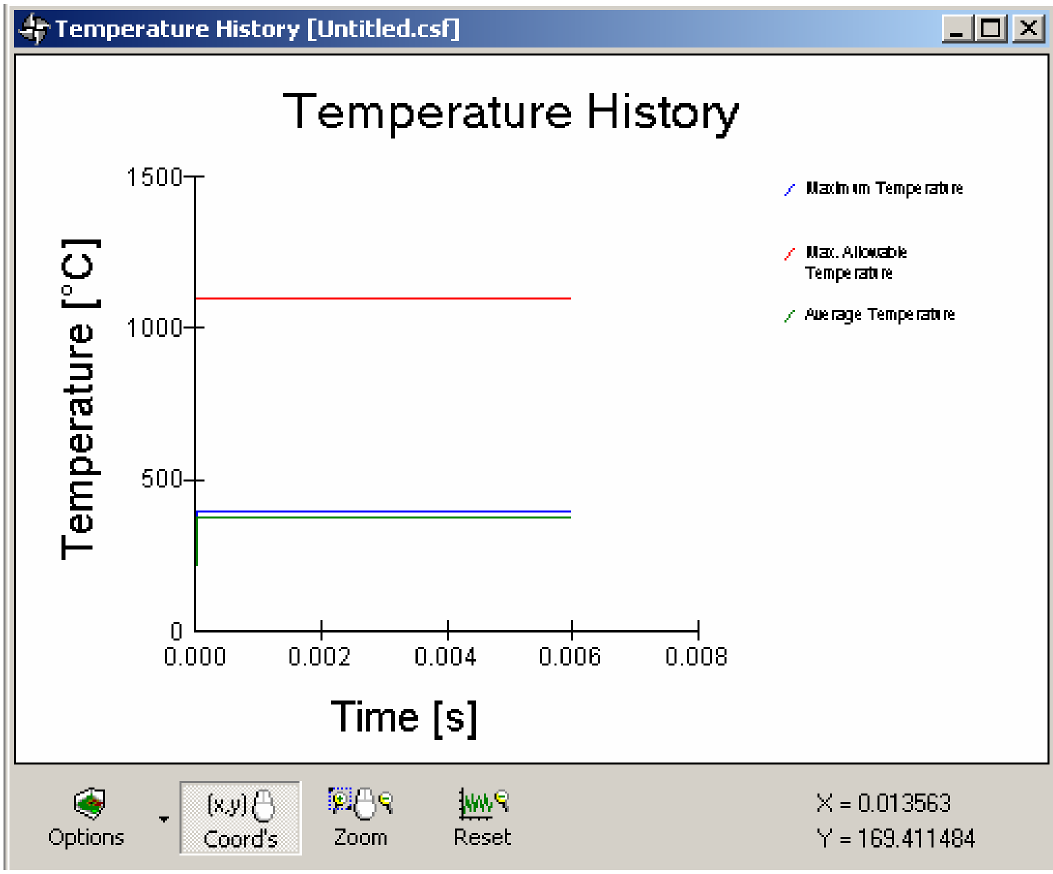
This plot shows the spindle power.

5.4.2.7 SPINDLE TORQUE



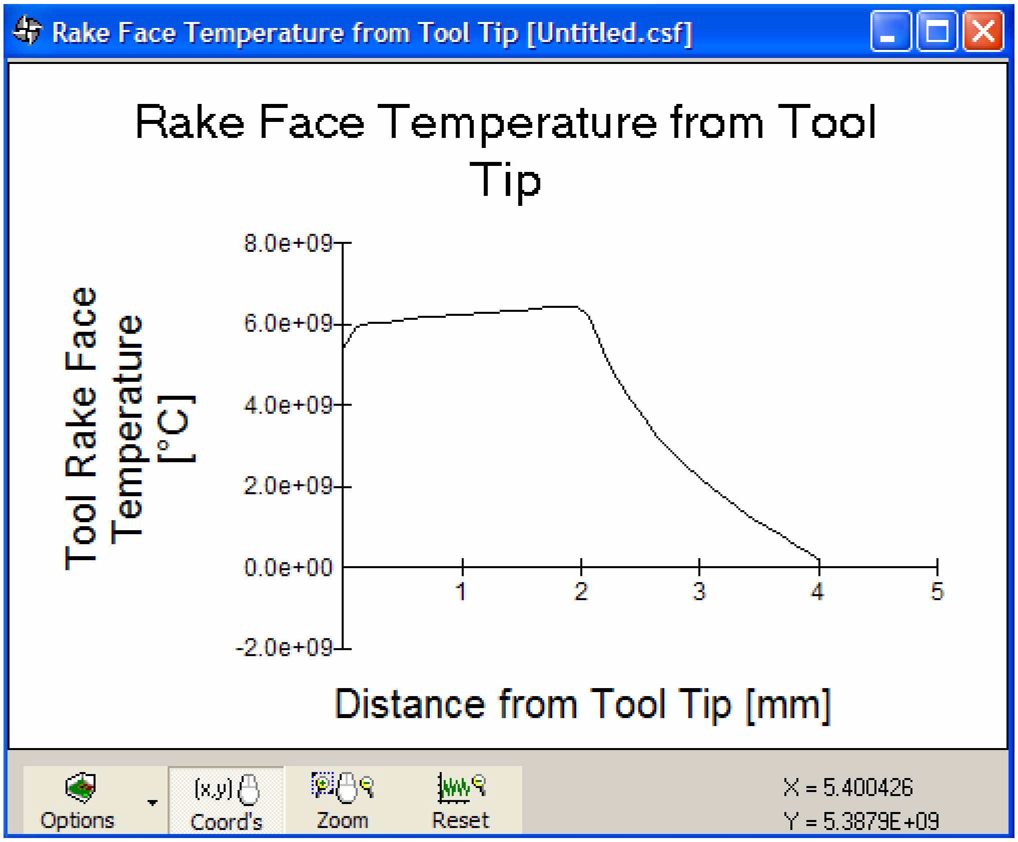
This plot shows the Spindle Torque.

5.4.2.8 TEMPERATURE HISTORY



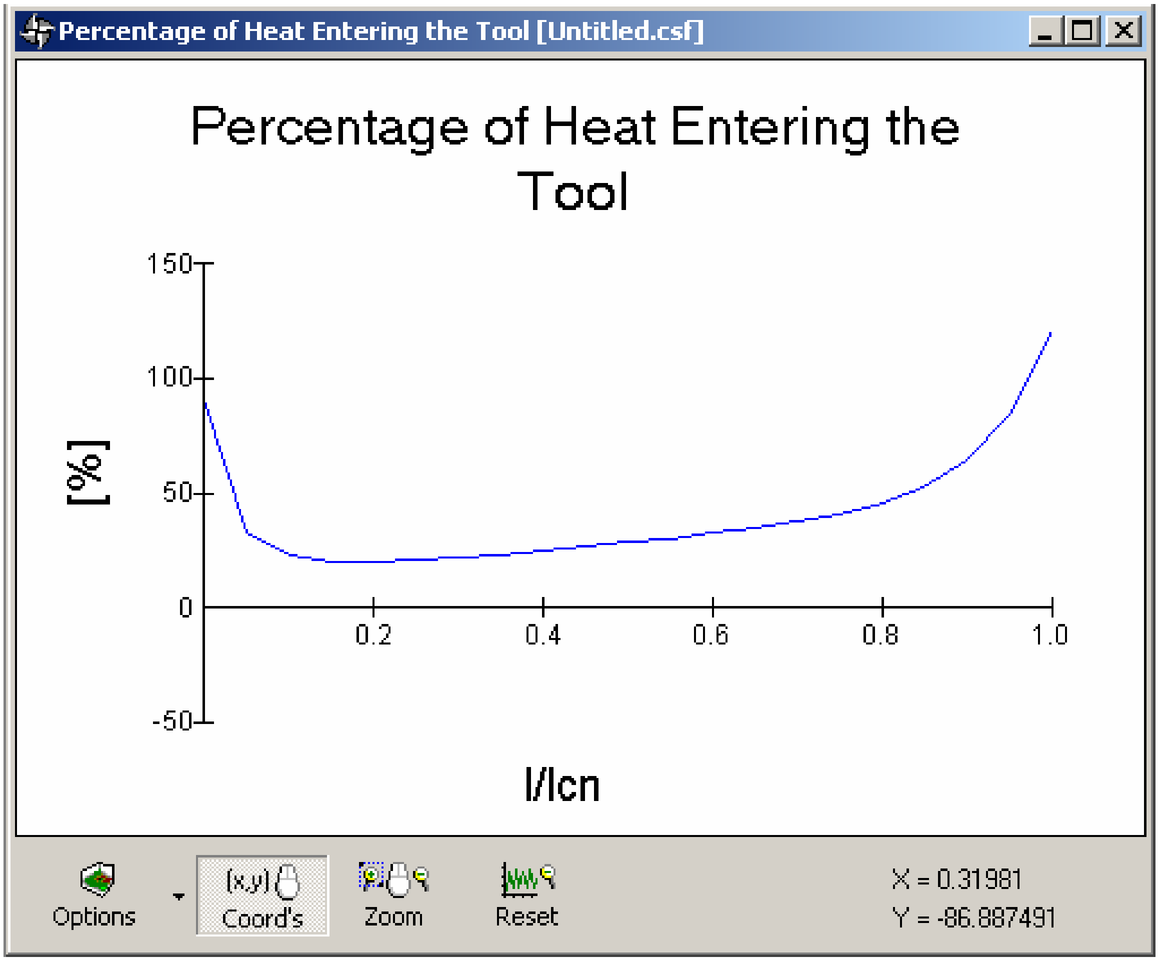
This plot shows the temperature history during the cut. Please refer to Section 3.1.10 TEMPERATURE/PROPERTIES for more information regarding Temperature Simulation

5.4.2.9 RAKE FACE TEMPERATURE FROM TOOL TIP



This plot shows the temperature profile along the rake face of the tool, measured from the tool tip to the contact length.

5.4.2.10 PERCENTAGE OF HEAT ENTERING THE TOOL



This plot shows the percentage of heat entering the tool as a function of the fractional length along the contact length on the tool rake face (l/lcn). Please refer to Figure 5.4.2-1 below to get a definition for l and lcn.

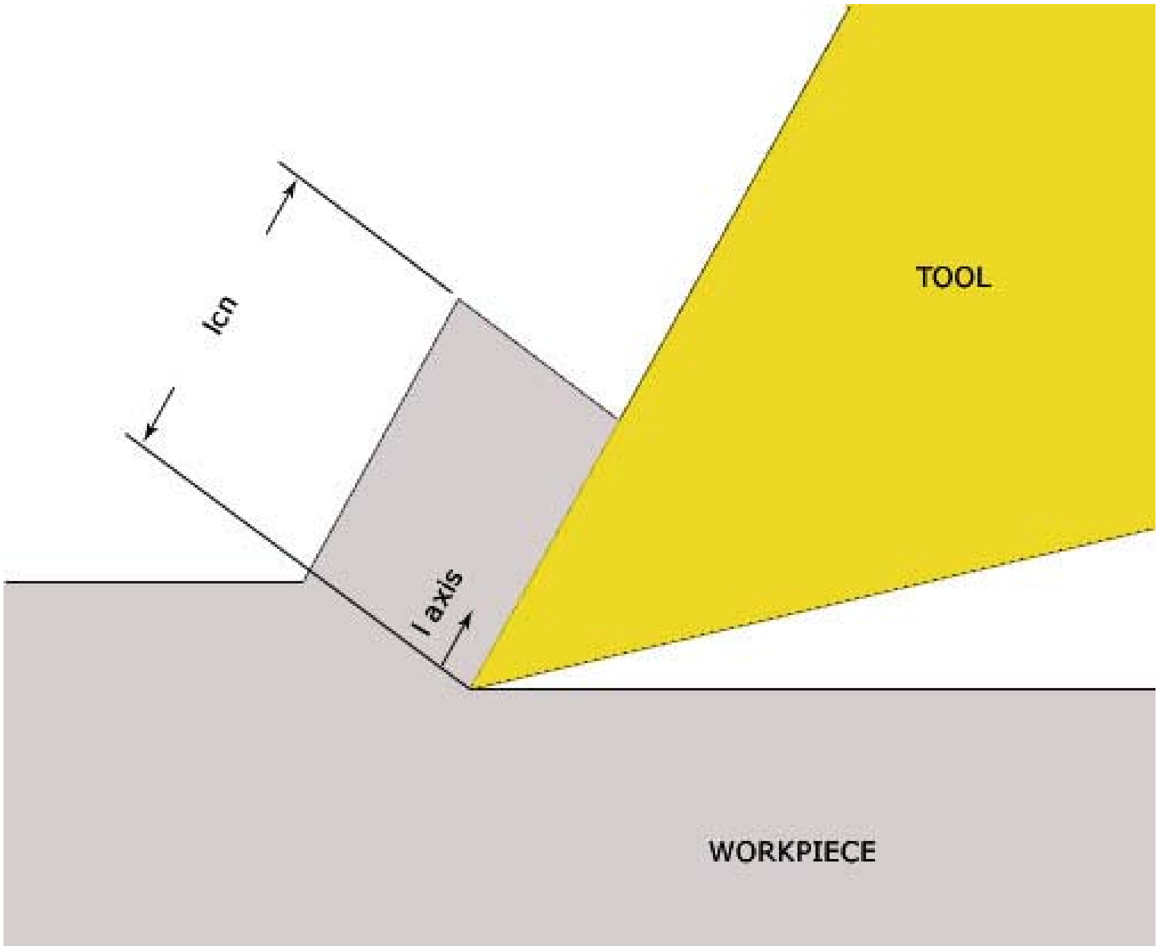


Figure 5.4.2-1: Definition of 'l' and 'lcn'

5.4.2.11 MATLAB TEMPERATURE PLOTS

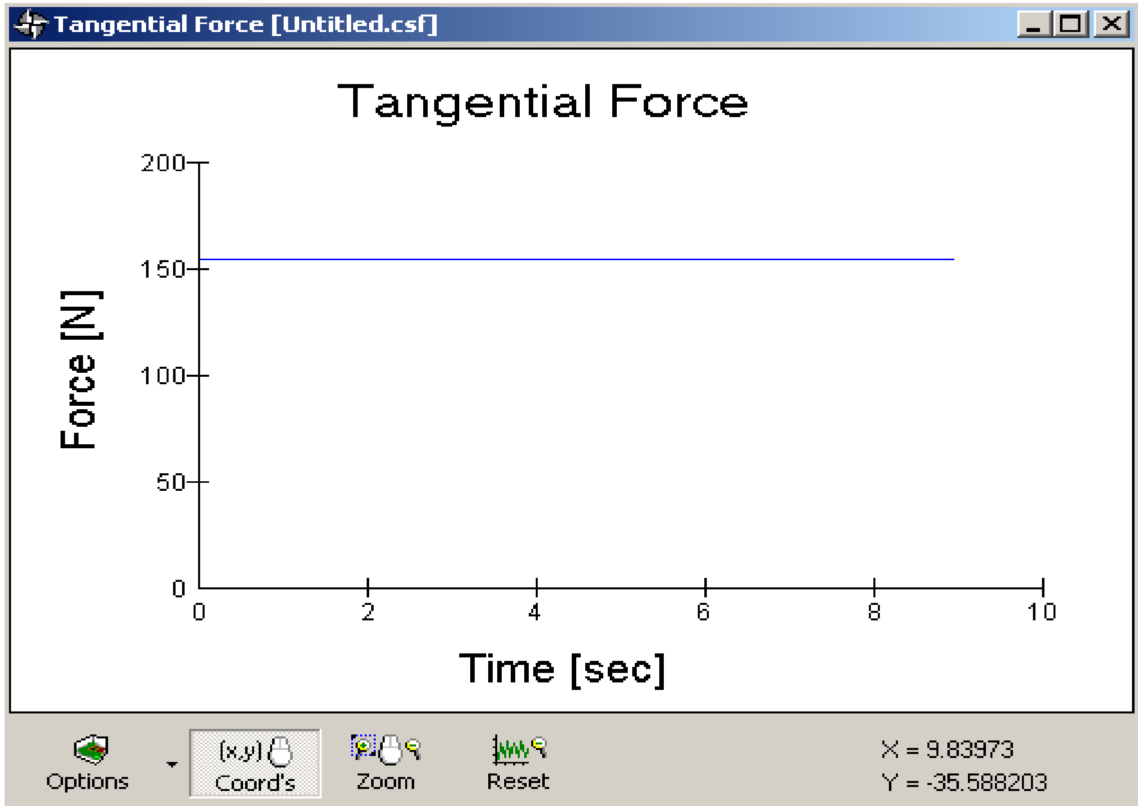
Please refer to the temperature plots starting in Section 1.1.1.1 for a description of the available results from MATLAB.

5.4.3 BORING MODULE PLOTS

5.4.3.1 CUTTING FORCES

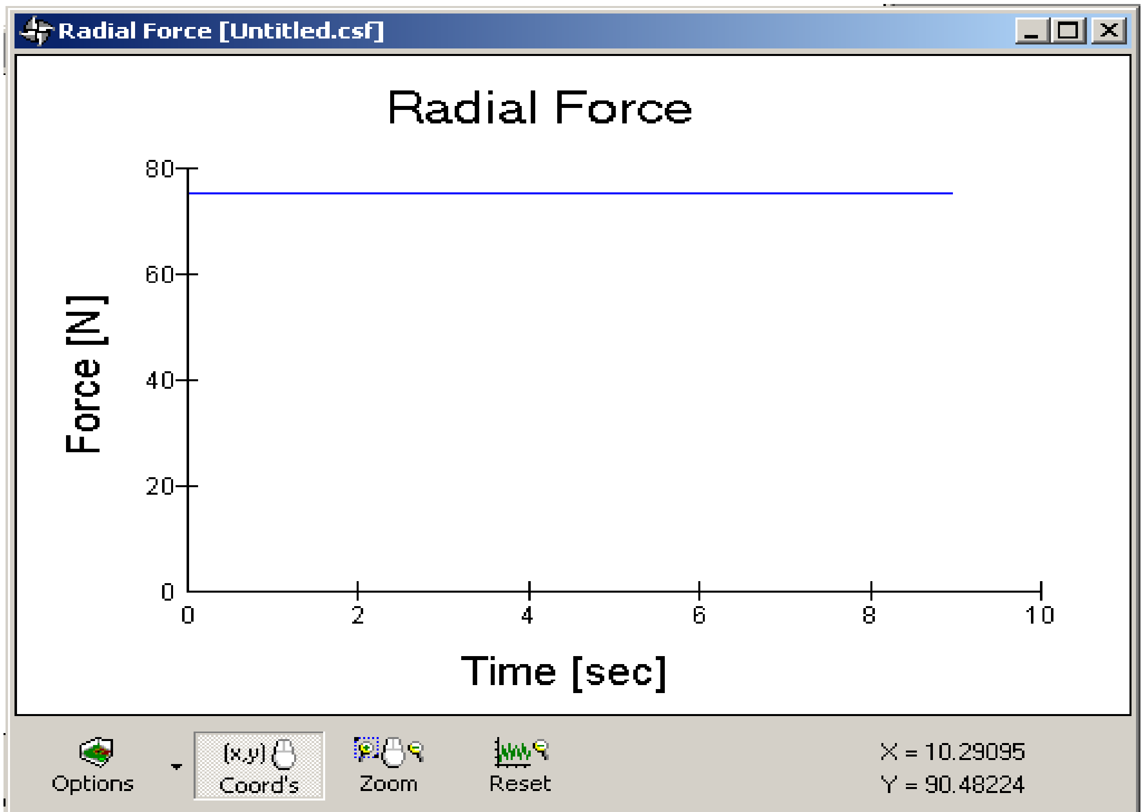
This figure shows the cutting forces in the X, Y, and Z directions, in three different colours. Please refer to Figure 2.3-2 in Section 2.4 BORING MODULE for the definitions of the axes.

5.4.3.2 TANGENTIAL FORCE



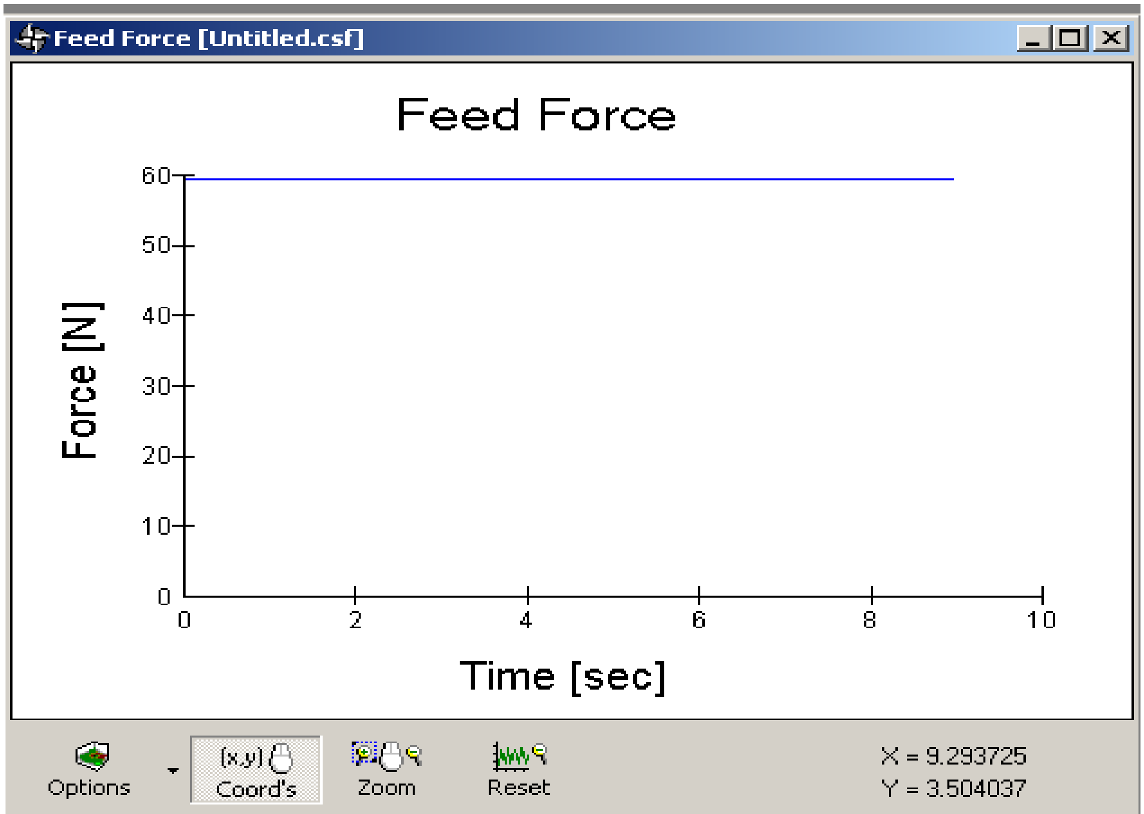
This result shows the force in the tangential direction.

5.4.3.3 RADIAL FORCE



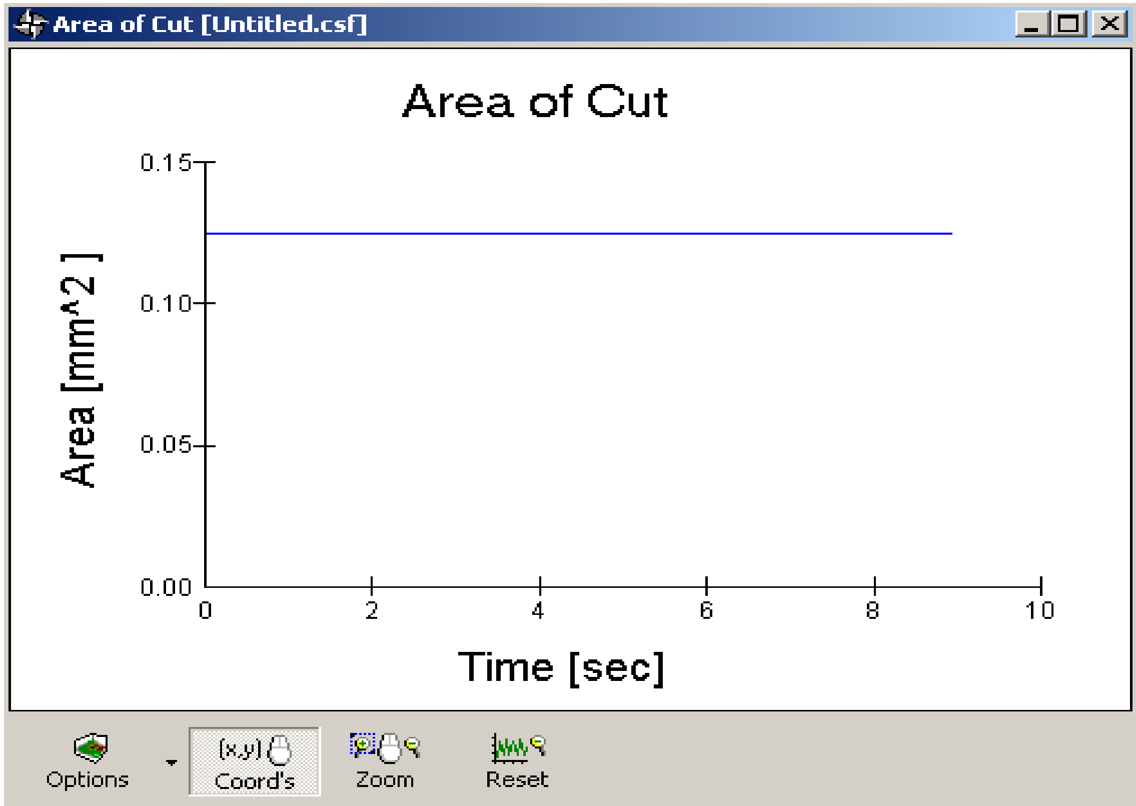
This figure displays the force in the radial direction.

5.4.3.4 FEED FORCE



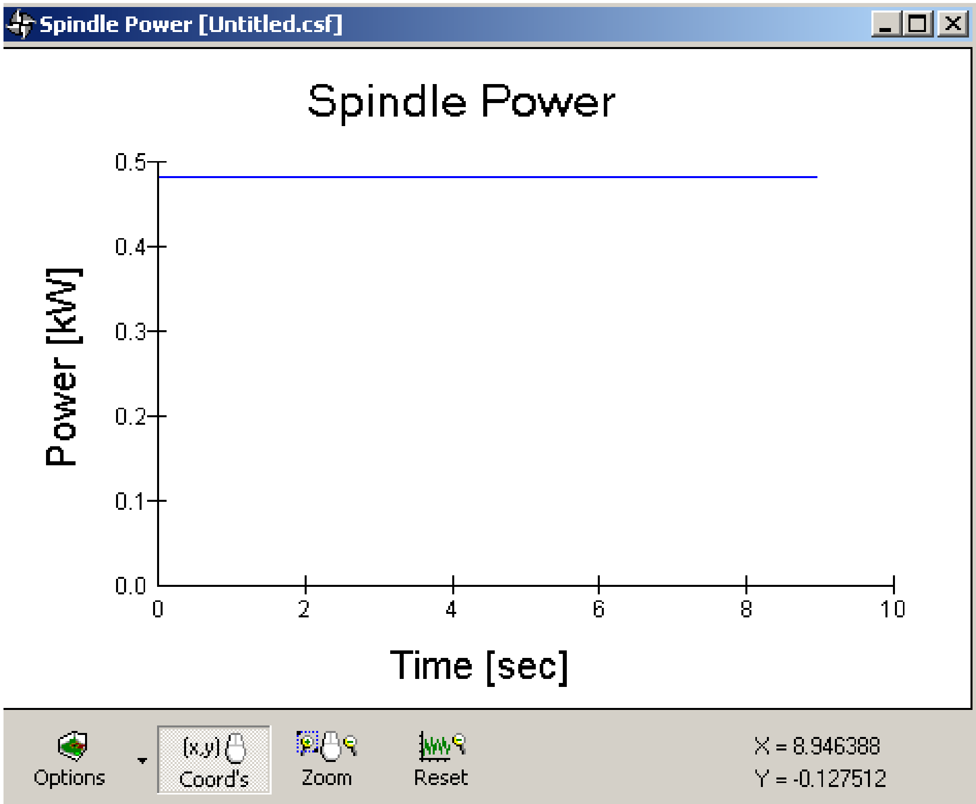
This figure shows the force in the feed direction.

5.4.3.5 AREA OF CUT



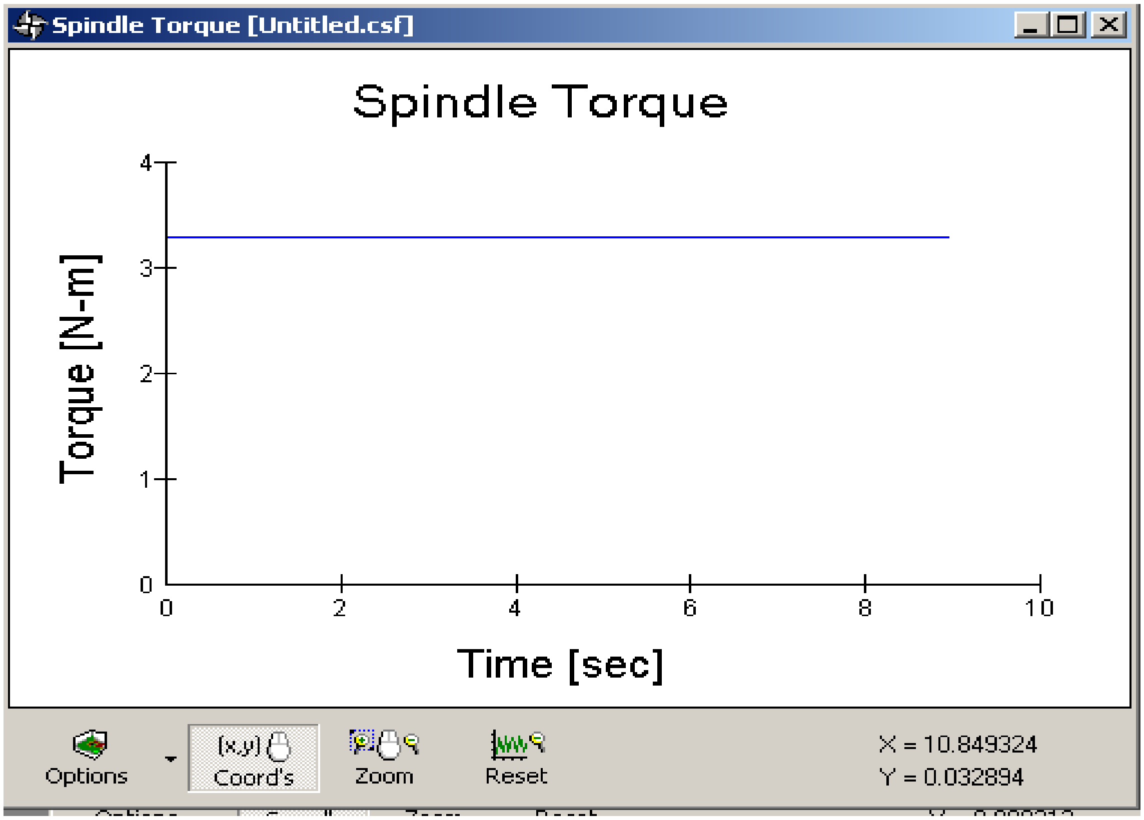
The area of cut in the boring process.

5.4.3.6 SPINDLE POWER



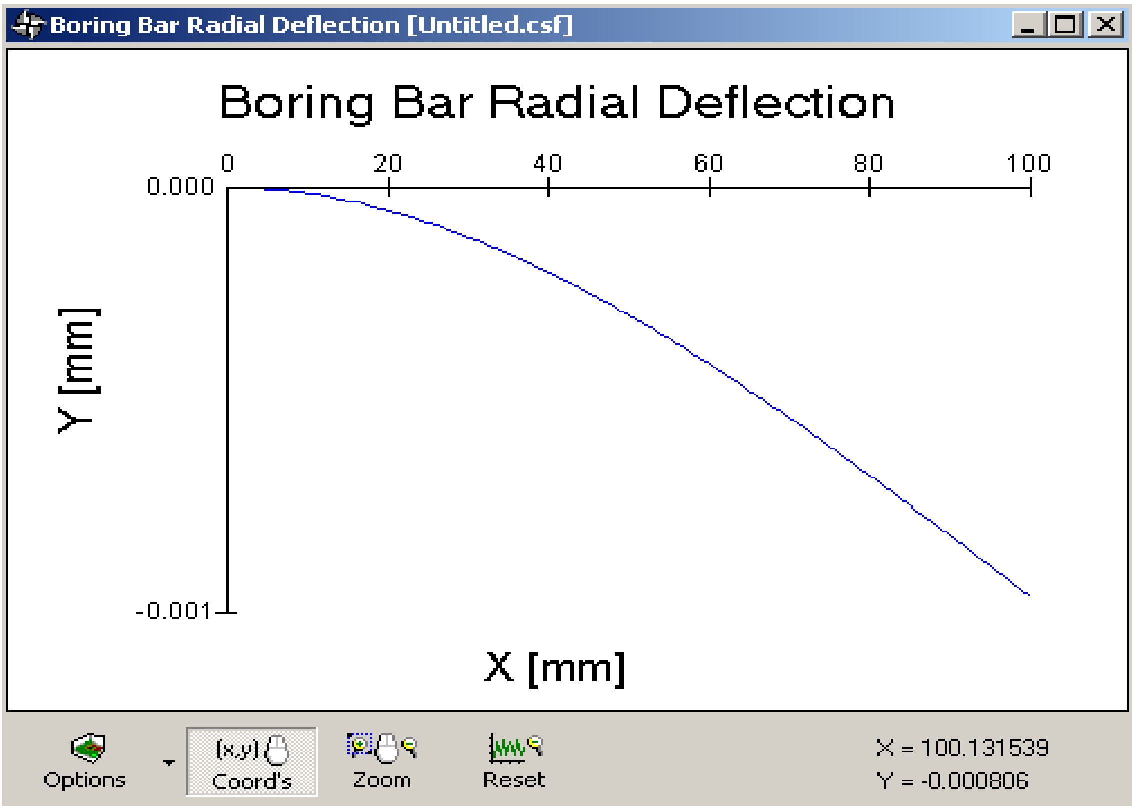
This plot shows the Spindle Power.

5.4.3.7 SPINDLE TORQUE



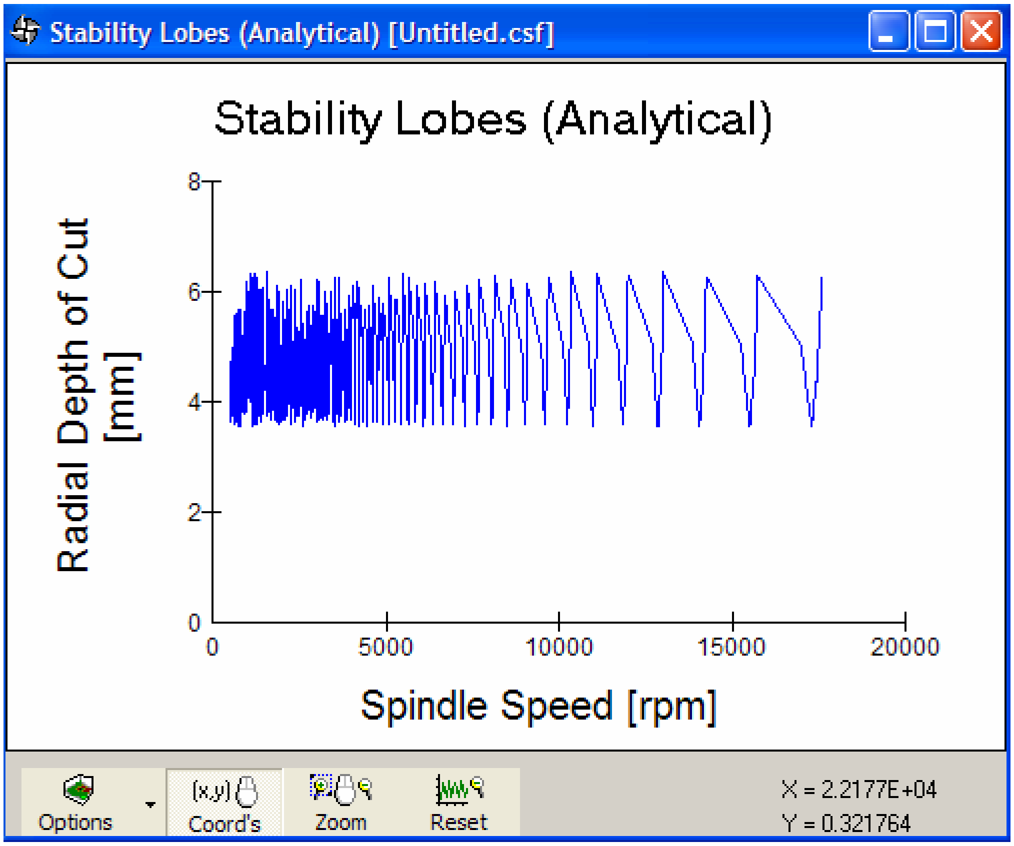
This plot shows the Spindle Torque.

5.4.3.8 BORING BAR RADIAL DEFLECTION



The radial deflection of the boring bar is displayed in this plot. X is the length along the boring bar, and Y is the radial deflection.

5.4.3.9 ANALYTICAL STABILITY LOBES



This plot displays the analytical stability lobes in the frequency domain.

5 SAVING RESULTS & RESULTS FORMAT

After a simulation is run, the entire simulation can be saved in a .csf (CutPro Simulation File) file. Individual results can also be exported into text files in ASCII format. The following is a description and instruction of saving .csf files and exporting results.

5.1 SAVING CUTPRO SIMULATION FILES

Before or after a simulation is run, the simulation can be saved in a .csf file. If the simulation has not been run, only the properties of the simulation will be saved (i.e. the tool material, workpiece material, cutting conditions, etc). If the simulation has been run already, the simulation properties as well as the results will be saved in the .csf file.

To save a simulation file, simply click Save on the main window toolbar:

Or, the file can be saved by clicking *File → Save*.

If a simulation file is open and you wish to save it under a different name, click *File → Save As* and a *Save Document* window will appear. Type in the desired file name and click *Save*.

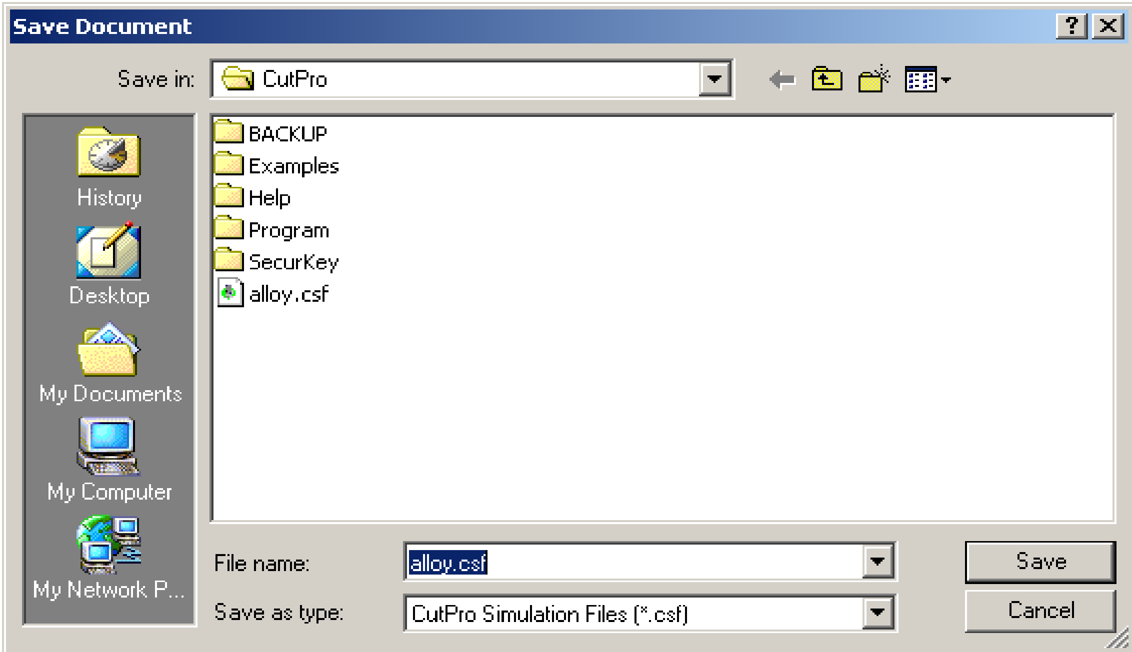
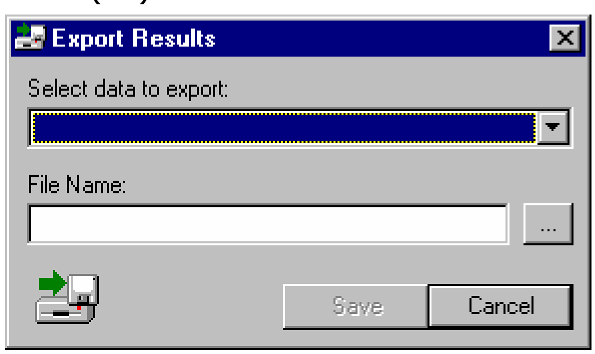


Figure 5.1-1: Save Document window

5.2 EXPORTING RESULTS

Select *Export* from the *Results* menu, then specify the ASCII text file (*.txt) to which you want to export it. The exportable results change after every simulation. You can either type the name of a text file in the box provided, or find an existing file to write over by pressing the browse (...) button.



The output file is in **ASCII** format. The format description is in the following section [6.3 RESULTS FORMATS](#).

5.3 RESULTS FORMATS

5.3.1 FORCES IN X, Y, Z AND TANGENTIAL DIRECTIONS

The first column is time [sec]

The second column is cutter rotation angle [deg]

The third column is Fx force [N]

The fourth column is Fy force [N]

The fifth column is Fz force [N]

The sixth column is Ft tangential force [N]

Example:

0.0000E+00	0.0000E+00	-3.4969E+01	3.6653E+01	-2.4108E+00	-3.5117E+01
1.2500E-04	4.5000E+00	-3.5070E+01	3.7246E+01	-2.5750E+00	-3.5706E+01
2.5000E-04	9.0000E+00	-6.7297E+01	8.1075E+01	-6.1615E+00	-7.5037E+01

5.3.2 TOOL VIBRATIONS IN X AND Y DIRECTIONS

The first column is time [sec]

The second column is vibration in X direction [mm]

The third column is vibration in Y direction [mm]

Example:

0.0000E+00	6.0987E-04	2.4275E-03
1.2500E-04	1.4336E-03	6.8409E-03
2.5000E-04	1.4878E-03	1.0149E-02

5.3.3 WORKPIECE VIBRATIONS IN X AND Y DIRECTIONS

Same as Tool Vibrations in X & Y Directions

5.3.4 UPMILLING SURFACE FINISH

The first column is point number

The second column is X coordinate value of the point [mm]

The third column is Y coordinate value of the point [mm]

The fourth column is Z coordinate value of the point [mm]

Example:

0.0000E+00	2.9167E-01	-2.9078E+00	-8.8399E-02
1.0000E+00	2.9167E-01	-2.8585E+00	-9.2159E-02
2.0000E+00	2.9167E-01	-2.8092E+00	-9.5662E-02

5.3.5 DOWNMILLING SURFACE FINISH

See Upmilling Surface Finish above.

5.3.6 CHIP THICKNESS (MIDDLE OF CUT)

The first column is time [sec]

The second column is chip thickness for flute number 1 [mm]

The third column is chip thickness for flute number 2 [mm]
The fourth column is chip thickness for flute number 3 [mm]
The fifth column is chip thickness for flute number 4 [mm]

The number of column will be change with number of flute

Example:

0.0000E+00	0.0000E+00	3.0453E-03	0.0000E+00	0.0000E+00
1.2500E-04	0.0000E+00	3.7579E-03	0.0000E+00	0.0000E+00
2.5000E-04	0.0000E+00	5.4013E-03	0.0000E+00	0.0000E+00

5.3.7 SPINDLE POWER

The first column is time [sec]
The second column is instantaneous spindle power [HP]
The third column is cumulative average spindle power [HP]

Example:

0.0000E+00	2.8183E-01	2.8183E-01
1.2500E-04	2.8656E-01	2.8421E-01
2.5000E-04	6.0222E-01	4.1802E-01

5.3.8 SPINDLE BENDING MOMENT

The first column is time [sec]
The second column is instantaneous bending moment [Nm]
The third column is cumulative average bending moment [Nm]

Example:

0.0000E+00	1.0132E+01	1.0132E+01
1.2500E-04	1.0232E+01	1.0182E+01
2.5000E-04	2.1073E+01	1.4736E+01

5.3.9 TIME DOMAIN STABILITY LOBES

The first column is spindle speed [rev/min]
The second column is axial depth of cut [mm]

Example:

2.0000E+03	3.4768E+00
2.1000E+03	1.4742E+01
2.2000E+03	1.0761E+01

5.3.10 ANALYTICAL STABILITY LOBES

The first column is spindle speed [rev/min]
The second column is axial dept of cut limit [mm]

The third column is chatter frequency [Hz]

Example:

2.2500E+02	1.7099E+01	4.4815E+02
2.3000E+02	1.3297E+01	4.5767E+02
2.3500E+02	1.0492E+01	4.6707E+02

5.3.11 ANALYTICAL STABILITY LOBES (VARIABLE PITCH)

The first column is spindle speed [rev/min]

The second column is axial dept of cut limit [mm]

The third column is chatter frequency [Hz]

The fourth column is phase shift for flute number 1 [deg]

The fifth column is phase shift for flute number 2 [deg]

The sixth column is phase shift for flute number 3 [deg]

The seventh column is phase shift for flute number 4 [deg]

The number of columns will change with the number of flutes

Example:

1.0947E+03	2.7511E+01	4.3178E+02	3.3500E+02	3.2500E+02	3.3500E+02	3.2500E+02
5.4350E+02	2.7511E+01	4.3178E+02	3.3500E+02	3.2500E+02	3.3500E+02	3.2500E+02
3.6149E+02	2.7511E+01	4.3178E+02	3.3500E+02	3.2500E+02	3.3500E+02	3.2500E+02

5.3.12 MULTIPLE ANALYTICAL STABILITY LOBES

The first column is y offset value between tool center and workpiece center [mm]

The second column is spindle speed [rev/min]

The third column is axial dept of cut limit [mm]

Example:

-1.9050E+01	2.2500E+02	1.7099E+01
-1.9050E+01	2.4000E+02	8.5334E+00
-1.9050E+01	2.5500E+02	6.9170E+00

5.3.13 OPTIMUM PITCH ANGLES

The first column is axial depth of cut limit [mm]

The second column is phase shift for flute number 1 [deg]

The third column is phase shift for flute number 2 [deg]

The fourth column is phase shift for flute number 3 [deg]

The fifth column is phase shift for flute number 4 [deg]

The number of column will be change with number of flute

Example:

3.0508E+01	9.0000E+00	1.7100E+02	9.0000E+00	1.7100E+02
2.9523E+01	1.0000E+01	1.7000E+02	1.0000E+01	1.7000E+02
2.7873E+01	1.1000E+01	1.6900E+02	1.1000E+01	1.6900E+02

5.3.14 EXPERIMENTAL AVERAGE CUTTING FORCES

The first column is feed-rate [mm/tooth]

The second column is experimental Fx average force [N]

The third column is experimental Fy average force [N]

The fourth column is experimental Fz average force [N]

Example:

5.0000E-02	1.0380E+02	1.4642E+02	-5.1815E+01
7.5000E-02	1.1600E+02	1.8847E+02	-7.0230E+01
1.0000E-01	1.2112E+02	2.4060E+02	-8.2586E+01

6 MODAL ANALYSIS

CutPro includes its own modal analysis software, which may be run from the **Tools** menu in the **Main CutPro Window**. The software reads either an acceleration or displacement frequency response function (FRF) file and generates modal parameters which may be used in CutPro to define the **Machine** and **Workpiece dynamics**.

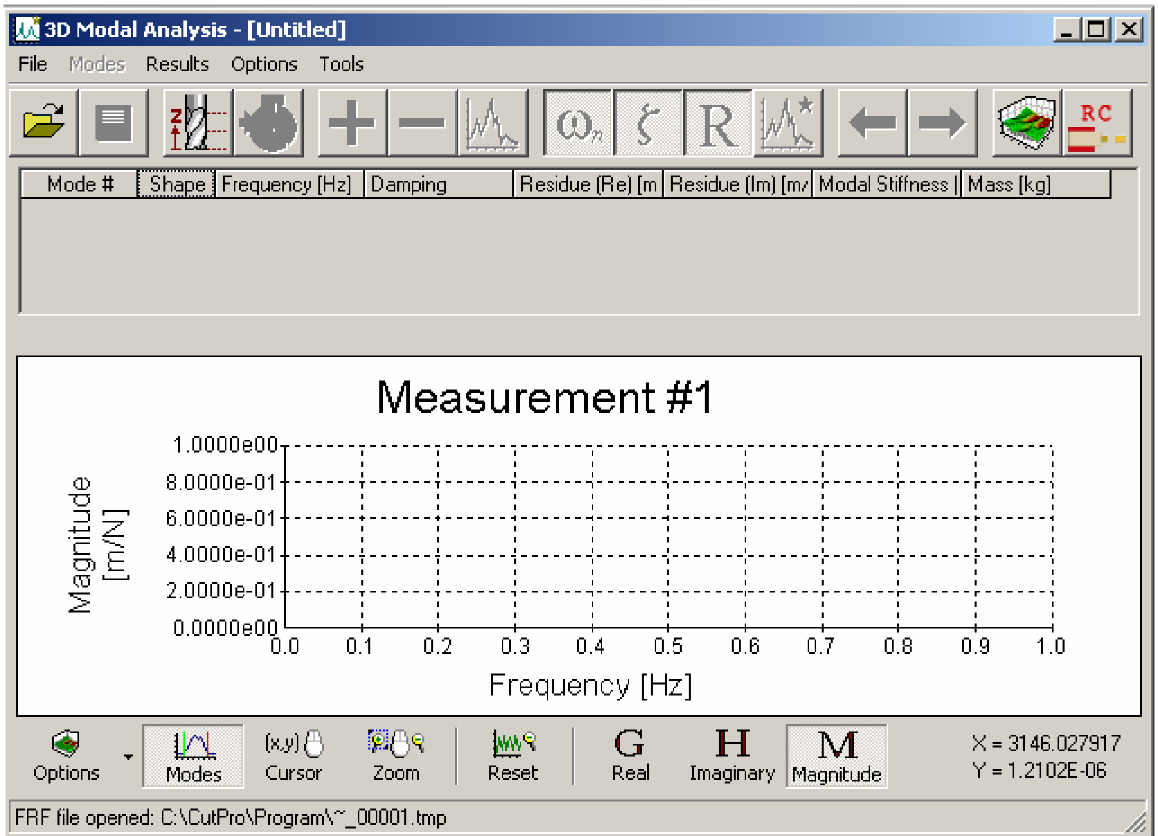


Figure 5.3-1: Modal Analysis window

6.1 3D MODAL ANALYSIS MENU

File

New	*Create a new 3D modal analysis file (*.mod)*
Open	*Open a 3D modal analysis file (*.mod)*
Save	*Save the current .mod file*
Save As	*Save the currently opened modal analysis file under a different name.*
Select FRF Files	*Open Frequency Response Function (Transfer Function) measurement files from the Select FRF Files window (Please see Section 6.3).*
Save	Bring up the standard *Windows Save dialog*, allowing

Para-meters	you to save the current modal parameters for use in CutPro.
Print	Print the currently displayed modal graph
Printer Setup	Bring up the standard Windows Printer Setup dialog, which allows you to select a printer and change print options such as paper size.
Copy Plot	Copies the graph onto the clipboard as a bitmap; to save as a file, click paste on a picture editing software.
Exit	Exit modal analysis

Modes

Add Mode	*Add the currently selected mode.*
Delete Mode	*Delete the mode currently selected in the **Modes Table**.*
Plot Modes	*Plot the currently defined modes, without optimization. See Defining and optimizing modes in Section 6.5 for more details.*
Display Modal Matrix	*Display the Modal Matrix in a new window*
Optimize	*Optimize the currently defined modes. See Defining and optimizing modes in Section 6.5 for more details.*

Results

Report	*Display the summary of simulation conditions*

Options

Units	*Change units between metric and imperial*
Language	*Change language among English, French, and German*

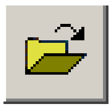
Tools

Receptive Coupling	*Open the Receptive Coupling window. Please see Section 6.9 RECEPTANCE COUPLING for more details.*

6.2 MODAL ANALYSIS WINDOW TOOLBAR BUTTONS

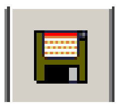
6.2.1 TOP TOOLBAR

6.2.1.1 OPEN



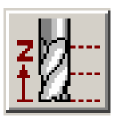
Same function as File → Open. Please see Section 6.1 3D MODAL ANALYSIS MENU.

6.2.1.2 SAVE



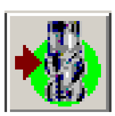
Same function as File → Save. Please see Section 6.1 3D MODAL ANALYSIS MENU.

6.2.1.3 SELECT FRF FILES



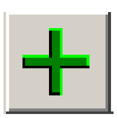
Same function as File → Select FRF Files. Please see Section 6.1 3D MODAL ANALYSIS MENU.

6.2.1.4 SAVE MODAL PARAMETERS



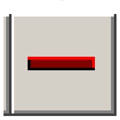
Same function as File → Save Parameters. Please see Section 6.1 3D MODAL ANALYSIS MENU.

6.2.1.5 ADD MODE



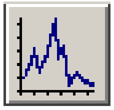
Same function as Modes → Add Mode. Please see Section 6.1 3D MODAL ANALYSIS MENU.

6.2.1.6 DELETE MODE

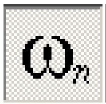


Same function as Modes → Delete Mode. Please see Section 6.1 3D MODAL ANALYSIS MENU.

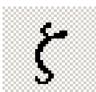
6.2.1.7 PLOT MODES

 Same function as Modes → Plot Modes. Please see Section 6.1 3D MODAL ANALYSIS MENU.

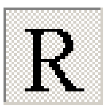
6.2.1.8 OPTIMIZE NATURAL FREQUENCY

 Select this button if you wish to optimize the natural frequency.

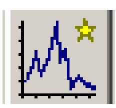
6.2.1.9 OPTIMIZE DAMPING RATIO

 Select this button if you wish to optimize the damping ratio.

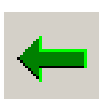
6.2.1.10 OPTIMIZE RESIDUES

 Select this button if you wish to optimize the residues.

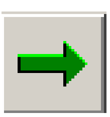
6.2.1.11 PERFORM OPTIMIZATION

 Same function as Modes → Optimize. Please see Section 6.1 3D MODAL ANALYSIS MENU.

6.2.1.12 SHOW PREVIOUS MEASUREMENT

 Shows the previous measurement. This button is enabled only when a previous measurement is present.

6.2.1.13 SHOW NEXT MEASUREMENT

 Shows the next measurement. This button is enabled only when a next measurement is present.

6.2.1.14 DISPLAY GRAPH OPTIONS

 This button opens up a new window (Figure 6.2-1: Graph Control) allowing you to control the graph properties. Please refer

to the help file Graphppr.hlp in the Help directory for the details regarding Graph Control.

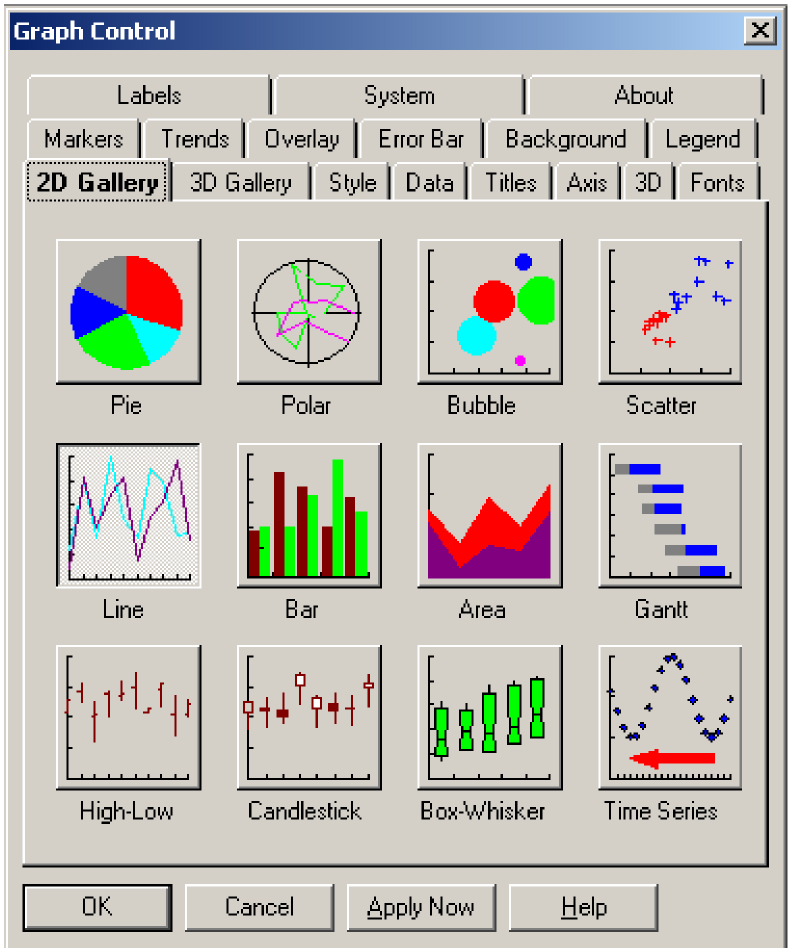
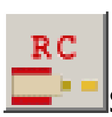


Figure 6.2-1: Graph Control

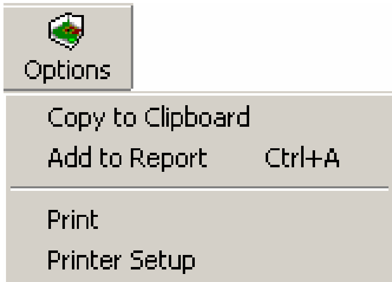
6.2.1.15 RECEPTANCE COUPLING



Same function as Tools → Receptance Coupling. Please see Section 6.1 3D MODAL ANALYSIS MENU.

6.2.2 BOTTOM TOOLBAR

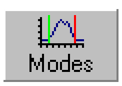
6.2.2.1 OPTIONS



The Options toolbar button provides five options:

Copy to Clipboard	*Copies the graph onto the clipboard as a bitmap; to save as a file, click paste on a picture editing software.*
Add to Report	*Adds the current result to the results Report*
Print	*Prints the graph on the current printer.*
Printer Setup	*Brings up the standard Windows* ***Printer Setup*** *window, allowing you to select the current printer and change other options such as paper size.*

6.2.2.2 MODES

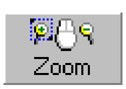


When this button is clicked, you may select and add modes on the graph. Use the left mouse button to select the left-most extent of a mode, and the right mouse button to select its right-most extent.

6.2.2.3 X-Y COORDINATES

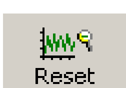
When this button is pressed, you may left-click on the graph to display the coordinates of a specific point.

6.2.2.4 ZOOM



When this button is pressed, you may use the left mouse button to click and drag a zoom rectangular on the graph. Use the right mouse button to go back to the previous view.

6.2.2.5 RESET



This button resets the original scale of the graph. It zooms out to the minimum magnification so the entire graph can be viewed.

6.2.2.6 REAL

When this button is clicked, real values are displayed on the graph.

6.2.2.7 IMAGINARY

When this button is clicked, imaginary values are displayed on the graph.

6.2.2.8 MAGNITUDE

When this button is clicked, magnitude (real + imaginary values) is displayed on the graph.

6.3 SELECTING FRF FILES

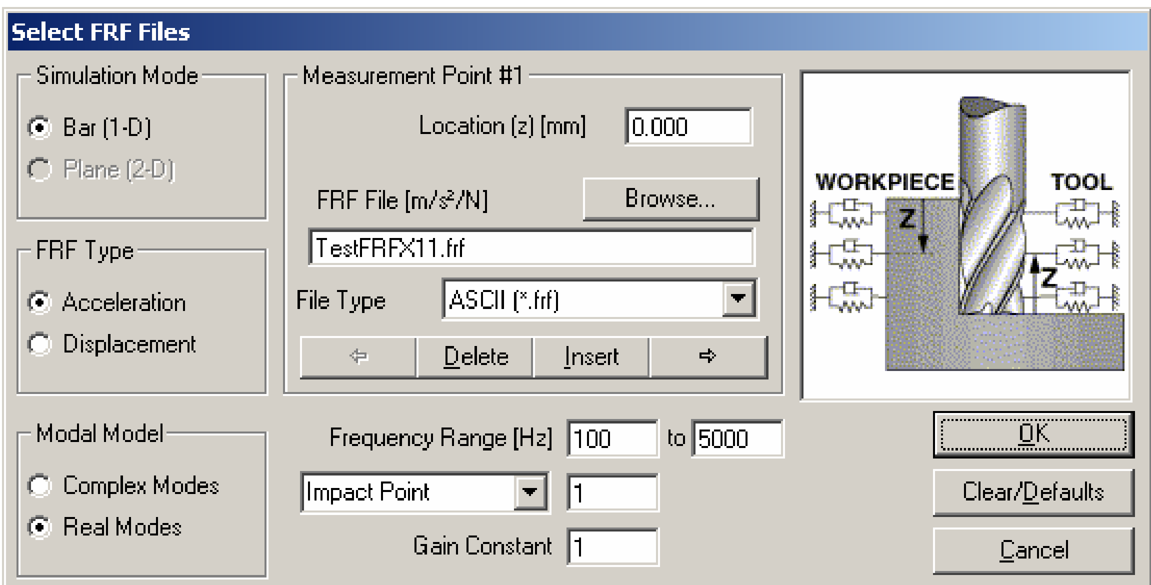


Figure 6.3-1: Select FRF Files window

6.3.1 BROWSING THE FILES

Here, you define frequency response functions (FRFs) at various points along the axial depth-of-cut. For each point, you must specify its location as measured from the tool tip or from the workpiece, and the corresponding *.frf file. Select a file by entering its name in the text box provided, or by clicking the **Browse** button. Click  and  to define other measurements in the same direction (i.e., X_{11}, X_{12}, X_{13},...).

6.3.2 MODAL MODEL

You can select **Complex Modes** for non-proportional damping, or **Real Modes** for proportional damping. **Real Modes** is sufficient to use in machining applications.

If you select **Complex Modes**, the parameters file will contain residue values. For the multiple transfer function measurements along the depth of cut, **Complex Modes** must be selected.

If you select **Real Modes**, the parameters file will contain mode shapes. For one point transfer function measurement in any direction, you can select both **Modes (Complex or Real)**. **Real Modes** are recommended, if you have only one measurement in one direction.

6.3.3 FRF TYPE

You can select **Acceleration** or **Displacement** sensor measurements. CutPro does the conversions automatically.

6.3.4 IMPACT POINT

This is the point where you hit with the hammer.

6.3.5 GAIN CONSTANT

All measurements are multiplied by the **Gain Constant**. It can be used to scale the sensor measurements if they have not already been scaled.

Example:

Transfer function measured using accelerometer and impact hammer with force sensor

Accelerometer type is **PCB 9690**. Sensitivity is **5.17 mV/g**. (ms^2=0.102g)

Hammer and force sensor type is **PCB 7902**. Sensitivity is **0.22 mV/N** with steel tip.

Total **gain constant** for the transfer function is,

$$\mathrm{TrFunc} = \frac{\ddot{x}}{F}\frac{\mathrm{Volt}}{\mathrm{Volt}}$$

$$\mathrm{TrFunc}\frac{\mathrm{Volt}}{\mathrm{Volt}} \cdot \frac{\text{hammer sensitivity}}{\text{accelerometer sensitivity}}$$

$$\mathrm{TrFunc}\frac{\mathrm{Volt}}{\mathrm{Volt}} \cdot \frac{0.22\dfrac{\mathrm{mV}}{\mathrm{N}}}{5.17\dfrac{\mathrm{mV}}{\mathrm{g}} \cdot 0.102\dfrac{\mathrm{g}}{\mathrm{m/s^2}}} = \mathrm{TrFunc} \cdot 0.417188\frac{\mathrm{m/s^2}}{\mathrm{N}}$$

6.3.6 FREQUENCY RANGE

This defines the range of frequencies in which the modal analysis is done. Do not give zero for the fist value. Modal Analysis package displace the transfer function as **displacement/force**. If you measured the acceleration and give the first range value as zero, the transfer function magnitude value will be infinite at zero frequency. It will also have very large amplitude value for low frequencies. Give an initial value for the first range to eliminate this error.

6.3.7 BUTTONS

Clear / Defaults	*Restores the values of all fields in the **Open FRF Files** window to the defaults.*
Cancel	*Closes the **Open FRF Files** window without saving any changes.*
OK	*Saves any changes which have been made, and closes the **Open FRF Files** window.*

You can try the example files provided – “TestFRFX11.frf” and "TESTFRFX12.frf" – which contain actual test measurements.

Modal uses only one of the files for curve fitting – the file that contains the highest flexibility (i.e., at the tool tip) – and the other files are handled automatically by Modal Analysis program.

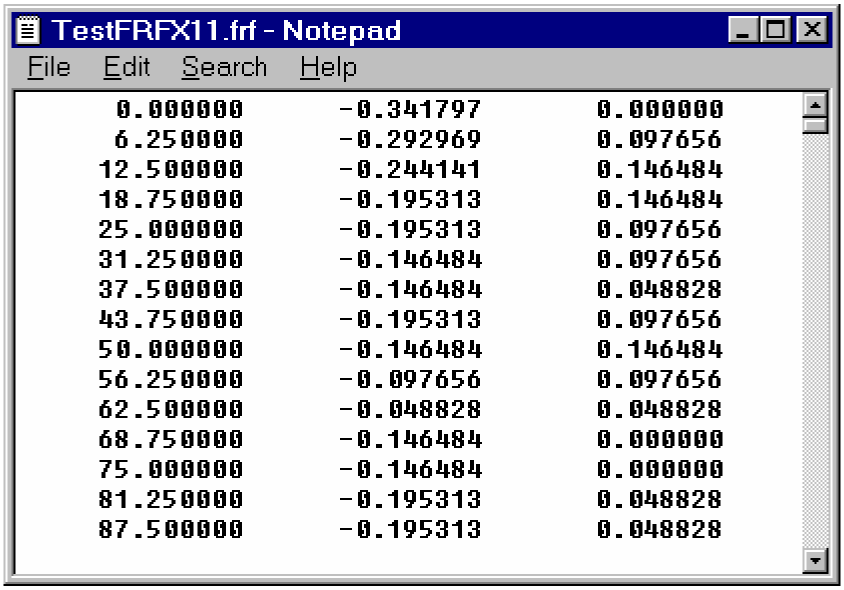
⚠ **In the CutPro DEMO version of Modal Analysis, you can only open the example files provided.**

6.4 FRF FILES FORMAT

Unless specified as HP SDF format (see below), FRF files must be **ASCII text** files consisting of three columns containing the following parameters. The widths of the columns, in characters, are 14, 15 and 15.

First Column	Second Column	Third Column
Frequency (Hz)	Real part of transfer function	Imaginary part of transfer function

For example:



0.000000	-0.341797	0.000000
6.250000	-0.292969	0.097656
12.500000	-0.244141	0.146484
18.750000	-0.195313	0.146484
25.000000	-0.195313	0.097656
31.250000	-0.146484	0.097656
37.500000	-0.146484	0.048828
43.750000	-0.195313	0.097656
50.000000	-0.146484	0.146484
56.250000	-0.097656	0.097656
62.500000	-0.048828	0.048828
68.750000	-0.146484	0.000000
75.000000	-0.146484	0.000000
81.250000	-0.195313	0.048828
87.500000	-0.195313	0.048828

Figure 6.4-1: A sample FRF file

6.5 DEFINING AND OPTIMIZING MODES

6.5.1 IDENTIFYING A MODE

Use the left and right mouse buttons to define the left and right boundaries of a mode, respectively – a mode is represented by a peak in the plot. A vertical green line marks the beginning of the mode, and a vertical red line marks the end of the mode. (See Figure 6.5-1)

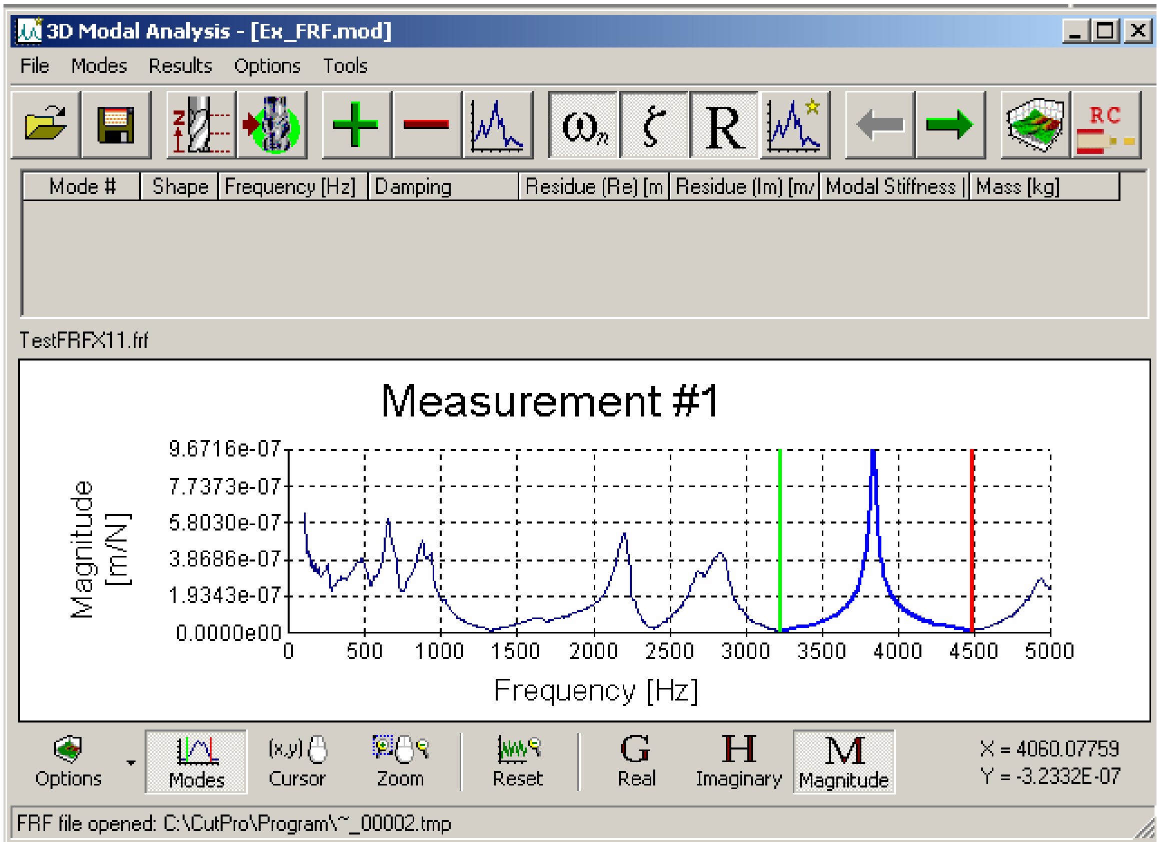


Figure 6.5-1: Sample modal analysis with a mode selected, between 3200Hz and 4500Hz.

6.5.2 ADDING THE MODE

Select **Add Mode** under the **Modes** menu, or click the **Add Mode** button on the toolbar. The mode you have identified is added to the **Modes Table**, displayed just below the toolbar. This process may be repeated until the desired number of modes is selected. (See Figure 6.5-2)

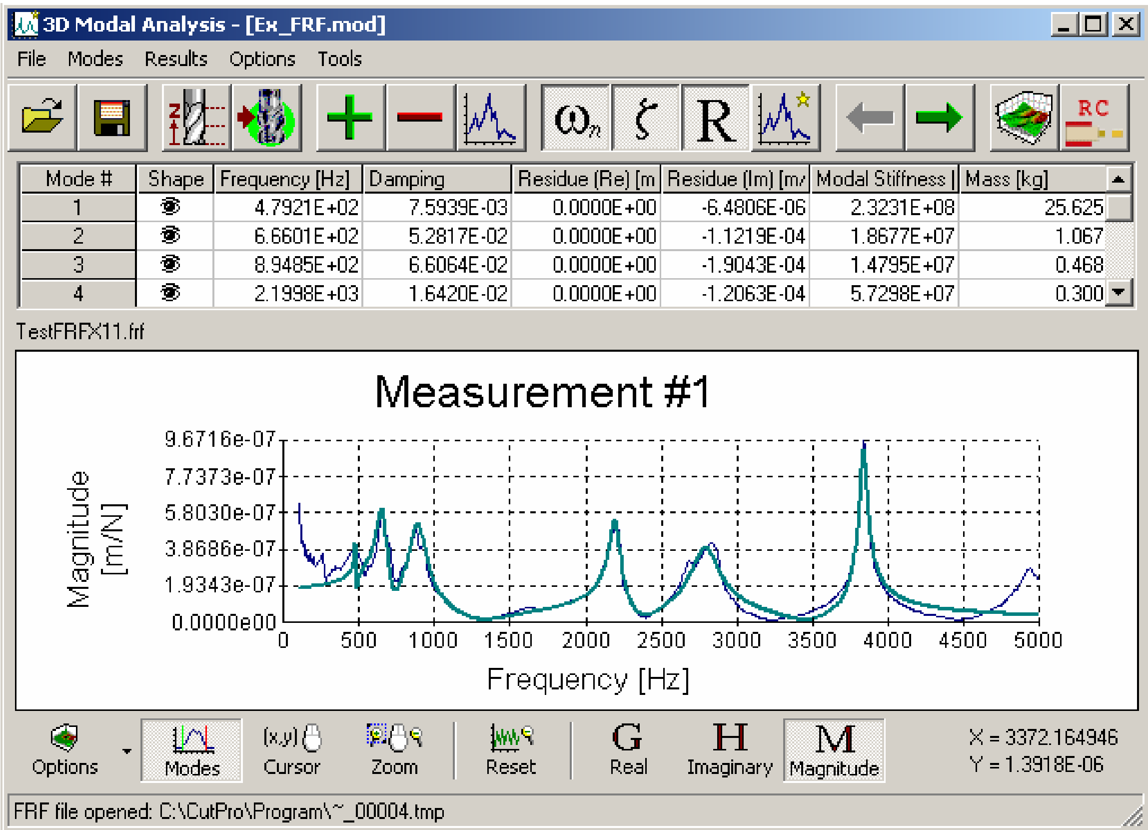


Figure 6.5-2: A sample modal analysis with four modes added.

6.5.3 DELETING A MODE

Select the mode you want to delete from **Modes Table**, just below the toolbar. Then select **Delete Mode** under the **Modes** menu, or click the **Delete Mode** button on the toolbar.

6.5.4 PLOTTING ALL THE MODES

Select **Plot Modes** under the **Modes** menu, or click the **Plot Modes** button on the toolbar. This automatically combines all the modes (without optimization) and displays the final transfer function fit. You can click on the thick **Arrow** buttons to see the subsequent measurements that have been automatically fit in the background.

6.5.5 OPTIMIZING THE MODES

If you want more accuracy, you can optimize the modes you have identified by selecting **Optimize** under the **Modes** menu, or by clicking the **Perform Optimization** button on the toolbar. The optimization uses a two-stage linear least-squares algorithm. You can select one to three parameters to optimize (below); the parameters are then added to the **Modes Table** and the fitted FRF is plotted within the selected range.

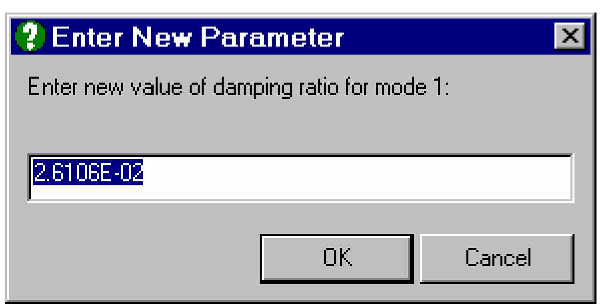
Natural frequency	*The **Optimize Natural Frequency** button must be depressed.*
Damping ratio	*The **Optimize Damping Ratio** button must be depressed.*
Residues	*The **Optimize Residues** button must be depressed.*

At least one of the three optimization parameter buttons must be selected.

Since this is an iterative search, a global optimum is not guaranteed. Should the solution diverge, the message "ERROR" will appear in one or some of the cells in the Modes Table.

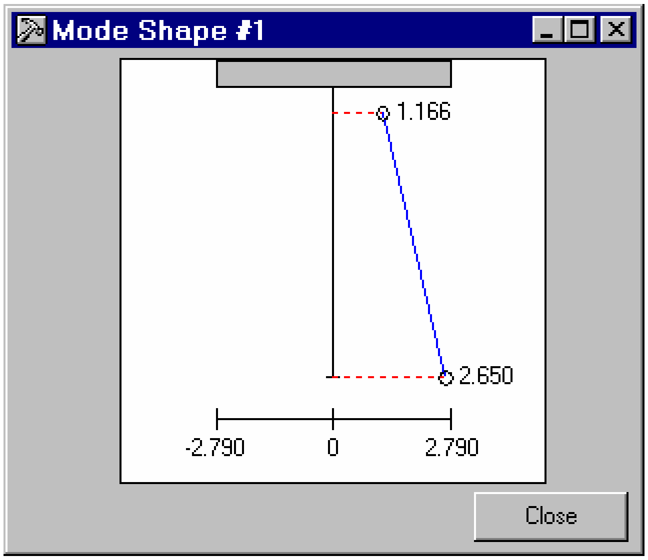
To avoid divergence, you can limit the optimization to certain parameters – any combination including natural frequency, damping ratio, and residues.

Furthermore, identified parameters may be changed by manually entering a value. By double clicking on any parameter in the **Modes Table**, the following dialog box allows the parameter to be overwritten:



6.5.6 VIEWING THE SHAPE OF A MODE

In the **Modes Table**, click on the first column of a mode to display its shape.



6.6 SAVING MODAL PARAMETERS

The modal parameters, as they appear in the **Modes Table**, may be saved by choosing **Save Parameters** from the **File** menu or from the button bar. A dialog box appears allowing a file name and directory to be chosen. The output is a text file with the extension **dat**.

The transfer function parameters file **example**:

If **Modal Model** is **Complex Modes** are selected:

MODES	2
PNTS	1
REALM	0
WN	476.834335632509
ZETA	4.04222522809633E-02
WN	602.222122314299
ZETA	1.90220641074104E-02
LOCNS	0
RESRE	-7.40900299071828E-7
RESIM	2.76537568544895E-7
RESRE	1.02231217282896E-7
RESIM	8.15334757887865E-7

If **Modal Model** is **Real Modes** are selected:

MODES	3
PNTS	2

REALM	1
WN	731.707078645867
ZETA	9.94415717171146E-02
WN	806.213295945486
ZETA	3.32206599430105E-02
WN	1590.91649391174
ZETA	3.84238738626789E-02
LOCNS	0
LOCNS	20
MODSH	0.3291973,0.2874119
MODSH	0.135213,0.1240283
MODSH	0.1611198,0.1219372

6.7 USING MODAL PARAMETERS IN CUTPRO

1. In the **Properties** window of CutPro, click the **General** tab.
2. Select **Dynamic vibrations** as the **Machine/Cutter or Workpiece Model**.
3. Click the **Dynamics** tab.
4. Select **Modal/residue data files** as the **Machine Dynamics Mode** or **Workpiece Dynamics Mode**.
5. Select the file(s) you want under **X modal/residue file** or **Y modal/residue file**.

⚠ **Note: You have to repeat the same modal analysis process for measurements in the Y-direction as well. For rigid directions, just give a very large stiffness (10e6) by selecting Dynamic parameters.**

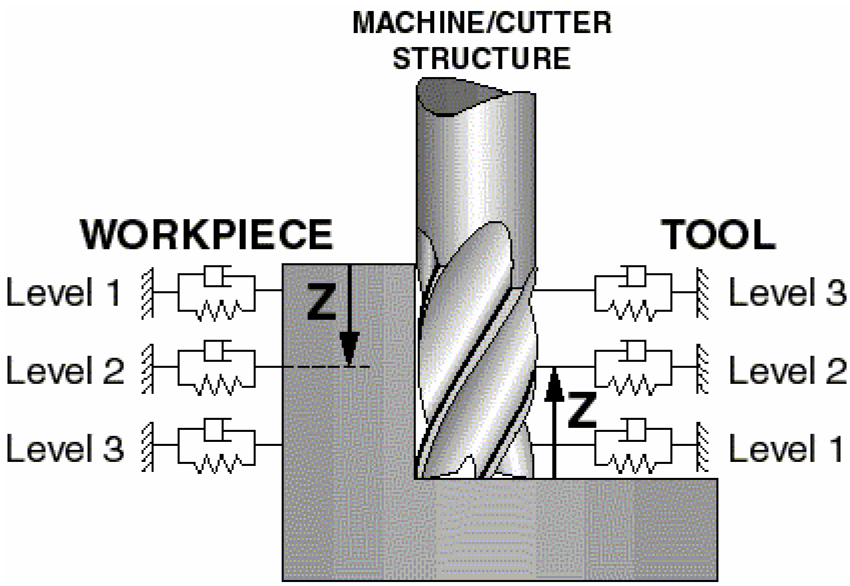
6.8 TRANSFER FUNCTION MEASUREMENT (FRF FILES)

For the typical transfer function measurement, you can use hammer with force sensor and accelerometer or displacement sensor. Before you measure the transfer function of the system, take into consideration for the following instructions:

If the machine/cutter and workpiece are flexible, measure the transfer functions for both.

If the depth of cut is not large you can take the transfer function measurement only from tool tip and workpiece at very close location of the surface.

If you are measuring the transfer function for multiple points along the depth of cut, take the first point at tool tip for **Machine Dynamics** or very close to the workpiece surface for **Workpiece Dynamics.**



Repeat the tests in X and Y directions separately.

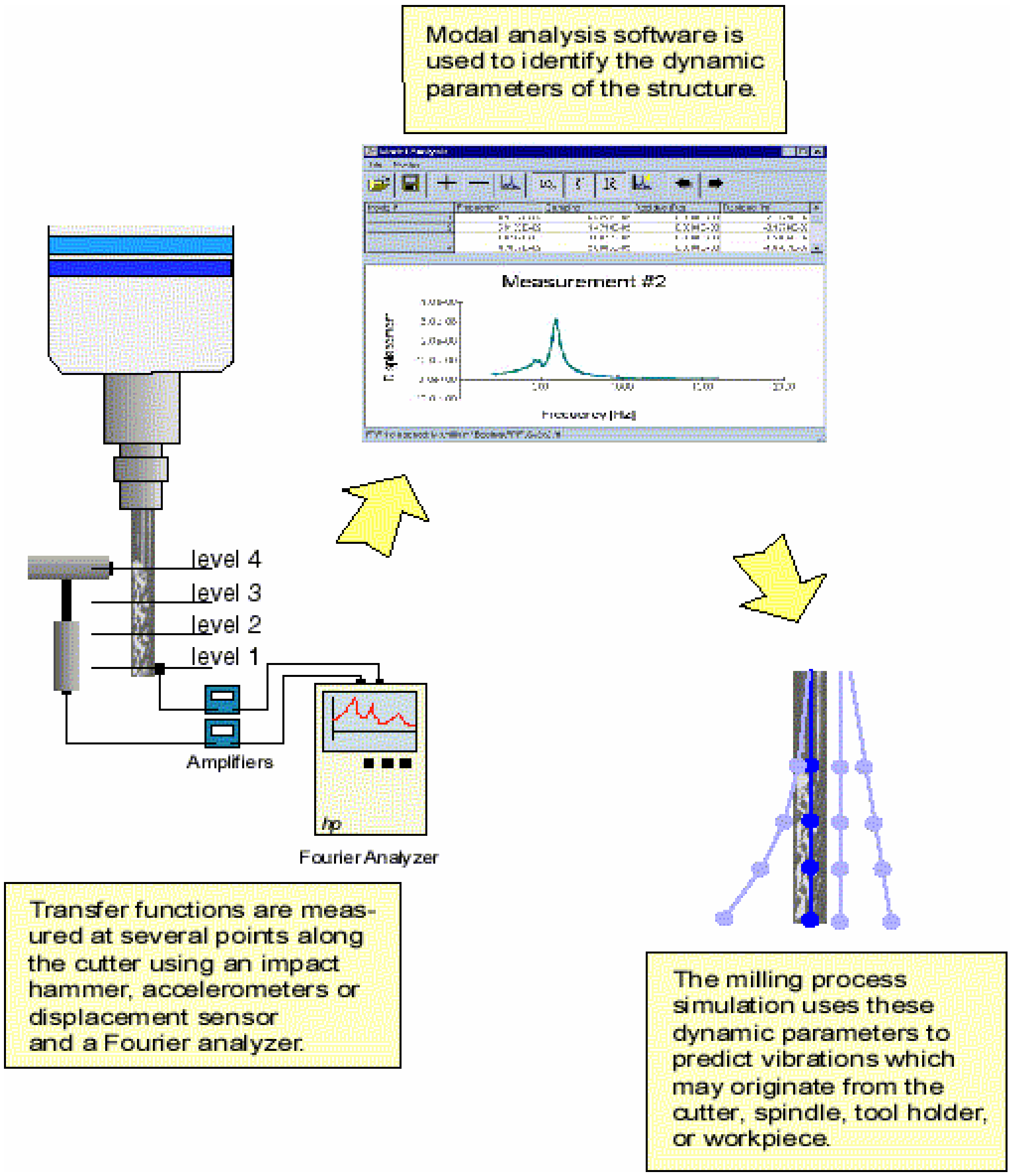


Figure 6.8-1: Flowchart describing the modal analysis process

6.9 RECEPTANCE COUPLING

6.9.1 INTRODUCTION

Receptance coupling is a method to acquire the assembled Frequency Response Function (or receptance or compliance) at the tool tip. The assembled FRF information can be used to predict chatter vibrations. Typically, the spindle dynamics do not change over the time (this should be checked regularly for preventive maintenance purpose) but the tool dynamics change whenever a new tool is inserted into a tool holder. This tool dynamics can be predicted by a FEM (Finite Element Method) to accurately come up with the tool dynamics. This requires material properties, and the tool geometries.

6.9.2 ADVANTAGES

The typical practice in shops to acquire predictions of FRFs is to measure the FRFs of each end mill used in the shop using impact modal tests with an instrumented piezoelectric force hammer and a vibration sensor. The Receptance Coupling technique allows coupling of analytical or experimental FRFs of the components in obtaining the response of the assembly. This eliminates the time consuming and repetitive FRF tests for each tool.

6.9.3 FUNCTIONS OF THE SOFTWARE

There are three sections in the Receptance Coupling Software:

1. Tool Coupling: Enables the identification of tool holder / spindle assembly on the machine tool and coupling of tools to the tool holder.

2. Coupling of Holder and Tool Assembly to Spindle: Enables the identification of the spindle on the machine tool and coupling of Shrink fit tooling to the spindle.

3. Tool Length Tuning: Guides in the selection of the optimum tool length for the selected tooling. It optimizes the tool length to achieve maximum productivity by utilizing the maximum spindle speed on the machine.

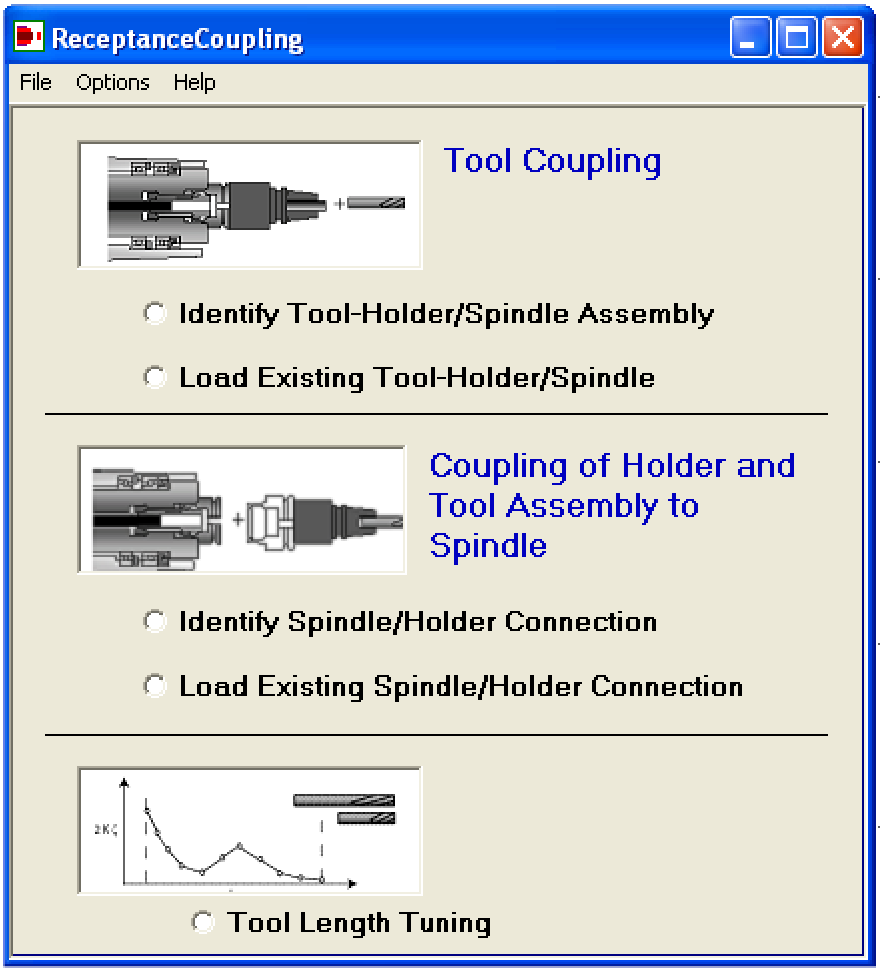


Figure 6.9-1: Receptance Coupling Functions

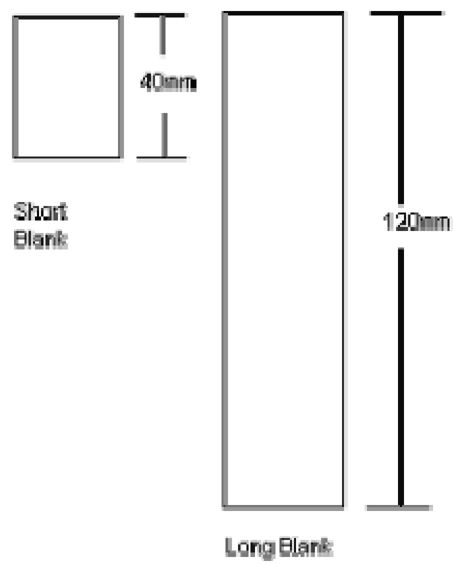
6.9.4 TOOL COUPLING

6.9.4.1 APPARATUS

It is recommended to use a medium length blank tool to perform the experiments to identify the tool holder spindle assembly.

1) Short blank tool (40 mm)

2) Long blank tool (120 mm or higher)


40mm
Short
Blank
120mm
Long Blank

6.9.4.2 EXPERIMENTAL ANALYSIS

⚠ **Note: Consistent frequency range and freq. interval are needed for the experiment.**

Insert the blank tool into the holder so that the stick out, L2, is 40-50 mm. The length inserted inside of the tool holder does not play an important role, although it has to be in the range recommended by the tool holder manufacturer. Attach an accelerometer on the blank tool and apply the impact hammer to acquire the frequency response functions. Perform at least 5-10 impact tests to average FRFs.

Three impact hammer tests are required:

Direct Transfer Function Measurement at the tool tip (TF 11)

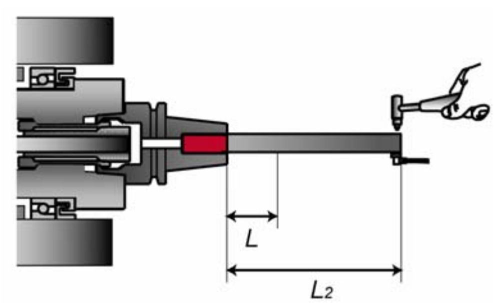


Figure 6.9-2: Direct Transfer Function Measurement at the tool tip (TF 11)

Cross Transfer Function Measurement between the tool tip, and a point on the blank at a distance L from the toolholder. L is recommended to be 10-20 mm (TF 12)

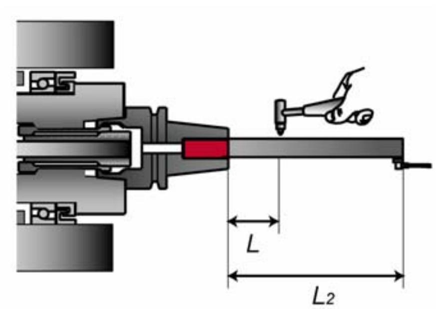


Figure 6.9-3: Cross Transfer Function Measurement (TF 11)

Direct Transfer Function Measurement at location L from the tool holder. (TF 22)

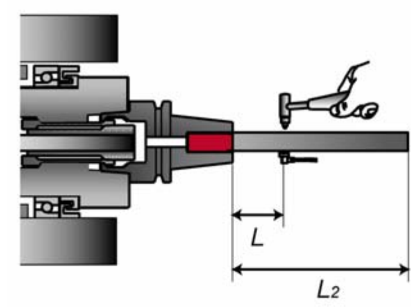


Figure 6.9-4: Direct Transfer Function Measurement at location L from the tool holder (TF 22)

6.9.4.3 IDENTIFICATION USING THE SOFTWARE

To start, select Identify Tool- Holder Spindle Assembly button.

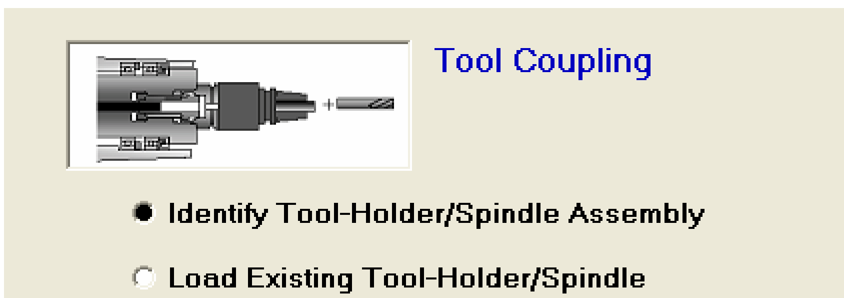


Figure 6.9-5: Tool Coupling

6.9.4.3.1 IDENTIFICATION - GEOMETRY PARAMETERS:

Input the blank tool dimensions and properties used to perform the experiments:

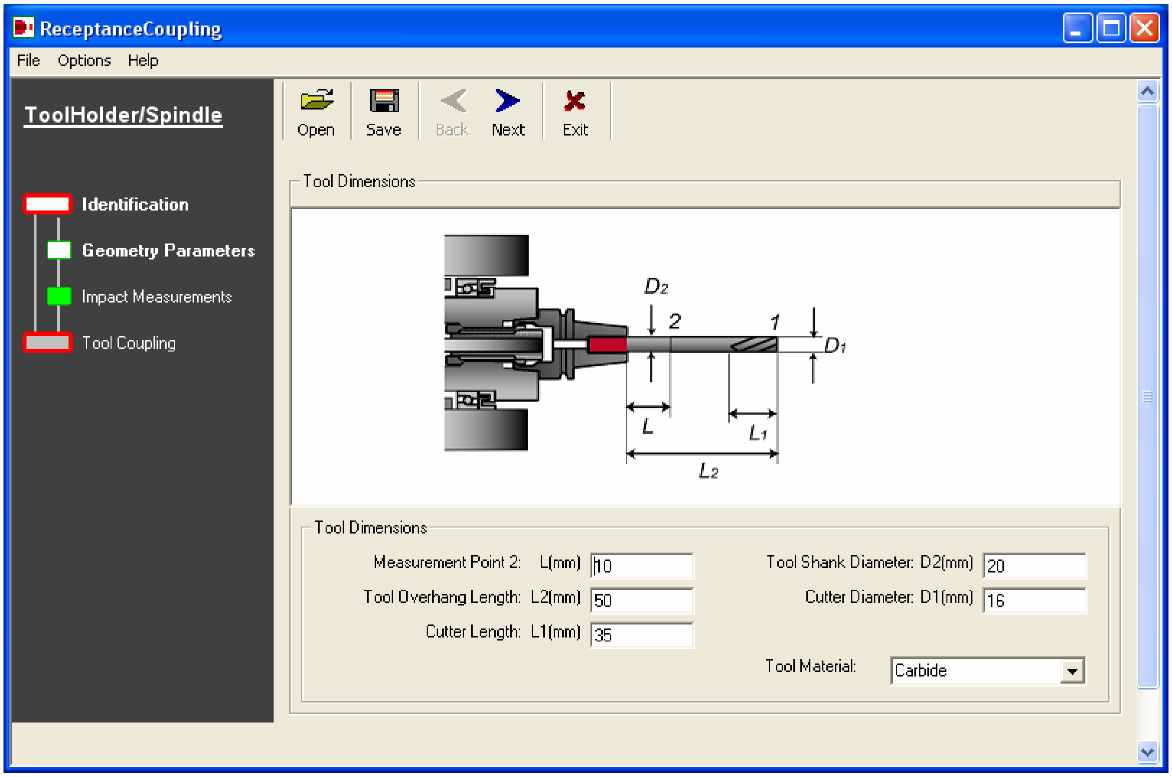


Figure 6.9-6: Tool Coupling- Identification - Geometry Parameters

Although it is recommended to use a blank tool to perform the experiments, in the case an end mill is used to perform the experiments the software allows the user to input the end mill geometry.

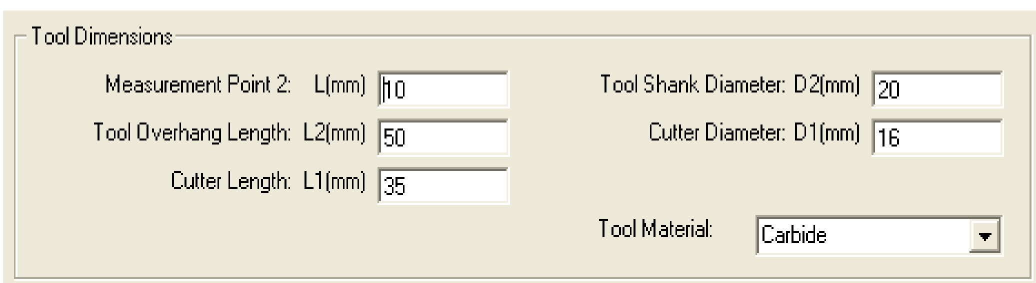


Figure 6.9-7: Tool Coupling- Identification - Geometry Parameters

The cutter diameter for a 4 fluted end mill is 80% of the tool shank diameter.

Press Next to input the FRF impact measurements.

6.9.4.3.2 IDENTIFICATION - IMPACT MEASUREMENTS:

Import the 3 measured FRF files in Figure 7.9-2, Figure 7.9-3 and Figure 7.9-4 respectively. The measured frequency response files have to be displacement – force FRF's.

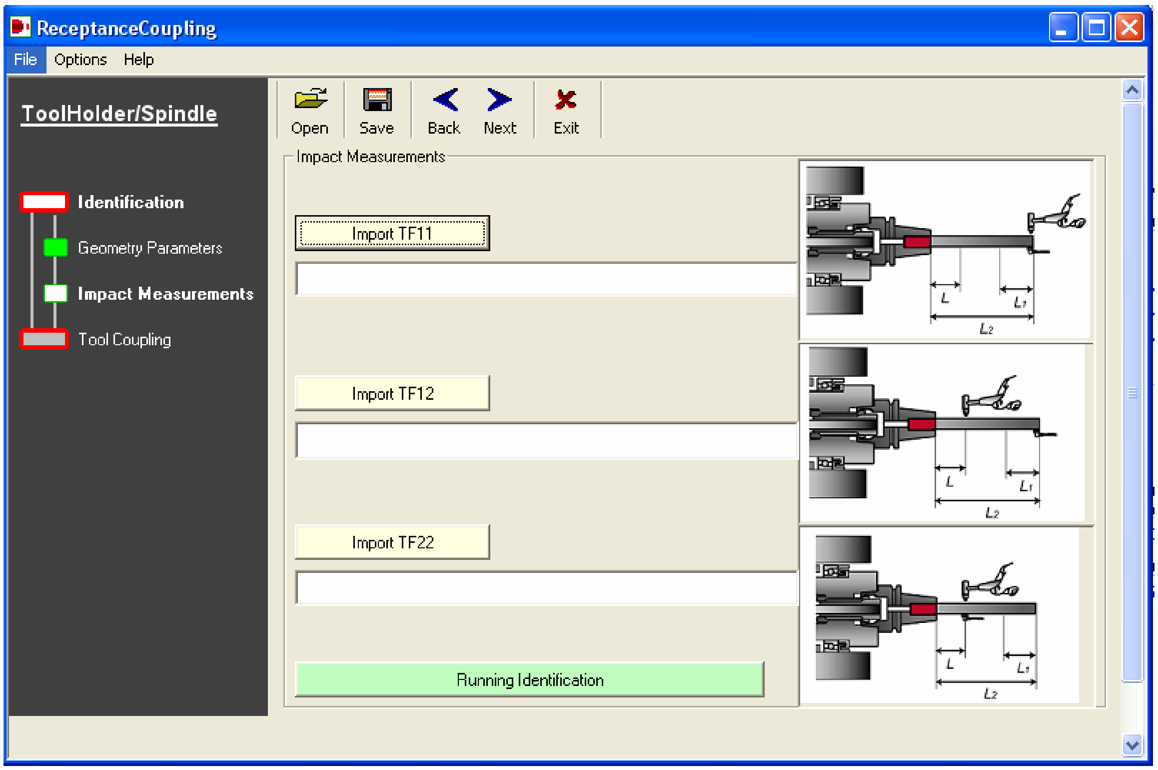


Figure 6.9-8: Tool Coupling- Identification - Impact Measurements

Press the Running Identification Button to start the Identification procedure.

Figure 6.9-9: Tool Coupling- Running Identification

It will open a command window and will take a few minutes, depending on the frequency selection and the speed of the computer.

z **Figure 6.9-10: Running Receptance Coupling Engine**

Once the identification procedure is complete, a prompt save window appears. Press Save. The software saves the identified spindle tool holder assembly project file, with the measurement files.

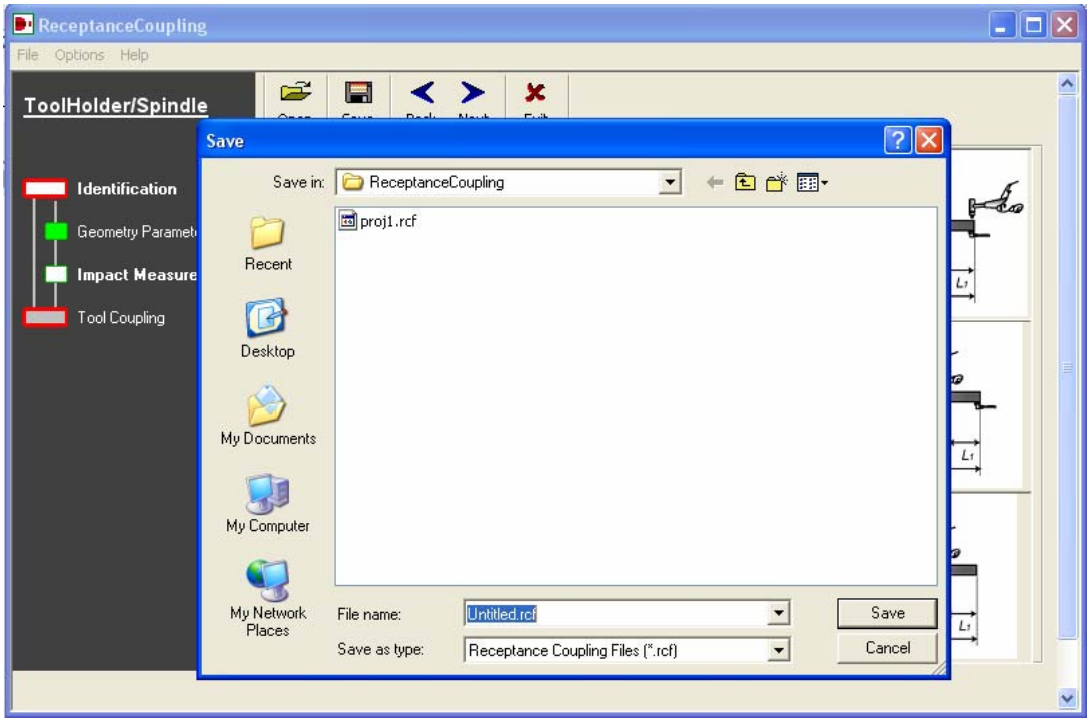


Figure 6.9-11: Tool Coupling- Save Project File

Press Next to Tool Coupling.

6.9.4.4 TOOL COUPLING

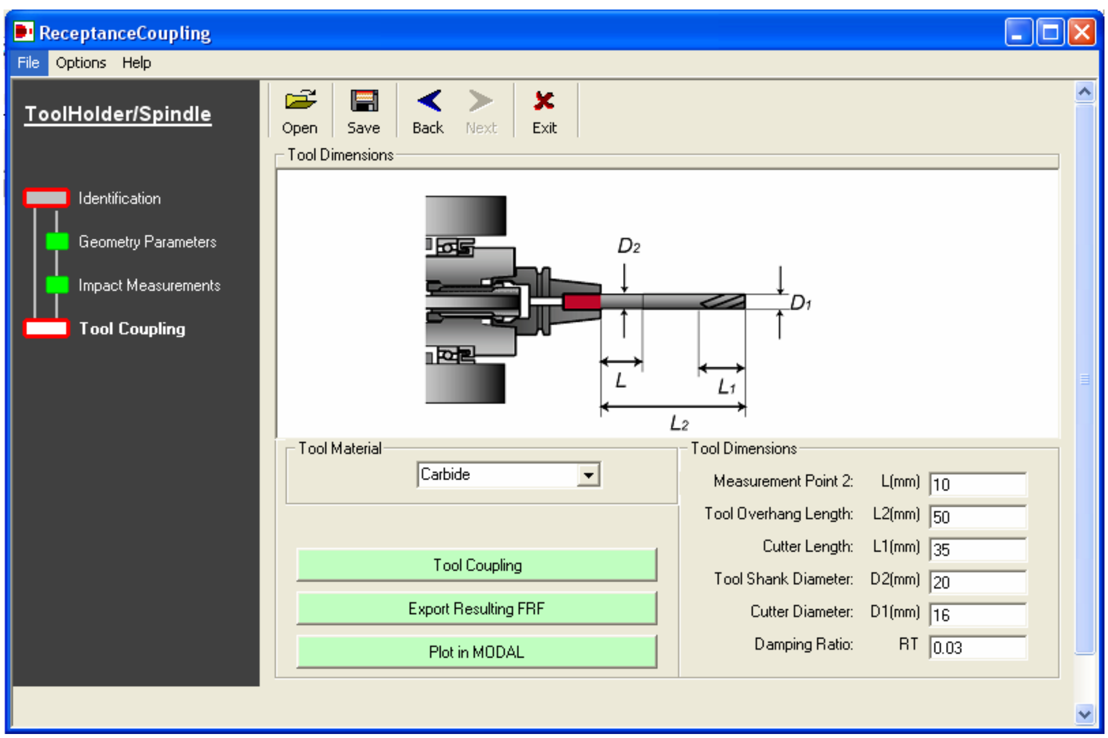


Figure 6.9-12: Tool Coupling- Assembly

Input the cutting tool dimensions and material you want to couple to the tool holder.

Measurement Point 2: L , is fixed from the previous step in the identification procedure and is given as additional information . It is disabled and can not be changed in this step.

Press Tool Coupling to Start the Coupling Procedure .

Figure 6.9-13: Tool Coupling

It will open a command window and will take a few minutes, depending on the frequency selection and the speed of the computer. See Figure 7.9-10.

Once the Tool Coupling is completed, you can export the predicted FRF at the tool tip or plot in Modal Analysis.

Figure 6.9-14: Tool Coupling- Export Resulting FRF or Plot in MODAL

After it is completed, click *Plot the Result on Modal Analysis*. A new plot should appear on Modal Analysis.

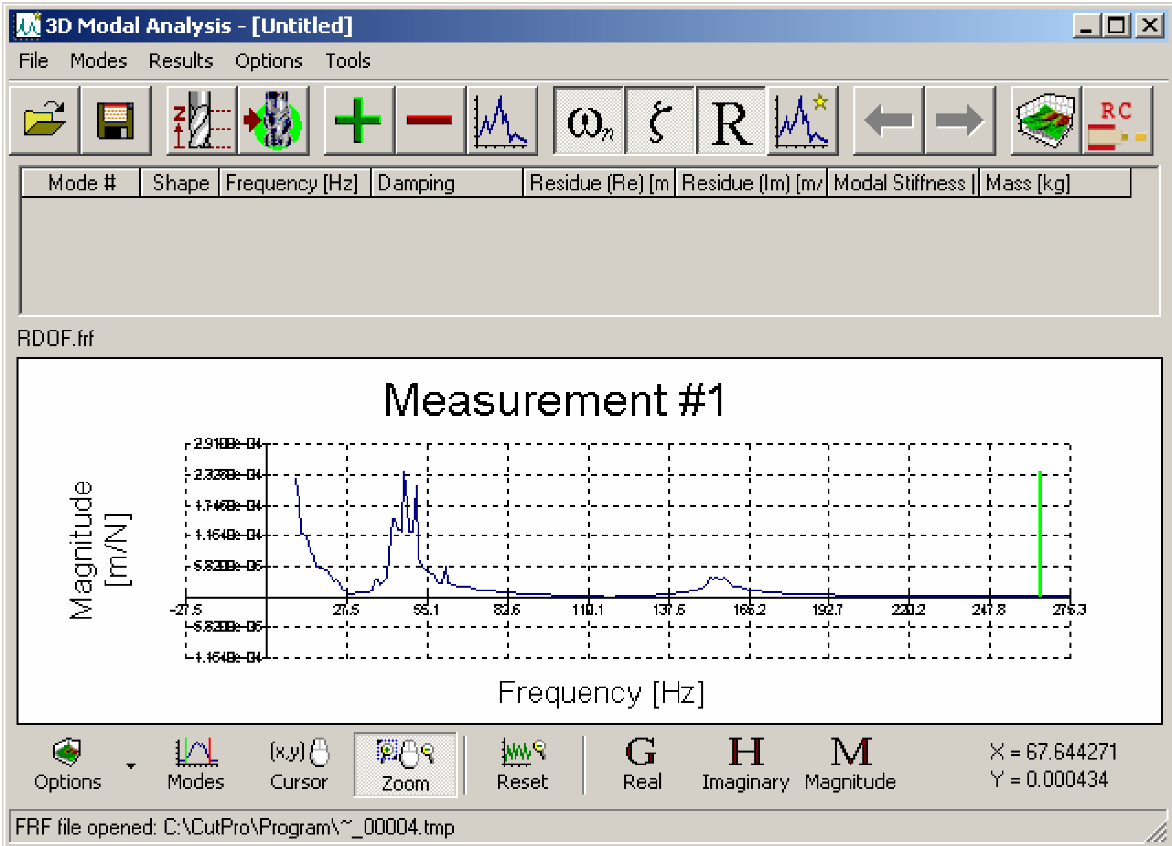


Figure 6.9-15: Sample Receptance Coupling at Tooltip on an arbitrary tool, displayed in Modal Analysis

Press Exit to go to the main menu.

6.9.4.5 LOADING EXISTING TOOL HOLDER SPINDLE ASSEMBLIES

Press Load Existing Tool-Holder / Spindle

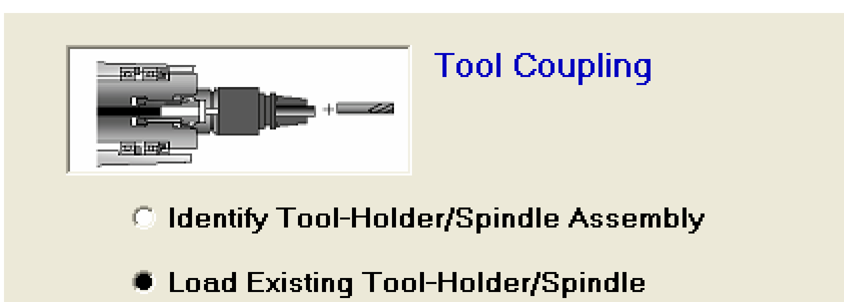


Figure 6.9-16: Tool Coupling- Load Existing Project

Browse for existing tool holder -spindle projects .rcf files and open the existing spindle tool holder assembly.

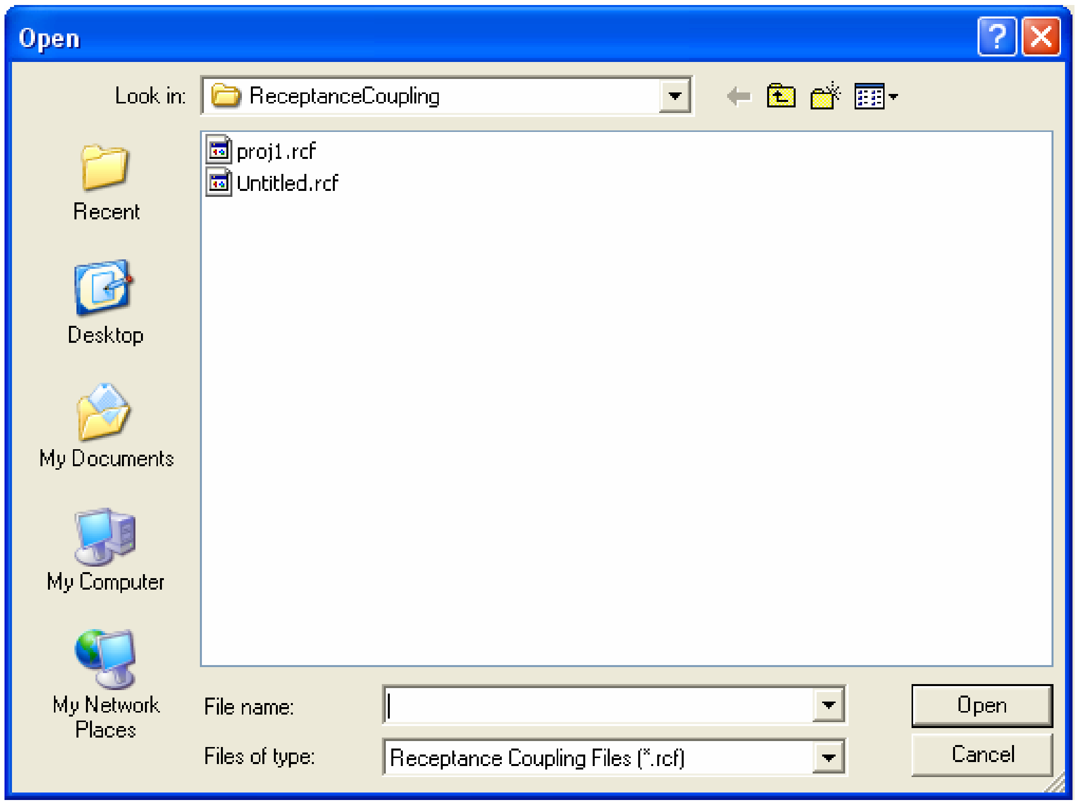


Figure 6.9-17: Tool Coupling- Opening an existed project file

Couple a tool to the tool holder as explained in 1.1.1.1

6.9.5 COUPLING OF HOLDER AND TOOL ASSEMBLY TO SPINDLE

6.9.5.1 EXPERIMENTAL PROCEDURE TO IDENTIFY THE SPINDLE HOLDER CONNECTION

6.9.5.1.1 APPARATUS

It is recommended to use a shrink fit tool holder without any tool to perform the experiments for the identification of the spindle holder connection.

6.9.5.1.2 EXPERIMENTAL PROCEDURE

Insert the shrink fit tool holder into the spindle. Attach an accelerometer on the holder shank and apply the impact hammer to acquire the frequency response functions. Perform at least 5-10 impact tests to average FRFs.

Three impact hammer tests are required:

Direct Transfer Function Measurement at the tip of the holder shank (TF 11)

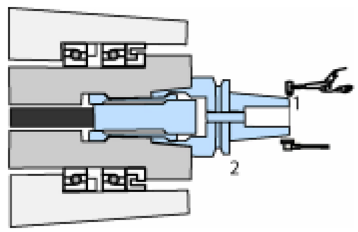


Figure 6.9-18: Tool/Tool Holder assembly to spindle - direct transfer function measurement at the tip of the holder shank (TF 11)

Cross Transfer Function Measurement between the tip of the holder shank, and the tool holder flange. (TF 12)

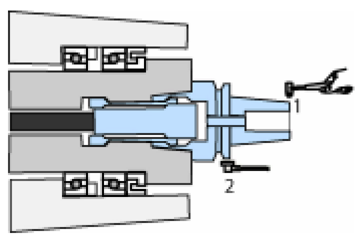


Figure 6.9-19: Tool/Tool-Holder assembly to spindle - cross transfer function measurement between the tip of the holder shank and the tool holder flange (TF 12)

Direct Transfer Function Measurement on the tool holder flange. (TF 22)

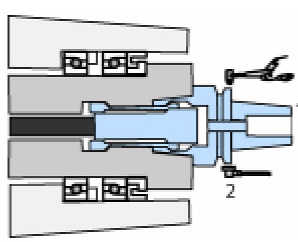


Figure 6.9-20: Tool/Tool Holder assembly to spindle - direct transfer function measurement on the tool holder shank (TF 11)

6.9.5.2 IDENTIFICATION USING THE SOFTWARE

To start, select Identify Spindle / Holder Connection button.

Figure 6.9-21: Tool/Tool Holder assembly to spindle - Identification

6.9.5.2.1 IDENTIFICATION - GEOMETRY PARAMETERS

Input the shrink fit dimensions used to perform the experiments: (The dimensions are provided in the tool holder manufacturer catalogue)

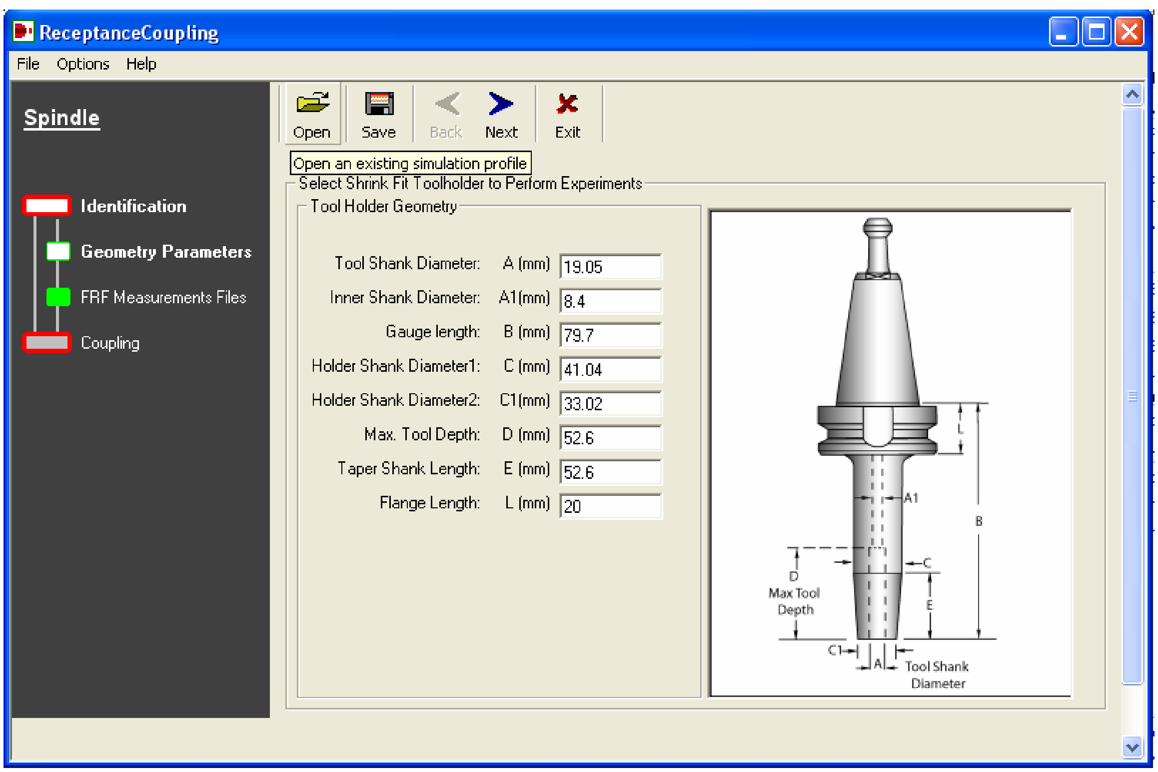


Figure 6.9-22: Tool/Tool Holder assembly to spindle – Identification-Geometry parameters

Press Next to input the FRF impact measurements.

6.9.5.2.2 IDENTIFICATION - IMPACT MEASUREMENTS:

Import the 3 measure FRF files in Figure 7.9-2-18, Figure 7.9-2-19 and Figure 7.9-2-20 respectively. The measured frequency response files have to be displacement – force FRF's.

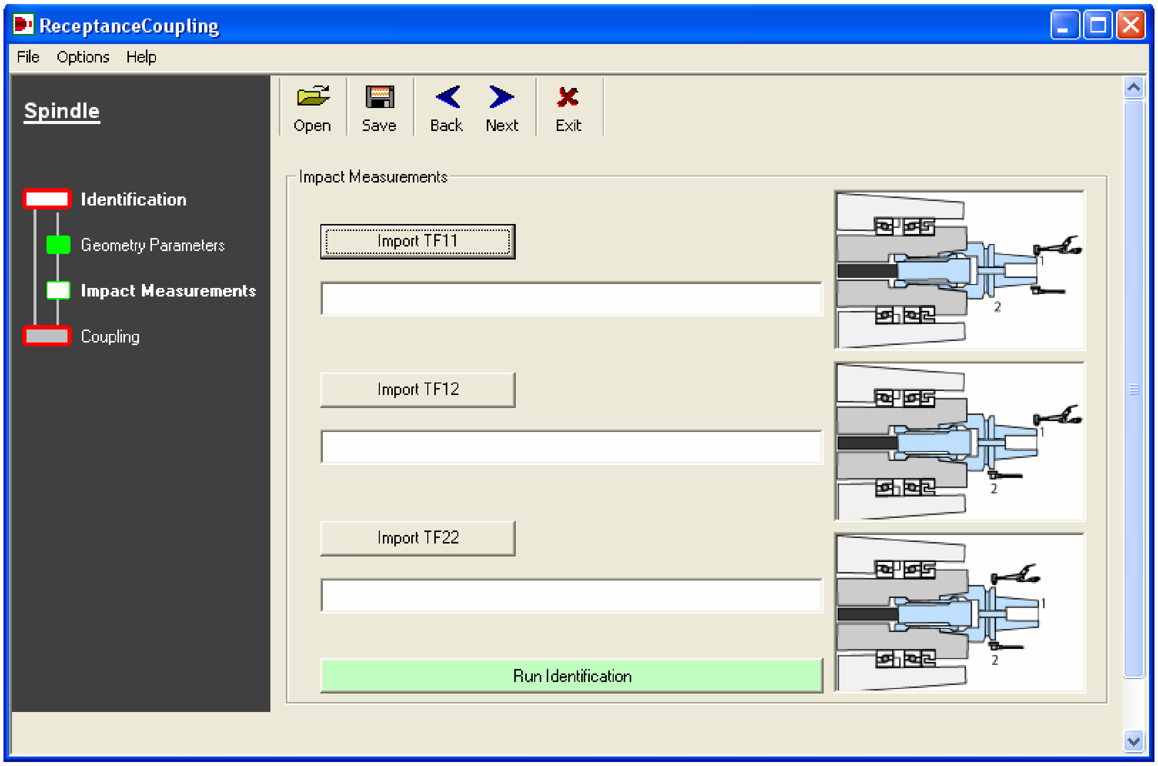


Figure 6.9-23: Tool/Tool Holder assembly to spindle – Identification-Geometry parameters

Press the Run Identification Button to start the Identification procedure.

Figure 6.9-24: Running Receptance Coupling Engine -Identification

It will open a command window and will take a few minutes, depending on the frequency selection and the speed of the computer. Reference See Figure 7.9-10

Once the identification procedure is complete, a prompt save window appears .Press Save. The software saves the identified spindle tool holder assembly project file, with the measurement files.

Press Next to Tool Holder Coupling.

6.9.5.3 TOOL HOLDER COUPLING

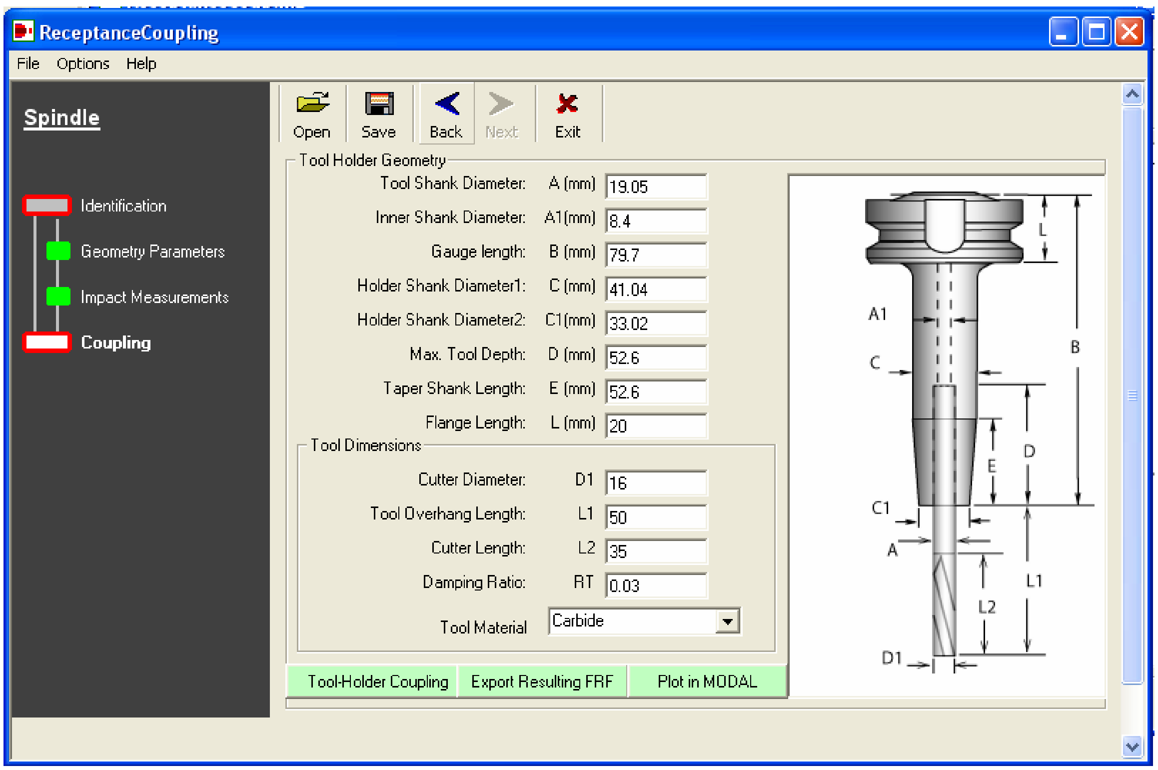


Figure 6.9-25: Tool Holder Assembly

Input the tool holder dimension and cutter dimensions in specified fields.

The cutter diameter for a 4 fluted end mill is 80% of the tool shank.

Recommended damping ratios for carbide tools are 0.01-0.03.

Press Tool-Holder Coupling to Start the Coupling Procedure.

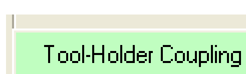


Figure 6.9-26: Running Receptance Coupling Engine

It will open a command window and will take a few minutes, depending on the frequency selection and the speed of the computer.

Once the Tool Coupling is completed, you can export the predicted FRF at the tool tip or plot in Modal Analysis.

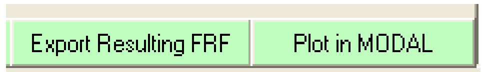


Figure 6.9-27: Export Resulting FRF or Plot in MODAL

Press Exit to go to the main menu.

6.9.5.4 LOADING EXISTING SPINDLE / HOLDER CONNECTIONS

Press Load Existing Spindle / Holder Connection

Figure 6.9-28: Loading an existed project

Browse for and open existing spindle holder project *.rsf files. Couple a tool / tool holder assemblies to the spindle as explained in 6.9.5.3

6.9.6 TOOL LENGTH TUNING

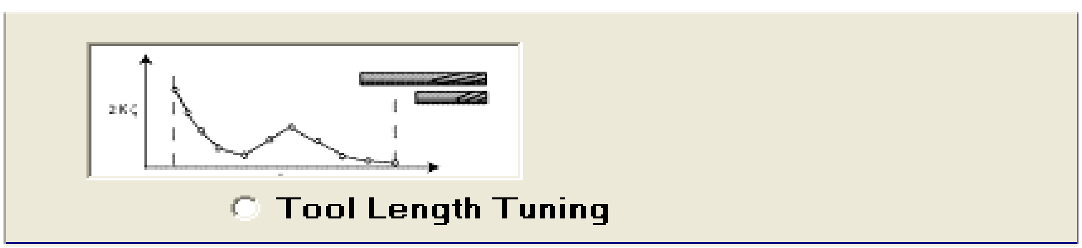


Figure 6.9-29: Tool Length Tuning

Tool Length tuning is based on the Tool Coupling – Identification. Through the Tool Coupling – Identification, a user selects the minimum of tool overhang length, the maximum of tool overhang length and the maximum spindle speed, then, runs the tool length optimization engine to get the optimized tool overhang length on the certain cutting conditions for the material of Aluminum.

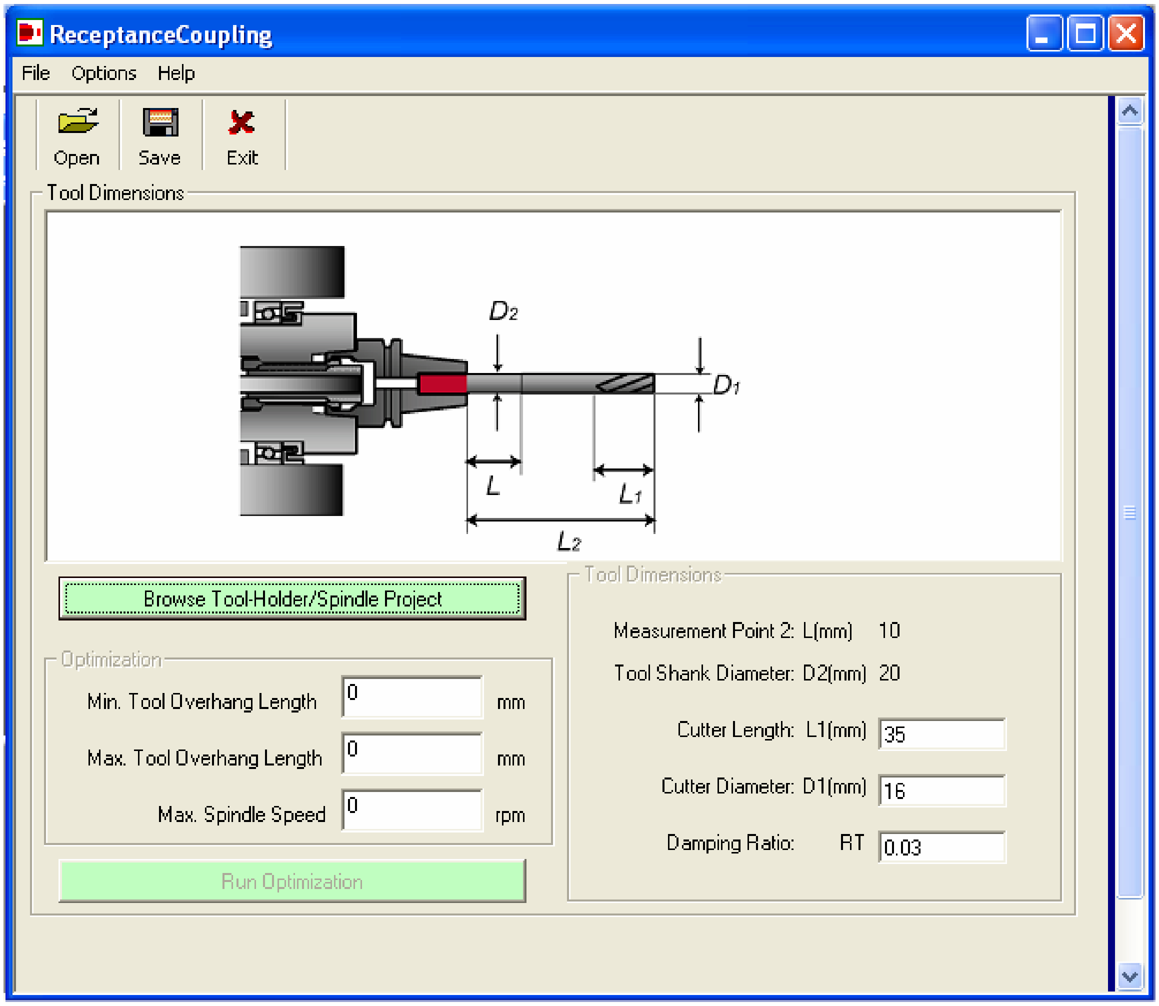


Figure 6.9-29: Tool Length Tuning- Browse Tool-Holder/Spindle Project

The procedures to optimize the tool length tuning:

1. Click the button “Browse Tool-Holder/Spindle Project”, then the open file dialogue box will pop up

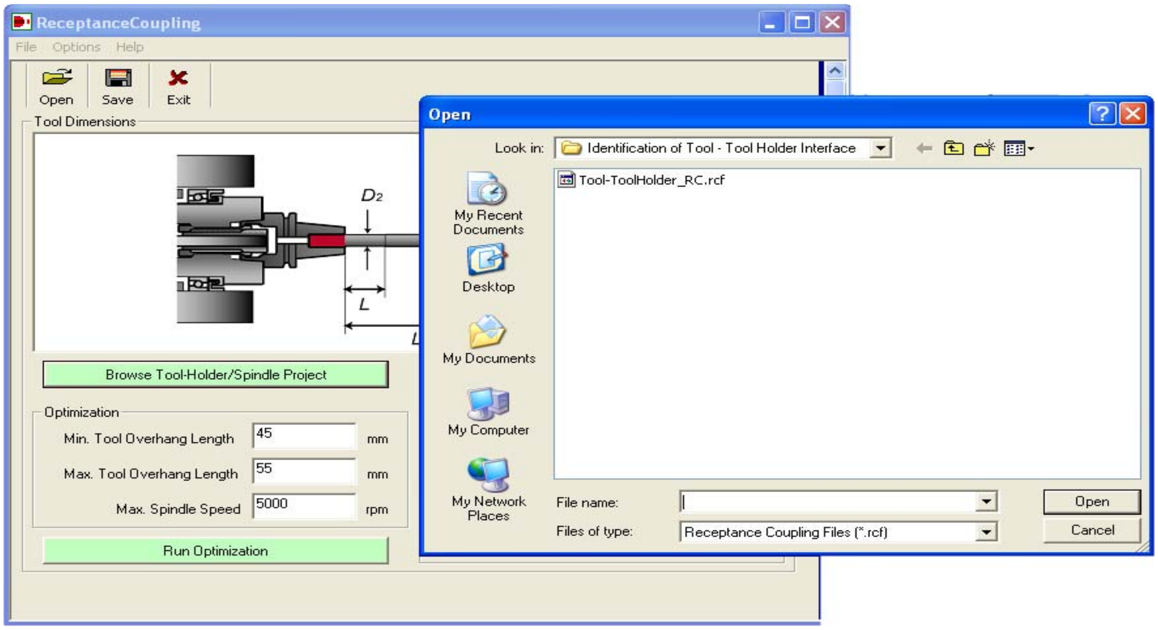


Figure 6.9-30: Tool Length Tuning- open a Tool-Holder/Spindle Project

2.
3. Select a project file in the dialogue box then click the button "Open". After the project file is loaded, the "Run Optimization" button is available. A user can click it to run the optimization engine after he/ she changes the optimization conditions.

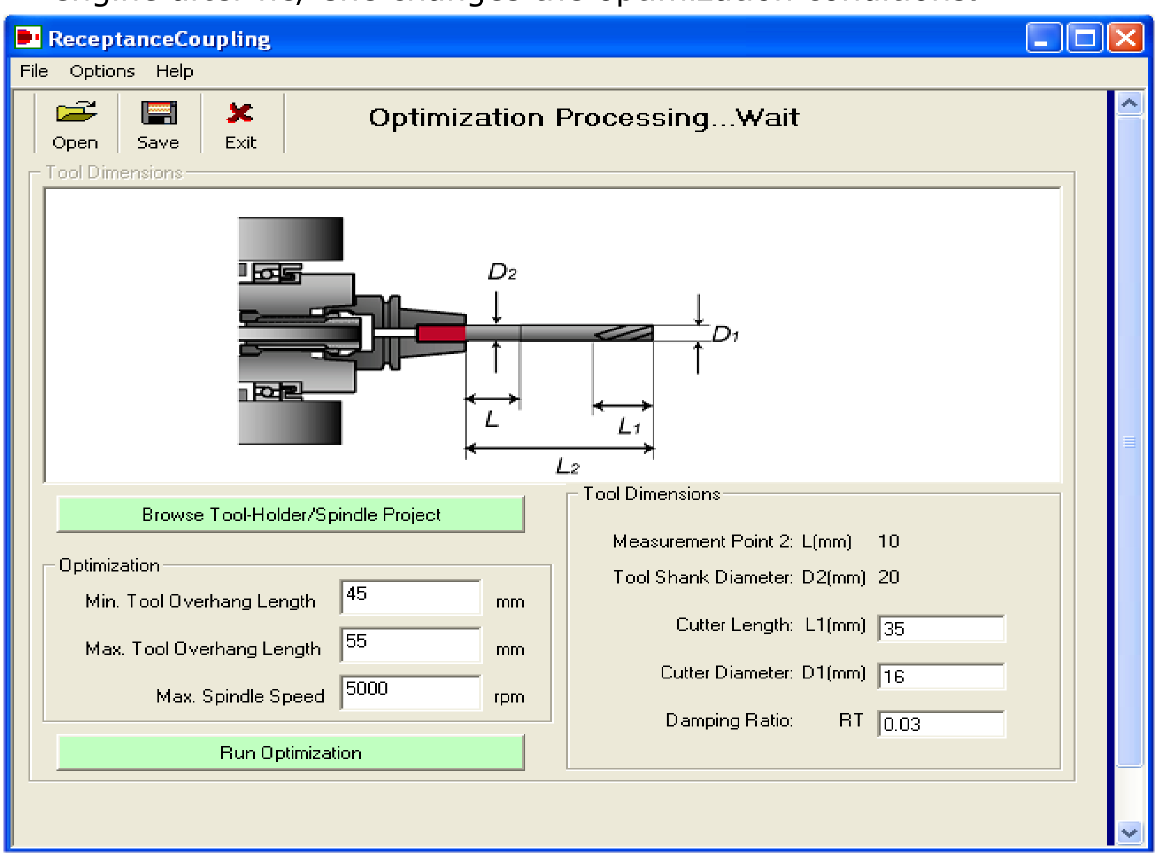


Figure 6.9-30: Tool Length Tuning- open a Tool-Holder / Spindle Project

6.9.7 WAYS TO MINIMIZE THE NOISE AND INCREASE ACCURACY OF THE PREDICTIONS

Perform more than 10 impact hammer tests

Perform the modal analysis on the short tool FRF. Must consider for the high modes as well.

Use same materials for tools.

Apply the impact hammers consistently at the same location (slight deviation of the appropriate location may cause big deviations).

Select the # of elements depending on the length. For example, L2 = 20 mm, L1 = 100 mm, you would like to have 1 to 5 ratio for the # of elements as well.

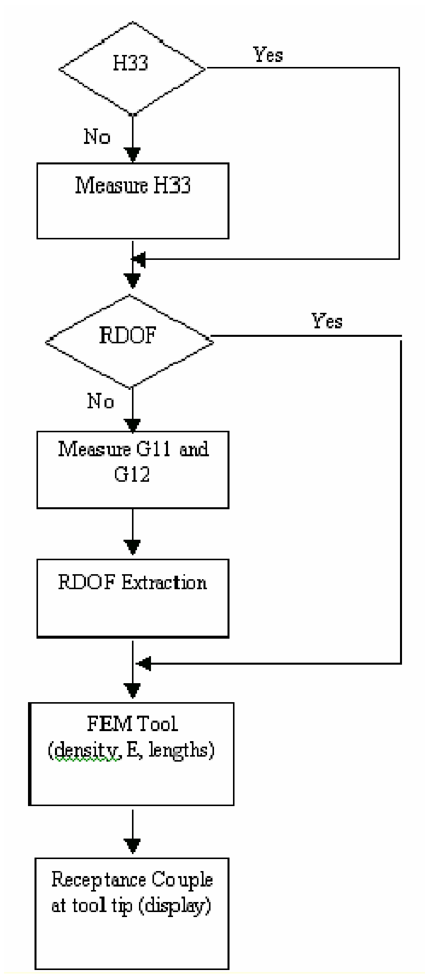
Select the appropriate damping ratio. The damping ratio can vary from 1% to 5% depending on materials.

Select the appropriate frequency range and the resolution. Try to have consistent freq. range and resolution for all the measurements and simulation

Make sure that the bandwidth of the impact hammer is within the desired freq. range.

6.9.8 PROCEDURES & RECEPTANCE COUPLING FLOW CHART

H33: FRF Measurements at the Spindle end with the small blank
G11: Assembled FRF Measurements at the tool tip.
G12: Assembled cross FRF measurements by applying the force at the joint location but measuring at the tool tip.
RDOF: Rotational degrees of freedom (RDOF) FRFs at the joint.



6.9.9 LIMITATION OF RECEPTANCE COUPLING

The accuracy of the Receptance Coupling software is depending on the measurement noise. This software is used for guidance, not an absolute final solution.

The accuracy of the receptance coupling technique depends on accurate identification of the joint dynamics of the substructures at the assembly joint, and the FRFs of each substructure.

7 MILLING ANIMATION

Milling Animation allows you to see how the chips are removed, and how the workpiece and cutter vibrate. Surface finish is graphically represented at different axial positions along the depth-of-cut.

When you open the **Milling Animation** program, by selecting **Tools > Milling Animation** from the **Main CutPro Window**, the most recently generated animation data is automatically loaded, if there is any available file.

Click the **Play/Stop** button to play or stop the animation. Alternately, you can use the **large scroll bar** to manually scroll through the animation. Use the **Up/Down Arrows** to change the **Level** (i.e., axial position along the depth-of-cut).

You can also change the **Speed** of the animation using the **small scroll bar**.

Under the **Units** menu, you can choose to display either **Metric** or **Imperial** units of measurement.

If you open the **Milling Animation** program and then run a different simulation under CutPro and would like to see the new results, click the **Reload** button.

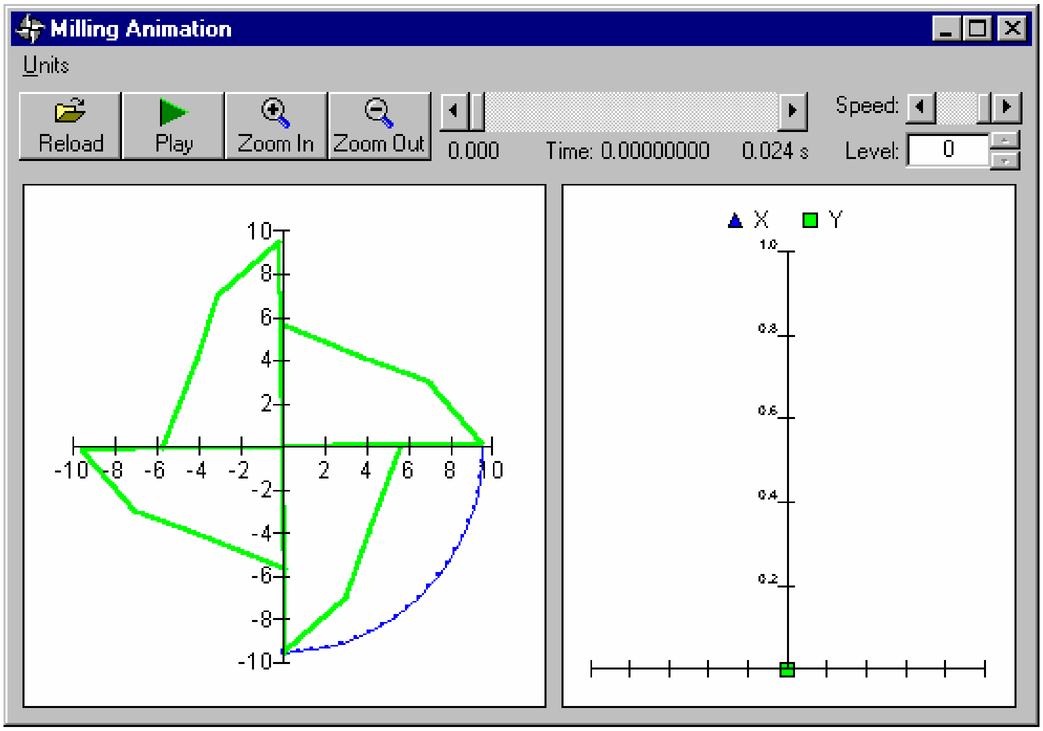


Figure 6.9-1: Milling Animation Window

8 EXAMPLES

8.1 EXAMPLE FILES

The following example files are provided with CutPro. They can be found in the **Examples** directory under your main **CutPro** directory. To open an example file, select **File > Open** or click the **Open** button in the main CutPro window.

8.1.1 Ex01_SingleAnalytical.csf

Single Analytical Simulation for Regular pitch cutter. This is a stability lobe simulation for a cylindrical end mill.

8.1.2 Ex02_SingleTime_6000rpm_3mm.csf

Single time domain simulation for cylindrical cutter in chatter area. Spindle speed 6000 rpm, 3 mm depth of cut.

8.1.3 Ex03_SingleTime_14300_6mm.csf

Single time domain simulation for one cutting condition in chatter free area. Spindle speed 14300 rpm, 6 mm depth of cut.

8.1.4 Ex04_MultipleAnalytical.csf

Multiple Analytical Simulation for Regular pitch cutter. This is a stability lobe simulation for cylindrical end mill in 3 dimensions, which are depth of cut, spindle speed and width of cut.

8.1.5 Ex05_Optimumpitch_5000.csf

Optimum variable pitch cutter design simulation at 5000 rpm for 4 flutes cutter. Optimize the tool flute angles to obtain as much as possible high chatter free depth of cut.

8.1.6 Ex06_SingleAnalytical_Var.csf

Single Analytical Simulation for Variable pitch cutter. This is a stability lobe simulation for cylindrical end mill.

8.1.7 Ex07_CuttingCoef.csf

This calculates the average cutting coefficients from milling experimental cutting forces. Experimental cutting conditions for the files:

Cutting type: Slotting, depth of cut 2.0 mm

Workpiece material: Al-7075

Cutter: 4 flutes, 30 degree helix angle

8.1.8 Ex08_SingleTime_BallEnd.csf

Single time domain simulation for Ball End Mill cutter.

8.1.9 Ex09_SingleTime_GeneralEnd.csf

Single time domain simulation for General Solid End Mill cutter.

8.1.10 Ex10_SingleTime_InsertCutter.csf

Single time domain simulation for an inserted cutter.

8.1.11 Ex11_SingleTime_Static_InsertCutter .csf

Single time domain simulation for an inserted cutter without vibration.

8.1.12 Ex12_SingleAnalytical_MaWp.csf

Single Analytical Simulation for Regular pitch cutter with Machine and Workpiece dynamics. This is a stability lobe simulation for cylindrical end mill.

8.1.13 Ex13_Temperature_Milling.csf

Temperature simulation for milling, with default cutting conditions.

8.2 EXAMPLE A: SIMULATING A DESIRED MILLING PROCESS

This example illustrates how to ensure the stability of a milling process at a particular spindle speed and depth of cut; as well as using Optimize Variable Pitch to achieve a stable process with the desired cutting conditions if they are found to be unstable with a uniform endmill.

In this example, a uniform Carbide cylindrical endmill of 32mm length is used for down-milling AL356-T6 at a radial depth of cut of 9.525mm. The spindle is clockwise and the feed rate is 0.05 mm/flute. The helix angle of the tool is 30° and the rake and relief angles are both 0°.

Suppose you wish to run the process at 6000RPM and an axial depth of cut of 7mm. You would first obtain the stability lobes to check if the conditions are stable. In this example, these conditions are not stable with a uniform pitch endmill. You can then find the optimal variable pitch to shift the stability lobes to ensure the process is stable at 6000RPM at 7mm axial depth of cut.

The details are contained in the simulation files Ex1 to Ex5 (See Section 8.1).

8.2.1 OBTAINING THE STABILITY LOBES

First, you can obtain the stability lobes for the desired process and check if the cutting conditions will be stable. The following steps and details are all contained in the example file EX01_SingleAnalytical.csf.

To do this, select the Advanced Milling Module and choose the Single Analytical Stability Lobes mode.

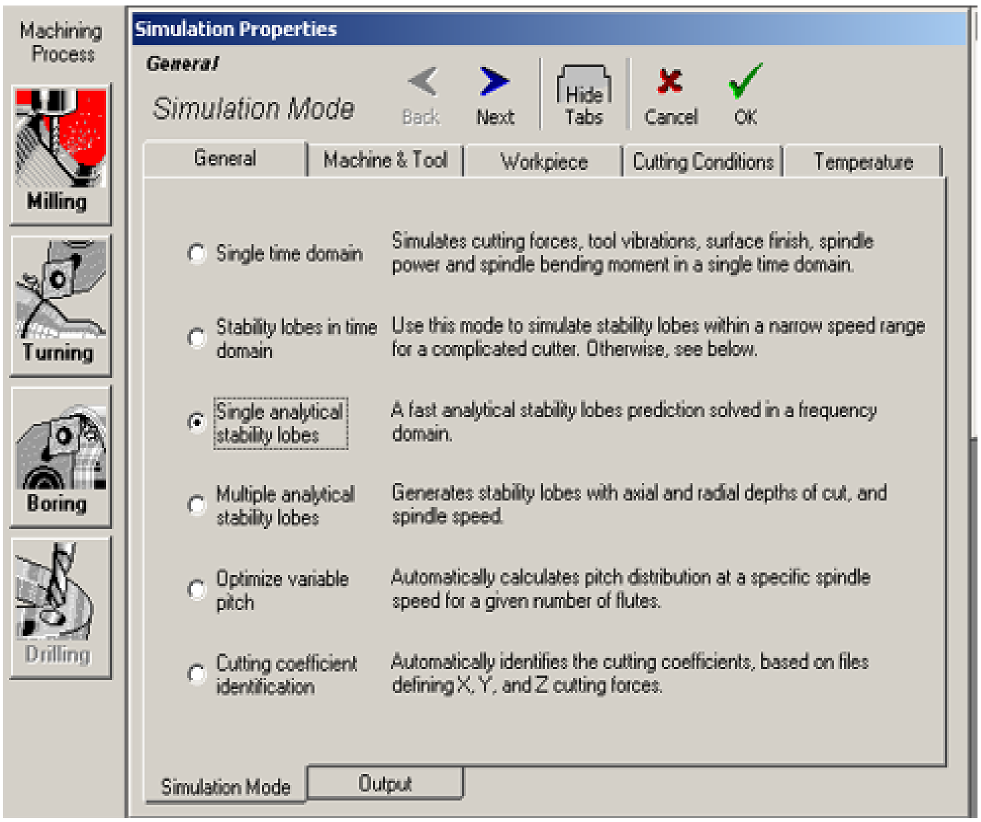


Figure 9-8.2-1: Select Single Analytical Stability Lobes in the General/Simulation Mode tab

Click Next to go to the General/Output tab. Check the Complete Results box if you wish to save all the results as text files.

Click Next to go to the Machine & Tool/Cutter Type tab. Select the Cylindrical endmill, with a uniform pitch of 4 flutes.

Click Next to go to the Machine & Tool/Cutter Properties tab. Select Carbide in the Cutter Material drop-down menu. Input the radius as 9.525mm, with a helix angle of 30, relief angle of 0 and rake angle of 0.

Click Next to go to the Machine & Tool/Structural Flexibility tab. Select Dynamic vibrations in the Machine & Tool Model. In this example, the machine dynamics will be entered as Dynamic Parameters. Therefore, select Dynamic Parameters in the Machine Dynamics Mode.

Enter the natural frequencies, damping ratios, and stiffness for each direction. In this example, there are two dynamic modes. The dynamic parameters are shown in the following table.

Direction	Mode 1			Mode 2		
	Nat. Freq.	Damp. Ratio.	Stiffness	Nat. Freq.	Damp. Ratio.	Stiffness
X	925	0.01	6.06E7	1004	0.01	4.33E7
Y	947	0.02	2.76E7	0	0	0

Click Next to go to the Workpiece/Material tab. Select the Average Cutting Coefficient mode for the purpose of this example. Select Aluminum AL356-T6 as the material of the workpiece from the drop-down menu.

Click Next to go to the Workpiece/Structural Flexibility tab. For this example, the workpiece is assumed to be rigid. Hence, select Rigid in the Workpiece Material.

Click Next to go to the Cutting Conditions/Milling Mode tab. Select Clockwise and Downmilling for the spindle direction and milling mode. Enter 9.525mm as the radial depth of cut as the process is half-emersion.

Click Next to go to the Cutting Conditons/Other Parameters tab. No other parameters can be entered.

Click Next to go to the Temperature/Properties tab. We are not interested in the temperature simulation for this process.

Click OK. Click Run on the main window toolbar to run the simulation; this will take a minute or two depending on the speed of the computer.

Click Results → Plot → Stability Lobes (Analytical).

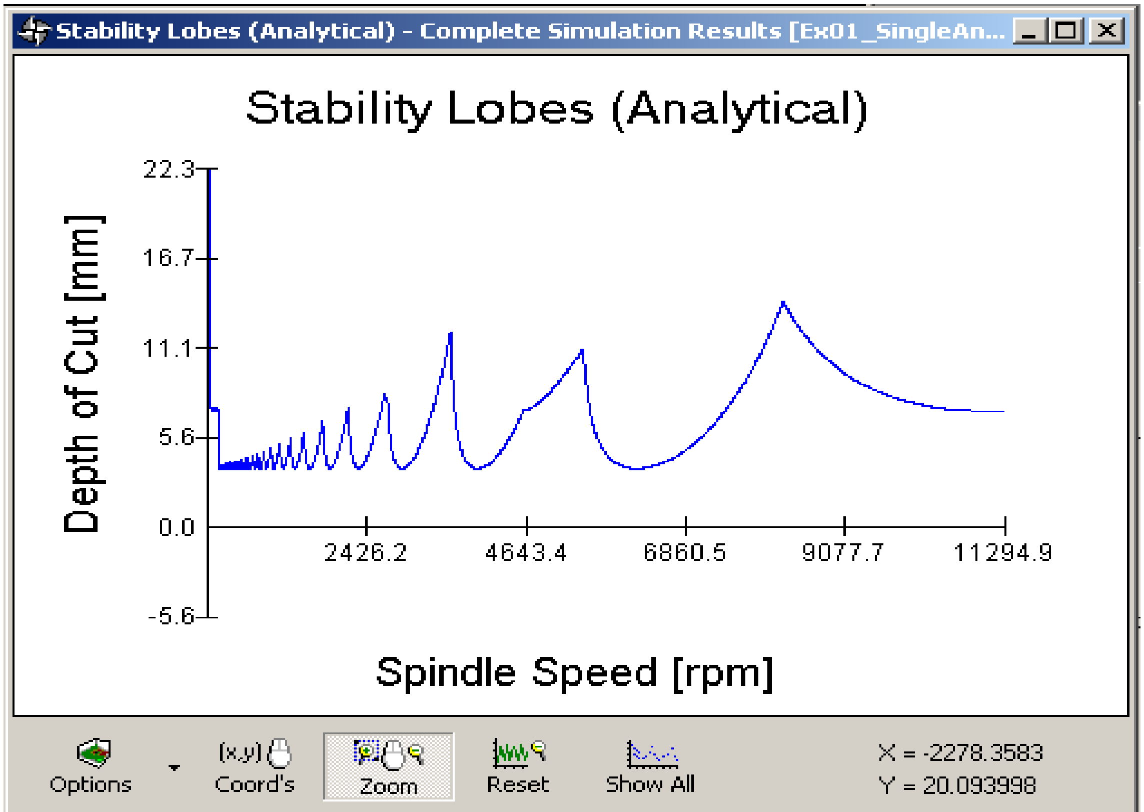


Figure 9-8.2-2: Stability Lobes result

As the graph indicates, at 6000RPM and and axial depth of cut of 7mm, the point is above the stability lobes, hence the process is unstable. Whereas at 8000RPM and 7mm depth of cut, the process is stable. In some circumstances, you may choose to run the process at 8000RPM to ensure stability. However, for the purpose of this example, it is supposed that a spindle speed of 8000RPM is not allowed.

What you can do, in this case, is to find the optimal variable pitch to shift the stability lobes to the left so the process will be stable at 6000 RPM. This is done in Section 9.2.4 – Optimizing Variable Pitch.

8.2.2 SIMULATING THE MILLING PROCESS AT 6000 RPM

This section of the example illustrates how to simulate the above process at 6000RPM and an axial depth of cut of 3mm in single time domain. The result of this simulation will show that the process is unstable. The following steps are contained in the example file Ex02-SingleTime_6000_7mm.csf.

Select the Advanced Milling Module, choose Single Time Domain.

Click Next to go to the General/Output tab. Select the files to be saved as text files during the simulation. Also, the revolution and level data can be entered in the Animation Options.

Click Next to go to the Machine & Tool/Cutter Type tab. Select Cylindrical endmill with 4 flutes at uniform pitch.

Click Next to go to the Machine & Tool/Cutter Properties tab. Select Carbide from the cutter material drop-down menu. Enter the appropriate parameters as indicated at the beginning of the example.

Click Next to go to the Machine & Tool/Structrual Flexibility tab. Select Dynamic vibrations for the Machine & Tool Model and enter the same dynamic parameters as the previous section.

Click Next to go to the Workpiece/Material tab. Select Average cutting coefficient mode and choose Aluminum AL356-T6 from the material drop-down menu.

Click Next to go to the Workpiece/Structural Flexibility tab. For the purpose of this example, the workpiece is assumed to be rigid.

Click Next to go to the Cutting Conditions/Milling Mode tab. The parameters to be entered are exactly the same as in the previous section. The Spindle Speed is specified to be 6000RPM and the number of revolutions is entered as 15. The sampling frequency scale can be entered as 10. Note that the Material Removal Rate and the Surface Speed are dependent on the other parameters entered.

Click Next to go to the Cutting Conditions/Other Parameters tab. No other parameters can be entered.

Click Next to go to the Temperature/Properties tab. We are not interested in the temperature simulation for this process.

Click OK. Click Run to run the simulation.

To see the tool vibrations, click Results → Plot → Tool Vibration. Click FFT on the Tool Vibration window toolbar.

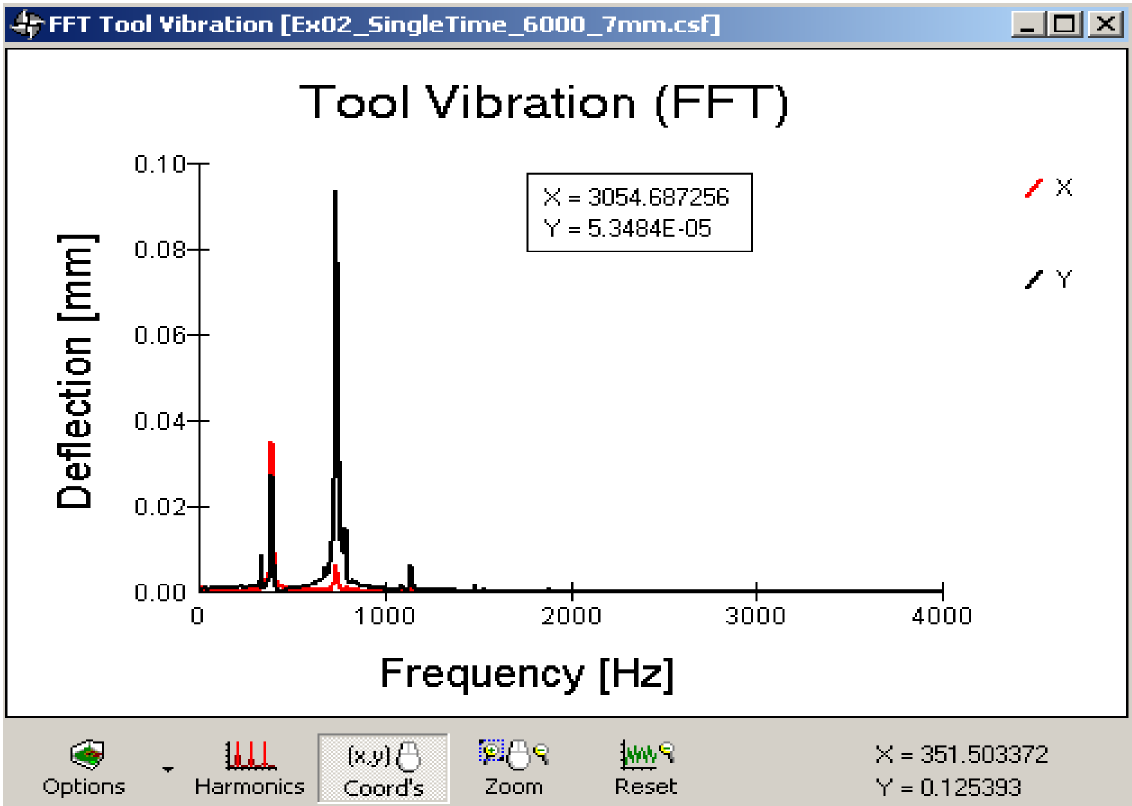


Figure 9-8.2-3: Tool vibration at 6000RPM, in frequency domain

Notice that there is a high peak at around frequency 700Hz and a lower peak at around 400Hz. The 700Hz peak is due to the natural frequency of the tool flexibility in the Y direction, whereas the 400Hz smaller peak is due to the tool during the cut. Note that spindle speed is at 6000RPM, meaning that the spindle rotates 100 times per second. Since there are 4 flutes on the tool, the flutes would hit the workpiece at 400Hz.

8.2.3 SIMULATING THE MILLING PROCESS AT 14300 RPM

This section of the example is contained in the example file Ex03_SingleTime_14300_6mm.csf.

The steps in this section are exactly the same as the steps in the previous section.

The tool vibration simulation obtained for 8000RPM shows only one peak at around 533Hz, which is the frequency at which the flutes hit the workpiece.

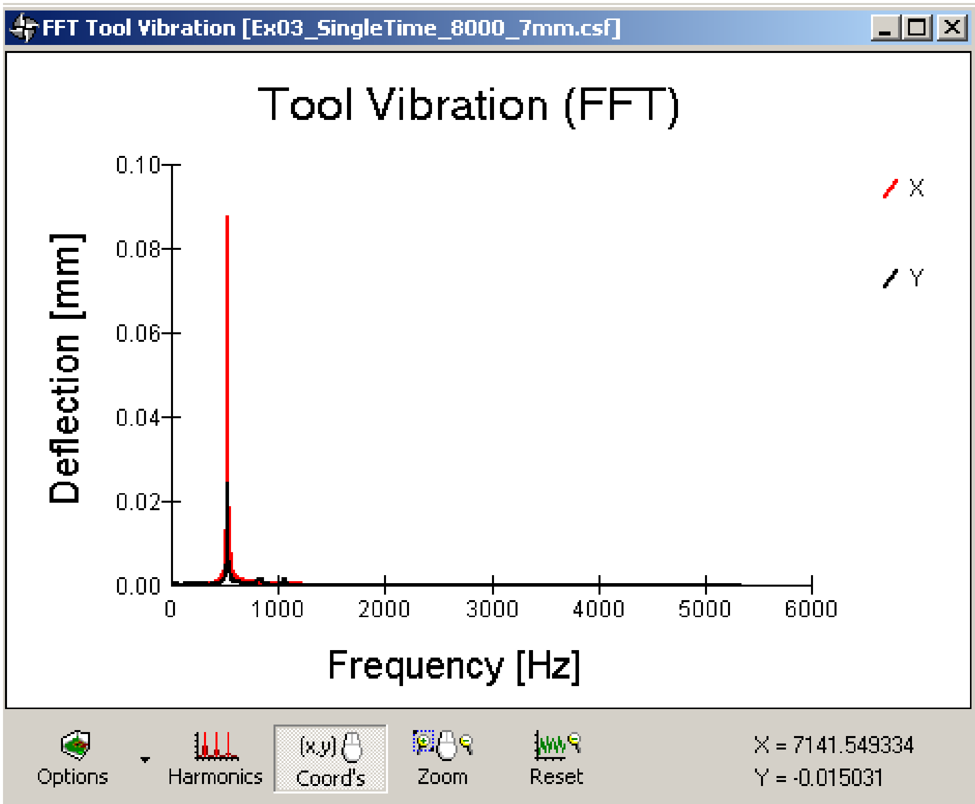


Figure 9-8.2-4: Tool vibration at 8000Hz, in frequency domain.

8.2.4 OPTIMIZING VARIABLE PITCH

This section of the example illustrates how to obtain the optimum variable pitch in order to run the process at 5000RPM and an axial depth of cut of 5mm with stability. The following steps are contained in the example file Ex05_Optimumpitch_5000.csf.

Select the Advanced Milling module, select Optimize Variable Pitch mode.

Click Next to go to the General/Output tab. Note that no selections can be made on this tab.

Click Next to go to the Machine & Tool/Cutter Type tab. Select Cylindrical endmill and 4 flutes for this example.

Click Next to go to the Machine & Tool/Cutter Properties tab. Select Carbide for the cutter material from the drop-down menu. Enter the same parameters as in the previous sections in this example.

Click Next to go to the Machine & Tool/Structural Flexibility tab. Select Dynamic vibrations for the machine & tool model and enter the same dynamic parameters as before (500Hz for X, 700Hz for Y).

Click Next to go to the Workpiece/Material tab. Select Aluminum AL356-T6 for the material of the workpiece. Select Average cutting coefficient mode for the purpose of this example.

Click Next to go to the Workpiece/Structural Flexibility tab. The workpiece is assumed to be rigid in this example. Select Rigid.

Click Next to go to the Cutting Conditions/Milling Mode tab. Select Clockwise spindle direction and downmilling. Enter the desired feed rate (0.05mm/flute) and the desired spindle speed (5000RPM). The surface speed is dependent on the two parameters mentioned. Enter the radial width of cut as mentioned before, 9.525mm.

Click Next to go to the Cutting Conditions/Other Parameters tab. Three pitch distribution types can be selected. For the purpose of this example, the type "Two different angles" is selected. Enter 0 as the starting angle. The increments of Chatter Frequency and Pitch Angle can be entered as 1. For more accurate results, use smaller increments (true?).

Click Next to go to the Temperature/Properties tab. We are not interested in the temperature simulation for this process.

Click OK. Click Run to run the simulation.

Click Results → Plot → Optimum Variable Pitch.

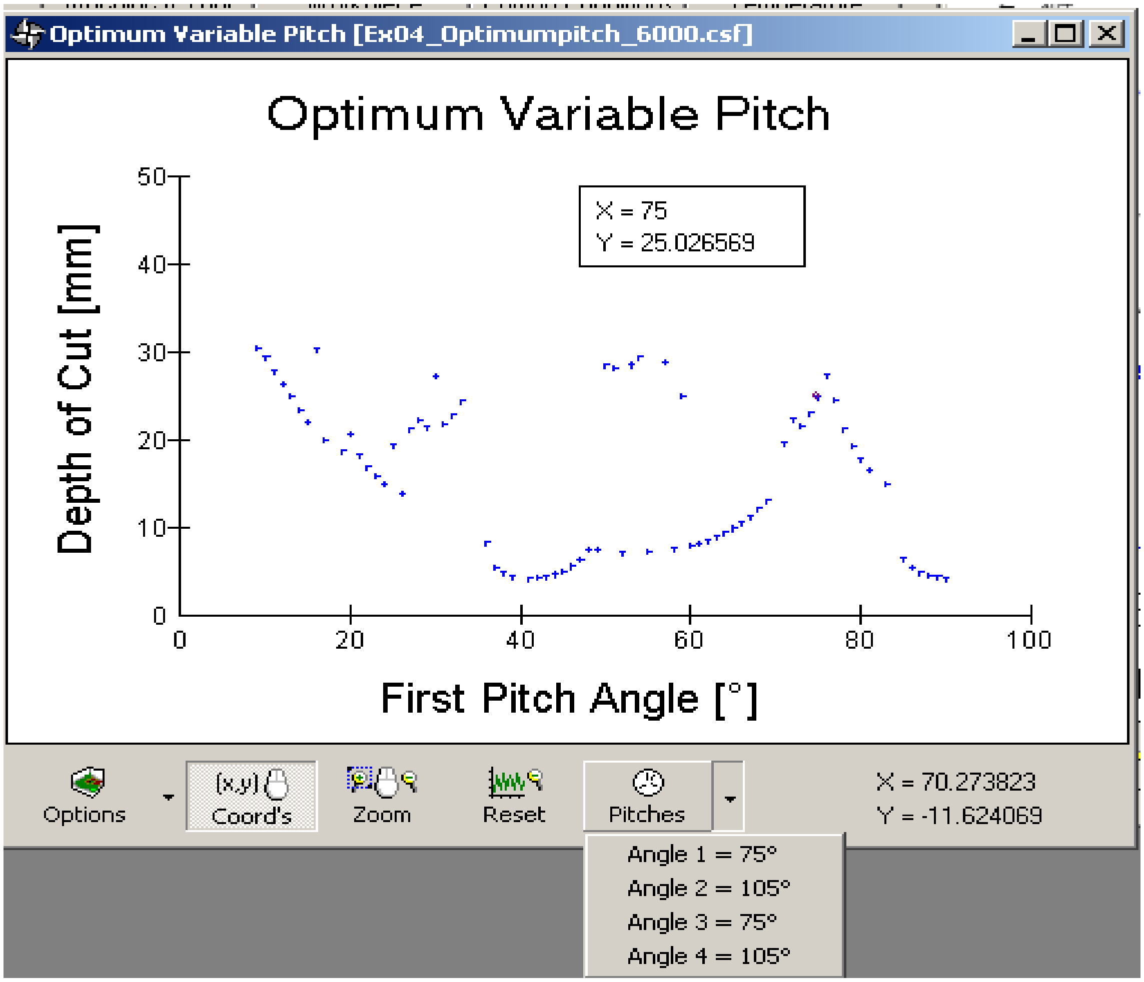


Figure 9-8.2-5: Optimum Variable Pitch result, the point at 75° is selected.

Click on a point on the graph with a Y value larger than the desired depth of cut. The point at first pitch angle 75° is selected in this case. Click on Pitches to view the pitch angles of the flutes. In this case, the pitch angles will be 75°, 105°, 75°, and 105°.

According to the simulation, the pitch angles 75° and 105° are stable for a spindle speed of 6000RPM and a depth of cut of 7mm. To check the stability of this variable pitch angle arrangement, please see the next section.

8.2.5 CHECKING THE STABILITY LOBES FOR THE OBTAINED VARIABLE PITCH

This section illustrates how to obtain the single stability lobes for the variable pitch obtained in section 9.2.4. The following steps are contained in the example file Ex06_SingleAnalytical_Var.csf.

Select the Advanced Milling Module. Select Single Analytical Stability Lobes mode.

The rest of the steps are identical to section 9.2.4, with the exception that on the Machine & Tool/Cutter Type tab, instead of selecting Uniform pitch, select Non-uniform pitch. Enter 75° for Pitch #1, 105° for Pitch #2, 75° for Pitch #3, and 105° for Pitch #4.

Run the simulation. Click Results → Plot → Stability Lobes (Anal.–Var. Pitch).

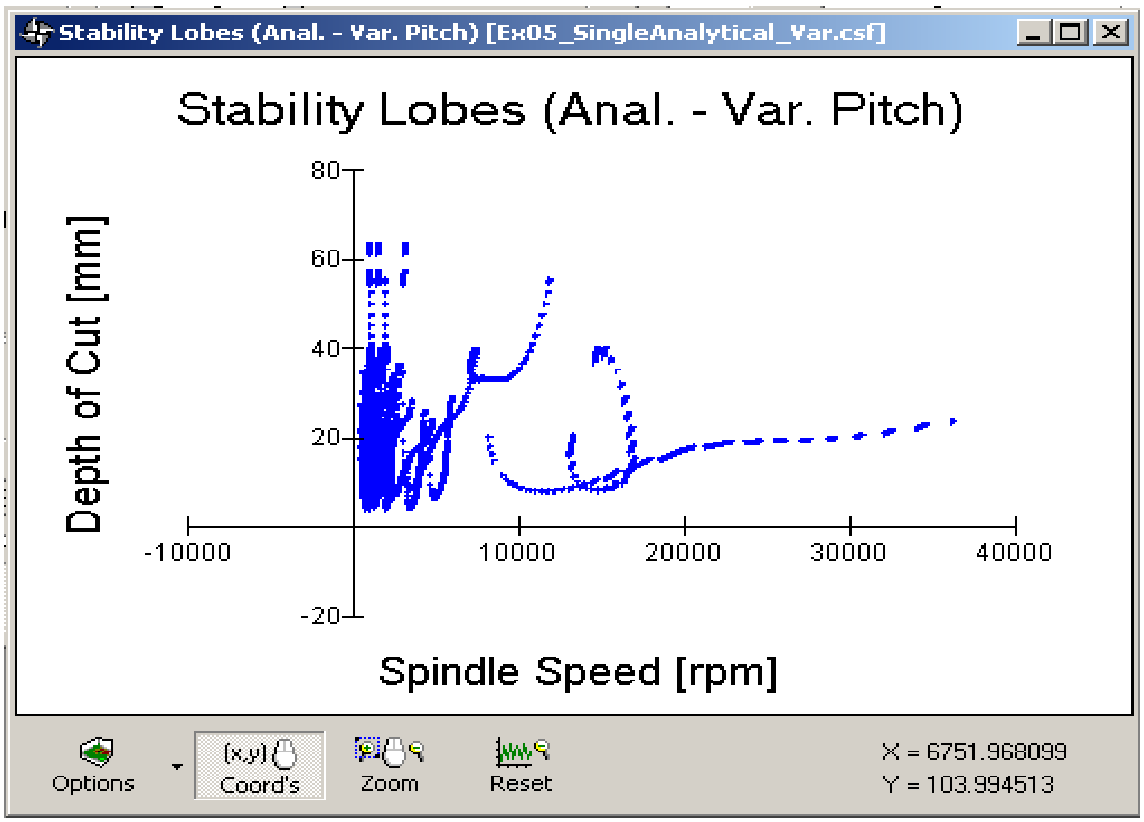


Figure 9-8.2-6: Unsorted Stability Lobes with the variable pitch tool.

The unsorted stability lobes for this process are displayed. Note that the stability lobes for variable pitch are not sorted. To ensure a condition is stable, make sure the corresponding point is beneath *all* curves on the stability lobes.

According to the stability lobes, the process is stable at Spindle Speed 6000RPM and Depth of Cut 7mm. You can run the process at 6000RPM with the 75° and 105° pitch angles on the machine.

8.3 EXAMPLE B: OBTAINING STABILITY LOBES IN A MULTIPLE-STEPS PROCESS

This example illustrates how to obtain the stability lobes for a process with different steps. In this example, three steps are performed in the process: half-emersion down-milling, full-emersion milling, and half emersion up-milling.

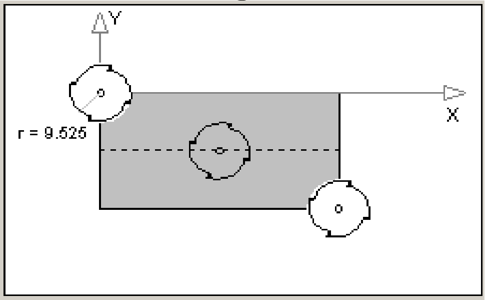


Figure: Multiple analytical stability lobes

A carbide cylindrical endmill with 4 flutes at uniform pitch is used for this process. The tool has radius 9.525mm, helix angle of 30°, relief and rake angles of 0°. The workpiece is Aluminum AL356-T6 and is rigid. The feed rate is 0.05mm/flute and the spindle direction is clockwise.

The following steps are contained in the example file Ex06_MultipleAnalytical.csf.

Select the Advanced Milling module. Select Multiple analytical stability lobes.

Click Next to go to the General/Output tab. Note that no selection can be made on this tab.

Click Next to go to the Machine & Tool/Cutter Type tab. Select Cylindrical end with 4 flutes at Uniform pitch.

Click Next to go to the Machine & Tool/Cutter Properties tab. Select Carbide as the cutter material. Enter the radius, Helix, Relief, and Rake angles of the tool.

Click Next to go to the Machine & Tool/Structural Flexibility. Select Dynamic vibrations for the Machine & Tool Model. Enter the Dynamic Parameters (select it first). The natural frequencies are respectively 500Hz and 700Hz in the X and Y direction for this example. The damping ratios are 0.05 for both directions and the stiffness is 1e7N/m for both directions.

Click Next to go to the Workpiece/Material tab. Select Aluminum AL356-T6 from the workpiece material drop menu. Select Average cutting coefficient mode for the purpose of this example.

Click Next to go to the Workpiece/Structural Flexibility tab. In this example, the workpiece is assumed to be rigid.

Click Next to go to the Cutting Conditions/Milling Mode tab. Select Clockwise as the spindle direction and enter the feed rate.

Click Next to go to the Cutting Conditions/Other Parameters tab. Enter the parameters indicating the offset and width of cut. Upon click on a textbox of one of the parameters, a red arrow will appear in the diagram, indicating what the parameter represents.

For this example, the Y-start offset is -19.05mm, Y-end offset is 19.05mm, Start width is -9.525mm, End width is 9.525mm, Workpiece width is 38.1mm, and the step is 19.05mm. If the parameters are changed, the number of analytical simulation to perform may change as a result.

Click Next to go to the Temperature/Properties tab. We are not interested in the temperature simulation for this process.

Run the simulation. Click Results → Plot → Stability Lobes (Multiple Anal.).

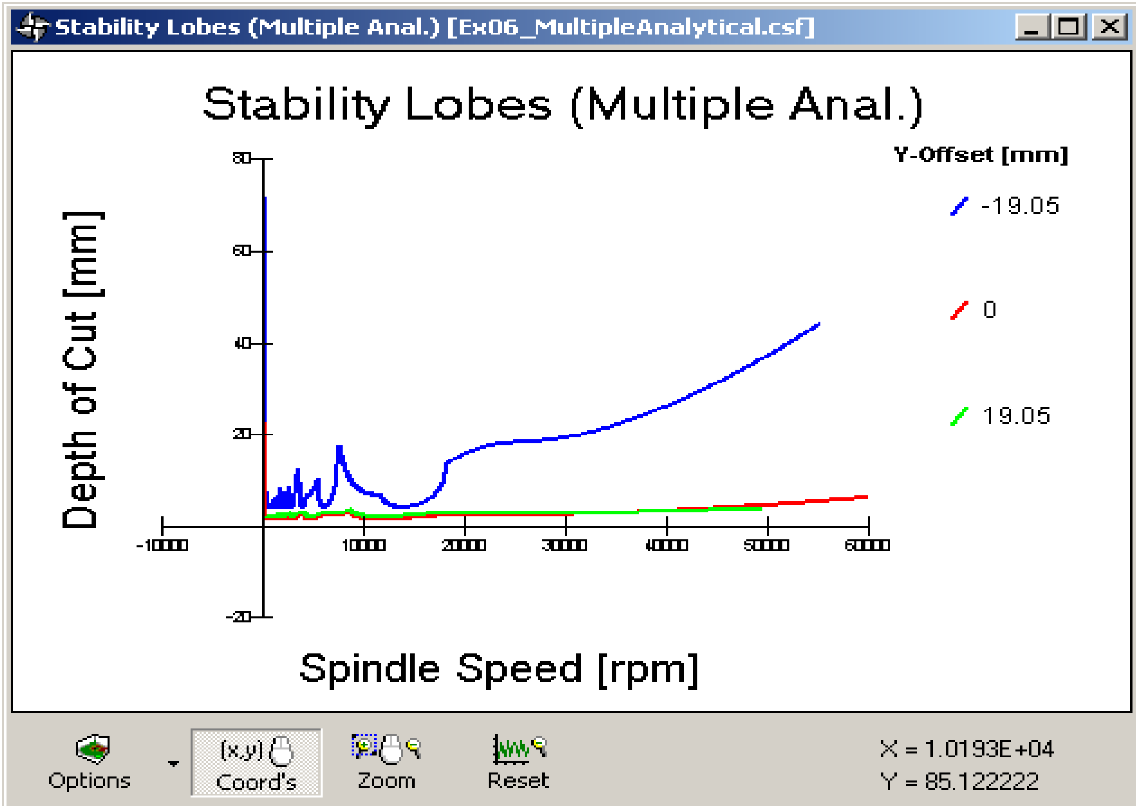


Figure 9-8.3-1: Multiple Analytical Stability Lobes result from the example

The stability lobes for the three steps are illustrated in three different colours. To ensure the stability of the entire process, select a point which is stable for all three steps.

8.4 EXAMPLE C: OBTAINING CUTTING COEFFICIENTS IN MILLING

This example illustrates how to identify cutting coefficients in a milling process with obtained experimental cutting forces. The following steps are contained in the example file Ex07_CuttingCoef.csf.

Select the Advanced Milling module. Select the Cutting coefficient identification mode.

Click Next to go to the General/Output tab. Note that no selection can be made on this tab.

Click Next to go to the Machine & Tool/Cutter tab. Only Cylindrical end is available for Cutting Coefficients Identification mode. Enter the number of flutes on the tool.

Click Next to go to the Machine & Tool/Cutter Properties tab. It does not matter what material you select.

Click Next to go to the Machine & Tool/Structural Flexibility tab. The tool is assumed to be rigid in Cutting Coefficients Identification.

Click Next to go to the Workpiece/Material tab. It does not matter what material you select.

Click Next to go to the Workpiece/Structural Flexibility tab. The workpiece is also assumed to be rigid in Cutting Coefficients Identification.

Click Next to go to the Cutting Conditions/Milling Mode tab. The spindle direction can only be clockwise and the milling mode can only be slotting in this simulation mode. Enter the axial depth of cut, which is 2mm for this example.

Click Next to go to the Cutting Conditions/Other Parameters tab. Select Average Method as the cutting coefficient calculation method. Click Browse for the experimental cutting forces for a particular feed rate and enter the feed rate as well. Click Next to enter the next set of data and its corresponding feed rate.

The Experimental Cutting Forces files for this example are under the names ExpCutForce_050_2.txt, ExpCutForce_075_2.txt, etc.

Click Next to go to the Temperature/Properties tab. We are not interested in the temperature simulation for this process.

Click Run to run the simulation. Click Results → Plot → Exp. Average Cutting Forces to plot the Force vs. Feed Rate.

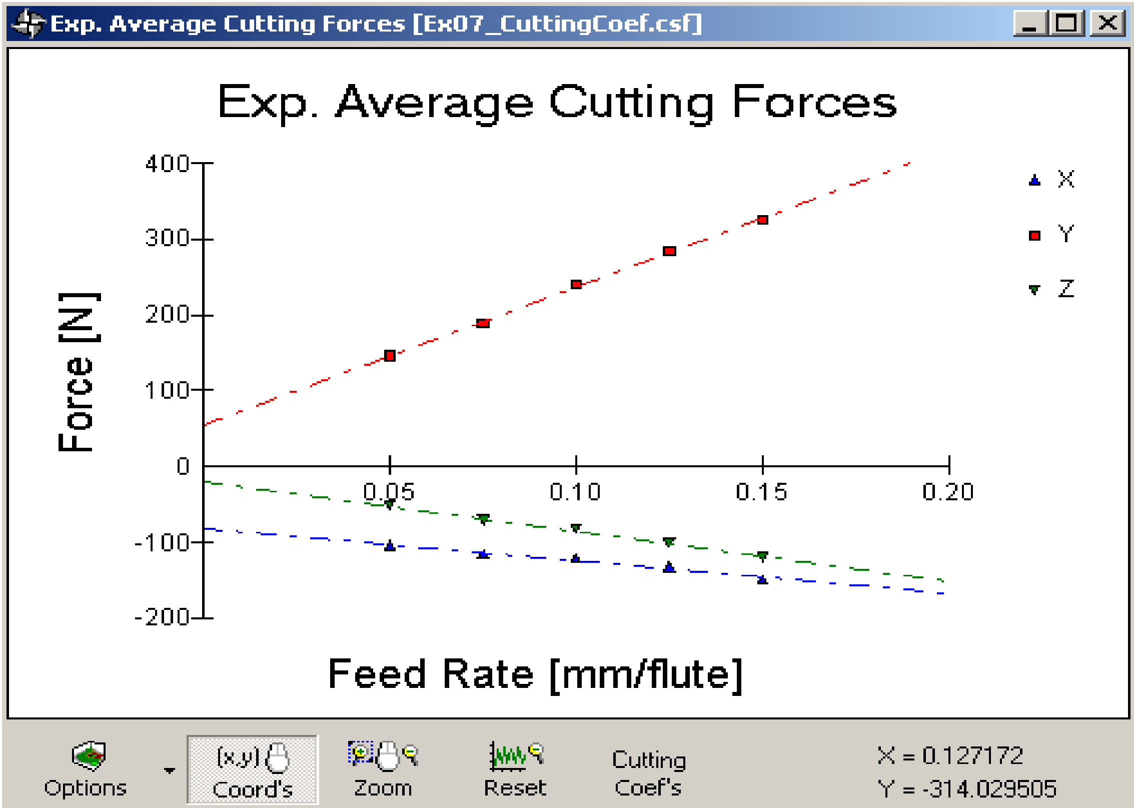


Figure 9-8.4-1: Average Cutting Forces, result from Example C.

Click on Cutting Coef's on the toolbar of the window to open Material Editor. The cutting coefficients automatically appear in the window. You can enter the material name, description, and geometry and save the data as a user defined material.

8.5 EXAMPLE D: OBTAINING MAXIMUM TEMPERATURE ALONG CUTTER ROTATION

This example illustrates how to run a temperature simulation to simulate the maximum temperature history along the cutter rotation. The following steps are contained in the example file Ex13_Temperature_Milling.csf.

A carbide 4-fluted cylindrical endmill with uniform pitch is used for this simulation. The workpiece is Aluminum AL7075-T6.

Select the Advanced Milling Module, choose Single Time Domain.

Click Next to go to the General/Output tab. Select the files to be saved as text files during the simulation. Also, the revolution and level data can be entered in the Animation Options.

Click Next to go to the Machine & Tool/Cutter Type tab. Select Cylindrical endmill with 4 flutes at uniform pitch.

Click Next to go to the Machine & Tool/Cutter Properties tab. Select Carbide from the cutter material drop-down menu. Enter the appropriate parameters as indicated at the beginning of the example.

Click Next to go to the Machine & Tool/Structural Flexibility tab. Select Dynamic vibrations for the Machine & Tool Model and enter the dynamic parameters. The natural frequencies are 500Hz and 700Hz respectively in X and Y directions. The damping ratio is 0.05 and the stiffness is 1e7N/m for both directions.

Click Next to go to the Workpiece/Material tab. Select Average cutting coefficient mode and choose Aluminum AL7075-T6 from the material drop-down menu.

Click Next to go to the Workpiece/Structural Flexibility tab. For the purpose of this example, the workpiece is assumed to be rigid.

Click Next to go to the Cutting Conditions/Milling Mode tab. The parameters to be entered are exactly the same as in the previous section. The Spindle Speed is specified to be 6000RPM and the number of revolutions is entered as 15. The sampling frequency scale can be entered as 10. Note that the Material Removal Rate and the Surface Speed are dependent on the other parameters entered.

Click Next to go to the Cutting Conditions/Other Parameters tab. No other parameters can be entered.

Click Next to go to the Temperature/Properties tab. Enter the number of divisions along chip thickness and divisions along the tool. It is recommended that at least 10 divisions be used for more accurate results. Enter the number of angular increments on the tool and the associated tolerance.

Select the Maximum temperature history along the full cutter rotation to find the maximum temperature in the process.

Click Run Temp to run the temperature simulation. Click Results → Plot → Maximum Temperature History Along the Cutter Rotation.

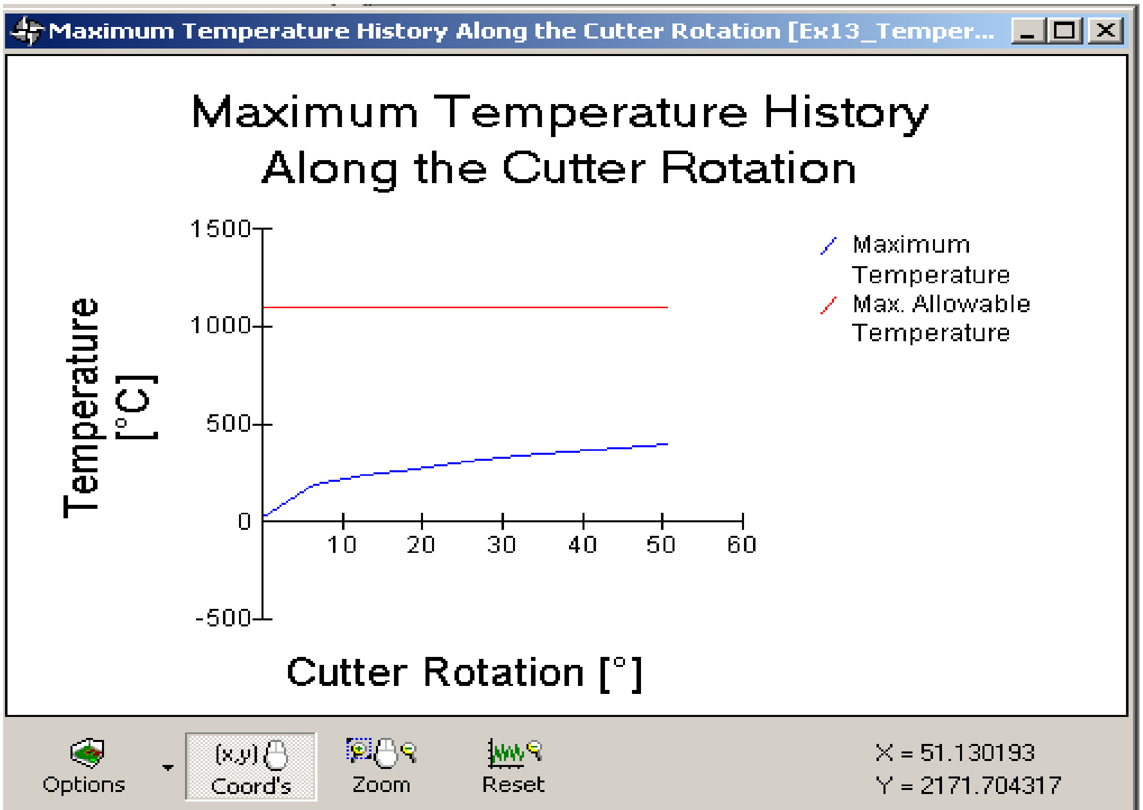


Figure 9-8.5-1: Maximum Temperature History, result from Example D.

Note that the temperature along the cutter rotation is below the maximum allowable temperature of 1100°C.

9 APPENDIX A

9.1 Appendix A1: Units

Metric Units	*Imperial Units*
Millimeter (mm)	*Inch (in)*
Newton (N)	*Pound Force (lbf)*
Meter (m)	*Foot (ft)*
Gram (g)	*Pound (lb)*
Newton / millimeter (N/mm)	*Pound force / inch (lbf/in)*
Newton / millimeter squared (N/mm^2)	*Pound force / squared inch (lbf/in^2)*
Newton / meter (N/m)	*Pound force / foot (lbf/ft)*
Meter / Newton (m/N)	*Foot / pound force (ft/lbf)*
*Newton-meter (N*m)*	*Pound force-foot (lbf*ft)*
Gram / centimeter cube (g/cm^3)	*Pound / inch cube (lb/in^3)*
Newton / meter squared (N/m^2)	*Pound force / squared inch (lbf/in^2)*
Degree Celsius (^oC)	*Degree Fahrenheit (^oF)*
Metric horsepower (Metric hp)	*Imperial Horsepower (Imperial hp)*
Watt /meter- Kelvin (W/m-K)	*Foot-pound inch / hour-foot^2-Fahrenheit (ft-lb in/(hr-ft^2-°F)*

9.2 Appendix A2: Modal/Residue data files

X modal/residue file	*Uses a file containing modal parameters. These modal parameter files are created using the modal analysis program.*
Y modal/residue file	*Uses a file containing modal parameters. These modal parameter files are created using the modal analysis program.*

Modal analysis program creates an **ASCII** file as follows:

Example:

MODES 3

PNTS	1
REALM	0
WN	503.252663429737
ZETA	9.68088610851847E-02
WN	667.318567093533
ZETA	5.15631722455325E-02
WN	891.394563382914
ZETA	5.93480547124278E-02
LOCNS	0
RESRE	1.92775517514935E-05
RESIM	-3.65695200216576E-05
RESRE	2.90756637986845E-05
RESIM	-3.58422199737442E-05
RESRE	1.54820897083893E-05
RESIM	-4.98397635177649E-05

9.3 Appendix A3: Dynamic Parameters

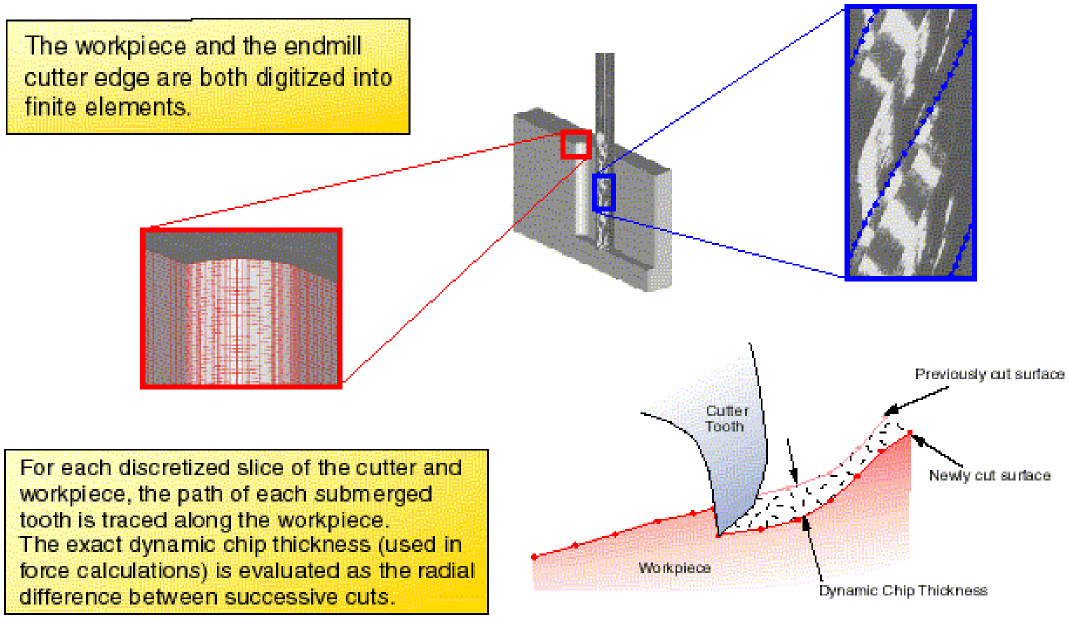
This uses the following dynamic parameters. It only allows for a single dominant mode in each of the X- and Y-directions.

Natural frequency(ω_n)	*Natural frequency of the system in [Hz]*
Damping ratio(ζ)	*Damping ratio for that mode*
Stiffness(k)	*Stiffness of the system [N/m]*

Transfer function values are calculated using following equation in frequency domain:

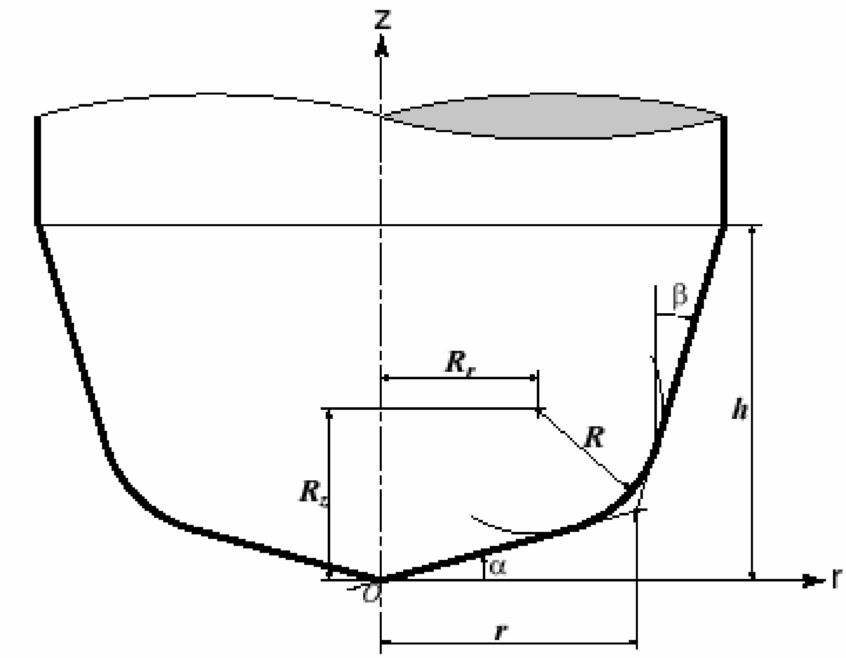
$$\Phi = \frac{\omega_n^2 k}{\omega_n^2 - \omega^2 + i2\zeta\omega_n\omega}$$

9.4 Appendix A4: How CutPro Calculates Dynamic Chip Thickness



9.5 Appendix A5: Geometric Figures for Tools

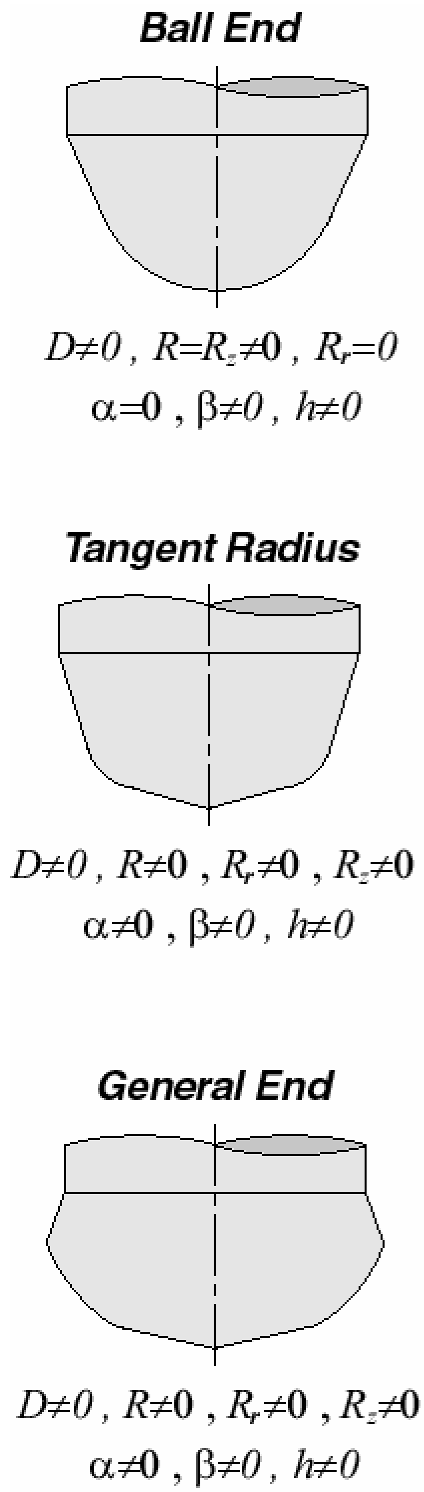
9.5.1 General Tool Geometry Parameters Figure



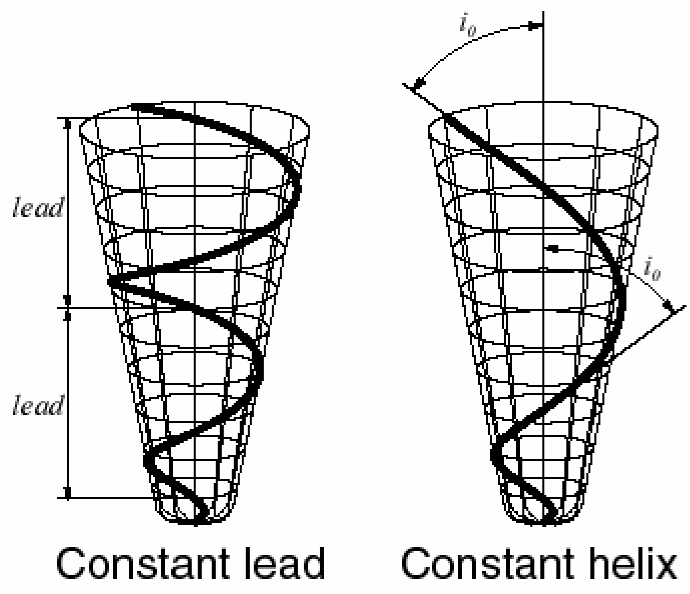
Cutter Parameters:

- ***r*** : *Radius of cutter [mm]*
- ***R*** : *Corner radius [mm]*
- ***R_r*** : *r coordinate of corner radius center [mm]*
- ***R_z*** : *z coordinate of corner radius center [mm]*
- α : *Slope angle for the first line [degree]*
- β : *Slope angle for the second line [degree]*
- ***h*** : *Valid cutting edge height [mm]*

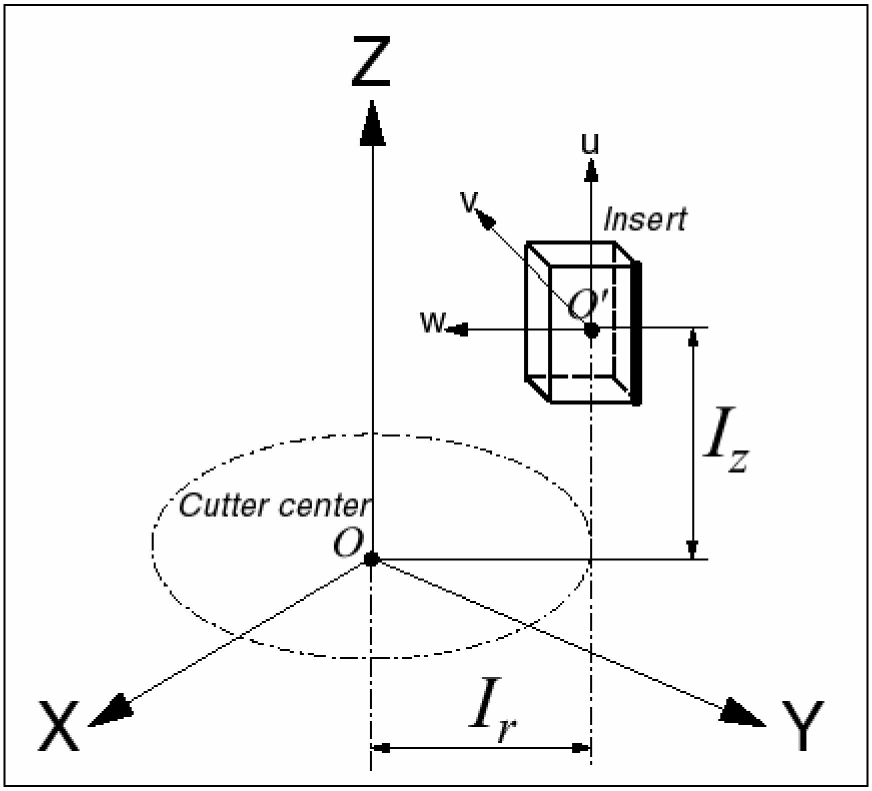
9.5.2 Geometry type

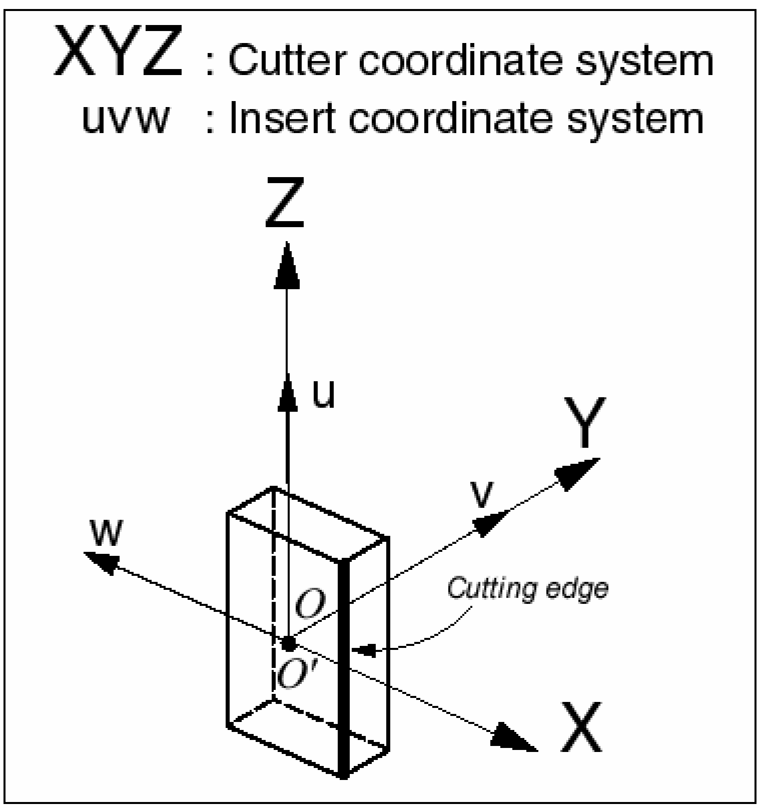


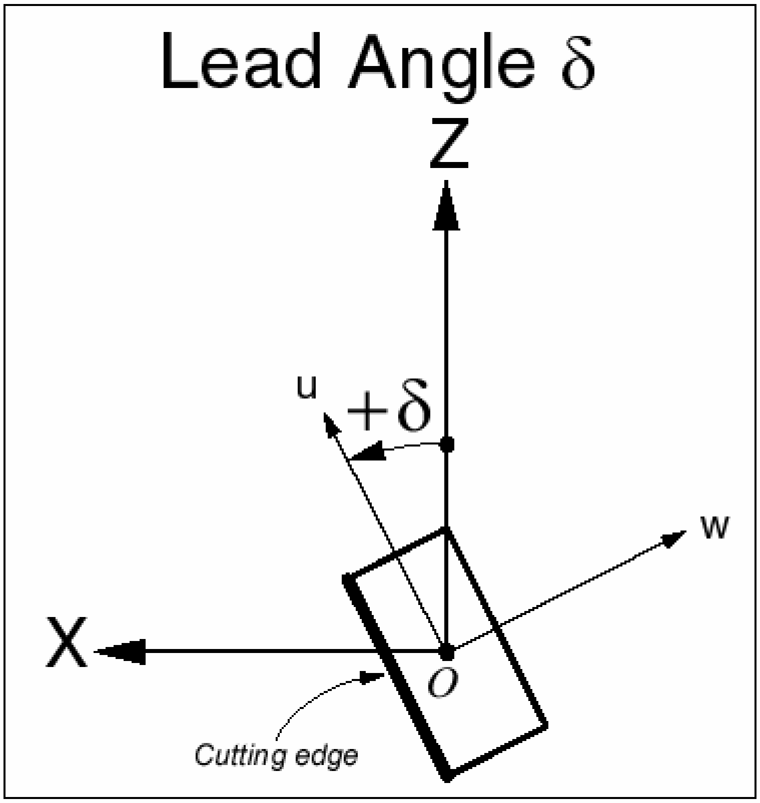
9.5.3 Flute type figure

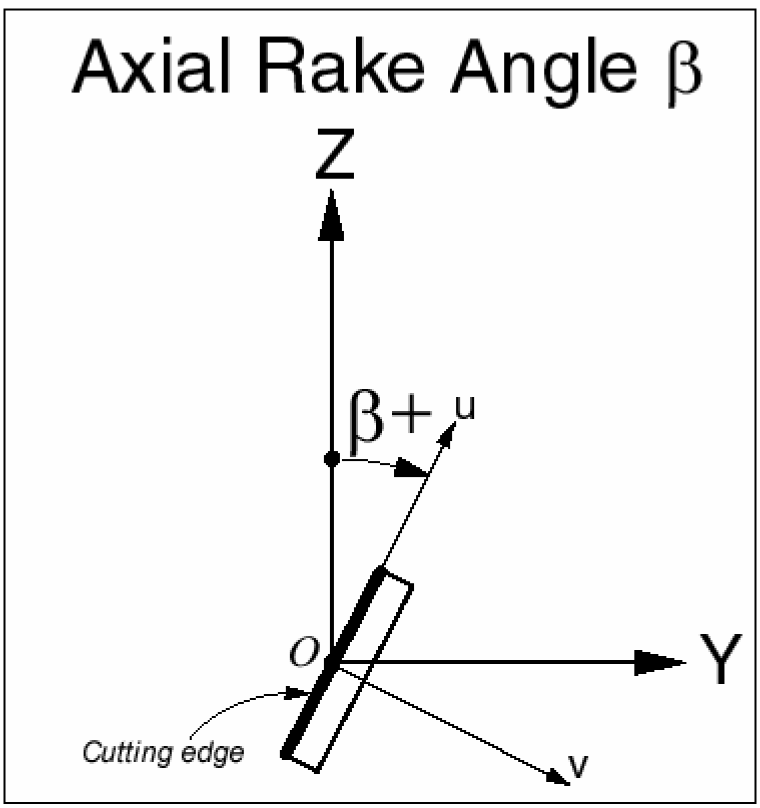


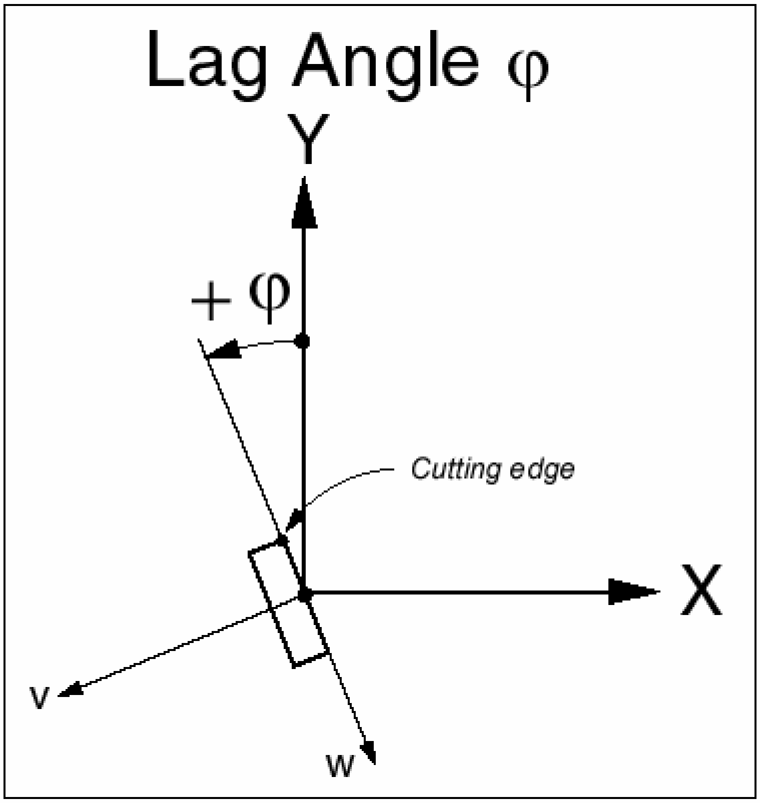
9.5.4 Cutter & Insert Coordinate Systems






Lead Angle δ
Z
u
+δ
w
X
O
Cutting edge


Axial Rake Angle β
Z
β+
u
O
Y
Cutting edge
v



Lag Angle φ
Y
+ φ
Cutting edge
X
v
w

10 Appendix B

10.1 Appendix B1: Orthogonal to oblique cutting transformation model [Equations]

$$dF_t = K_{te} \cdot dS + K_{tc} \cdot h \cdot dz$$
$$dF_r = K_{re} \cdot dS + K_{rc} \cdot h \cdot dz$$
$$dF_a = K_{ae} \cdot dS + K_{ac} \cdot h \cdot dz$$

$$K_{tc} = \frac{\tau}{\sin\phi_n} \frac{\cos(\beta_n - \alpha_n) + \tan\eta_c \sin\beta_n \tan i}{c}$$
$$K_{rc} = \frac{\tau}{\sin\phi_n \cos i} \frac{\sin(\beta_n - \alpha_n)}{c}$$
$$K_{ac} = \frac{\tau}{\sin\phi_n} \frac{\cos(\beta_n - \alpha_n)\tan i - \tan\eta_c \sin\beta_n}{c}$$
$$c = \sqrt{\cos^2(\phi_n + \beta_n - \alpha_n) + \tan^2\eta_c \sin^2\beta_n}$$

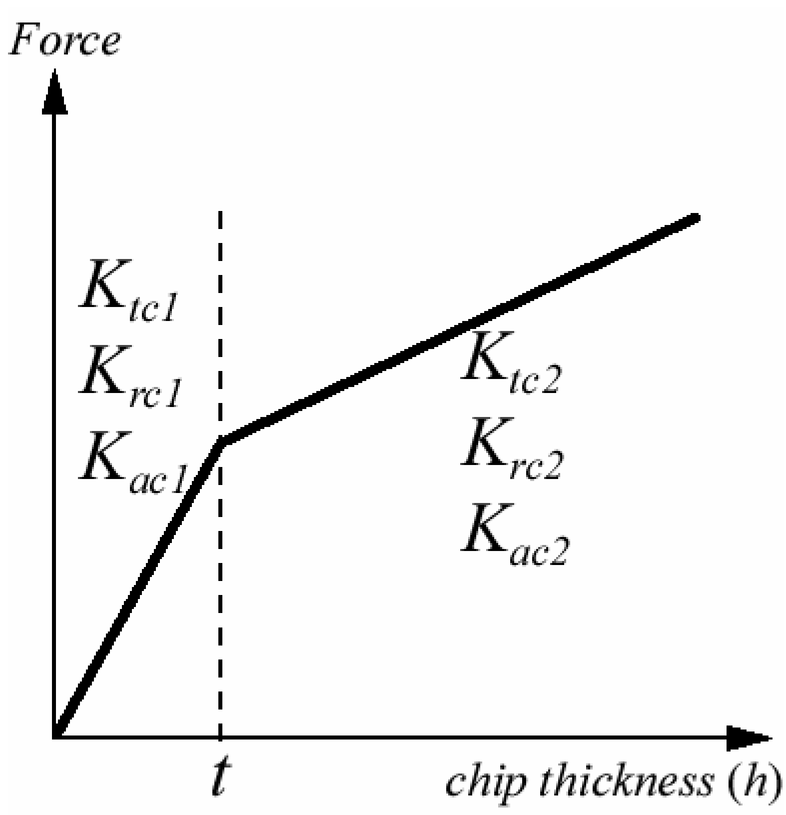
dF_t: differential tangential force [N]
dF_r: differential radial force [N]
dF_a: differential axial force [N]
dS: differential cutting edge length [mm]
dz: differential axial depth of cut [mm]
h: chip thickness [mm]
τ: shear stress [N/mm²]
ϕ: shear angle [°]
β: friction angle [°]
α: rake angle [°]
η: chip flow angle [°]
i: helix angle [°]
K_{te}: tangential edge force coefficient [N/mm]
K_{re}: radial edge force coefficient [N/mm]
K_{ae}: axial edge force coefficient [N/mm]
K_{tc}: tangential shearing coefficient [N/mm²]
K_{rc}: radial shearing coefficient [N/mm²]
K_{ac}: axial shearing coefficient [N/mm²]

10.2 Appendix B2: Bi-linear force model [Equations]

$$dF_t = K_{te} \cdot dS + K_{tc} \cdot h \cdot dz$$
$$dF_r = K_{re} \cdot dS + K_{rc} \cdot h \cdot dz$$
$$dF_a = K_{ae} \cdot dS + K_{ac} \cdot h \cdot dz$$

$$\left.\begin{array}{lll} K_{te} = 0.0 & ; & K_{tc} = K_{tc1} \\ K_{re} = 0.0 & ; & K_{rc} = K_{rc1} \\ K_{ae} = 0.0 & ; & K_{ac} = K_{ac1} \end{array}\right\} \text{if } h < t$$

$$\left.\begin{array}{lll} K_{te} = (K_{tc1} - K_{tc2}) \cdot t & ; & K_{tc} = K_{tc2} \\ K_{re} = (K_{rc1} - K_{rc2}) \cdot t & ; & K_{rc} = K_{rc2} \\ K_{ae} = (K_{ac1} - K_{ac2}) \cdot t & ; & K_{ac} = K_{ac2} \end{array}\right\} \text{if } h > t$$



dF_t : differential tangential force [N]

dF_r : differential radial force [N]

dF_a : differential axial force [N]
dS : differential cutting edge length [mm]
dZ : differential axial depth of cut [mm]
h : chip thickness [mm]
K_{te} : tangential edge force coefficient [N/mm]
K_{re} : radial edge force coefficient [N/mm]
K_{ae} : axial edge force coefficient [N/mm]
K_{tc} : tangential shearing coefficient [N/mm²]
K_{rc} : radial shearing coefficient [N/mm²]
K_{ac} : axial shearing coefficient [N/mm²]

10.3 Appendix B3: Exponential chip thickness [Equations]

$$dF_t = K_{te} \cdot dS + K_{tc} \cdot h \cdot dz$$
$$dF_r = K_{re} \cdot dS + K_{rc} \cdot h \cdot dz$$
$$dF_a = K_{ae} \cdot dS + K_{ac} \cdot h \cdot dz$$

$$K_{te} = K_{re} = K_{ae} = 0.0$$
$$K_{tc} = KT \cdot h^{-p}$$
$$K_{rc} = KR \cdot KT \cdot h^{-q}$$
$$K_{ac} = KA \cdot KT \cdot h^{-r}$$

dF_t : differential tangential force [N]
dF_r : differential radial force [N]
dF_a : differential axial force [N]
dS : differential cutting edge length [mm]
dZ : differential axial depth of cut [mm]
h : chip thickness [mm]
KT : tangential shearing coef. Parameter
KR : radial shearing coef. Parameter
KA : axial shearing coef. parameter
p : tangential chip thickness order
q : radial chip thickness order
r : axial chip thickness order
K_{te} : tangential edge force coefficient [N/mm]
K_{re} : radial edge force coefficient [N/mm]
K_{ae} : axial edge force coefficient [N/mm²]
K_{tc} : tangential shearing coefficient [N/mm²]
K_{rc} : radial shearing coefficient [N/mm²]
K_{ac} : axial shearing coefficient [N/mm²]

10.4 Appendix B4: Semi-mechanistic model [Equations]

$$dF_t = K_{te} \cdot dS + K_{tc} \cdot h \cdot dz$$
$$dF_r = K_{re} \cdot dS + K_{rc} \cdot h \cdot dz$$
$$dF_a = K_{ae} \cdot dS + K_{ac} \cdot h \cdot dz$$

$$K_{te} = K_{re} = K_{ae} = 0.0$$
$$K_{tc} = k_n \left[\cos\alpha_n + k_f \cos\eta \sin\alpha_n + k_f \tan i \sin\eta \right]$$
$$K_{rc} = k_n \left[-\frac{\sin\alpha_n}{\cos i} + k_f \cos\alpha_n \frac{\cos\eta}{\cos i} \right]$$
$$K_{ac} = k_n \left[\tan i \cos\alpha_n - k_f \sin\eta + k_f \tan i \cos\eta \sin\alpha_n \right]$$

dF_t : differential tangential force [N]
dF_r : differential radial force [N]
dF_a : differential axial force [N]
dS : differential cutting edge length [mm]
dZ : differential axial depth of cut [mm]
h : chip thickness [mm]
α : rake angle [°]
η : chip flow angle [°]
ι : helix angle [°]
k_n : cutting pressure on rake face [N/mm²]
k_f : cutting pressure rate on flank face
K_{te} : tangential edge force coefficient [N/mm]
K_{re} : radial edge force coefficient [N/mm]
K_{ae} : axial edge force coefficient [N/mm]
K_{tc} : tangential shearing coefficient [N/mm²]
K_{rc} : radial shearing coefficient [N/mm²]
K_{ac} : axial shearing coefficient [N/mm²]

10.5 Appendix B5: High-order force model [Equations]

$$dF_t = K_{te} \cdot dS + K_{tc} \cdot h \cdot dz$$
$$dF_r = K_{re} \cdot dS + K_{rc} \cdot h \cdot dz$$
$$dF_a = K_{ae} \cdot dS + K_{ac} \cdot h \cdot dz$$

$$K_{te} = K_{te2} \cdot h^3 + K_{te2} \cdot h^2 + K_{te1} \cdot h + K_{te0}$$
$$K_{re} = K_{re2} \cdot h^3 + K_{re2} \cdot h^2 + K_{re1} \cdot h + K_{re0}$$
$$K_{ae} = K_{ae2} \cdot h^3 + K_{ae2} \cdot h^2 + K_{ae1} \cdot h + K_{ae0}$$
$$K_{tc} = K_{tc2} \cdot h^3 + K_{tc2} \cdot h^2 + K_{tc1} \cdot h + K_{tc0}$$
$$K_{rc} = K_{rc2} \cdot h^3 + K_{rc2} \cdot h^2 + K_{rc1} \cdot h + K_{rc0}$$
$$K_{ac} = K_{ac2} \cdot h^3 + K_{ac2} \cdot h^2 + K_{ac1} \cdot h + K_{ac0}$$

dFt : differential tangential force [N]
dFr : differential radial force [N]
dFa : differential axial force [N]
dS : differential cutting edge length [mm]
dZ : differential axial depth of cut [mm]
h : chip thickness [mm]
Ktei : polynomial tangential edge force coefficients
Krei : polynomial radial edge force coefficients
Kaei : polynomial axial edge force coefficients
Ktci : polynomial tangential edge shearing coefficients
Krci : polynomial radial edge shearing coefficients
Kaci : polynomial axial edge shearing coefficients
i : 0,1,2
Kte : tangential edge force coefficient [N/mm]
Kre : radial edge force coefficient [N/mm]
Kae : axial edge force coefficient [N/mm]
Ktc : tangential shearing coefficient [N/mm²]
Krc : radial shearing coefficient [N/mm²]
Kac : axial shearing coefficient [N/mm²]

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