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DYNXPERTS

Plug and Produce Components for Optimum Dynamic Performance Manufacturing Systems

Small / Medium Scale Collaborative Project

PUBLISHABLE SUMMARY

FINAL REPORT

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Dissemination Level		
PU	Public	**PU**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

1. Executive summary.

Current machine tools are complex mechatronic structures full of sensors and drives where control laws are implemented. However, in these systems the **measurement and action points are usually far from the cutting zone** and **frequently the actuation bandwidth is not wide enough** to avoid self excited vibrations and assure a proper dynamic behavior. **<u>DYNXPERTS project</u>** will **<u>overcome these limitations introducing actuators and sensors as close as possible to the machining point.</u>**

With this objective in mind, DYNXPERTS project has focused in the development of a new generation of plug and produce adaptive components. These components are able to **improve** the **dynamic behavior** of machine tools in several aspects and **increase their productivity** introducing new features in existing machines.

- A **new concept of spindle head for heavy roughing operations: "The 5F Active Inertial Spindle Head"**. With this head is possible to obtain the dynamic properties of the machine in all working area, to monitor the state of the mechanical components of the head, to change the spindle speed to avoid unstable cutting conditions, to introduce active damping using an inertial drive, and improve the motion control introducing acceleration signals in the control loops. The dynamic stiffness has been increased 150% applying smart functions and the material removal rate has been quadrupled with this new spindle head. A patent has been submitted protecting the concept.
- An **innovative spindle head for High Speed Machining: "The 5F Magnetic Active Spindle Head".** It will make use of magnetic bearing technology and will feature the aforementioned 5 functionalities of the new roughing head. In this component the actuation to calibrate the machine and to avoid self-excited vibrations were made using the capability of the magnetic bearings to induce a force in the shaft. The damping ratio has increased more than 40% and the material removal rate has increased 8 times taking advantage of the new five functions. The spindle head has been presented in a workshop to important aerospace aluminum part manufacturers.
- New **smart fixturing devices will be developed in the project based on an active damper and clamping system**. The damping will be implemented with magnetorheological elastomers and eddy currents which will be able to adapt to the dynamics of different large and flexible work pieces. A big improvement of more than 630% has been measured in the cutting test performed by the consortium. The concept of the adaptive dampers is in patenting process.
- A new **component will be created to introduce the stability charts into the production lines in an automatic way**: This device will measure the critical dynamics of the tool, generating the stability charts and providing automatically the best process parameters to guarantee optimal machining and chatter free cutting conditions. The system has been able to increase the material removal rate more than three times and the surface roughness has decreased 55%.
- To reinforce the self-sufficiency, portability and plug-and-produce features the **project will focus on energy harvester devices and wireless communication bridges**. The energy harvesting functionality will allow locating numerous monitoring sensors in positions extremely close to the points where the action takes place during a machining operation: the interior of the head and the clamps of the fixture. The wireless bridge will be used to transmit the information monitored by these sensors to the control units of each of the components, but also to link the new plug-and-produce devices to the machine's control. A wireless monitored high speed spindle has been developed during the project.

2. Summary description of the project.

Current machine tools are complex mechatronic structures full of sensors and drives where control laws are implemented. However, in these systems the **measurement and action points are usually far from the cutting zone** and **frequently the actuation bandwidth is not wide enough** to avoid self excited vibrations and assure a proper dynamic behavior. **DYNXPERTS project** will **overcome these limitations introducing actuators and sensors as close as possible to the machining point.**

With this objective in mind, DYNXPERTS project will focus in the achievement of several active spindle heads and smart fixtures proposing a new generation of plug and produce adaptive components. These components are able to **improve** the **dynamic behavior** of machine tools in several aspects and **increase their productivity** introducing new features in existing machines.

- A **new concept of spindle head for heavy roughing operations: "The 5F Active Inertial Spindle Head"**. With this head is possible to obtain the dynamic properties of the machine in all working area, to monitor the state of the mechanical components of the head, to change the spindle speed to avoid unstable cutting conditions, to introduce active damping using an inertial drive, and improve the motion control introducing acceleration signals in the control loops.
- An **innovative spindle head for High Speed Machining: "The 5F Magnetic Active Spindle Head"** It makes use of magnetic bearing technology and features the aforementioned 5 functionalities of the new roughing head. In this component the actuation to calibrate the machine and to avoid self-excited vibrations will be made using the capability of the magnetic bearings to induce a force in the shaft.
- A new **component has been created to introduce the stability charts into the production lines in an automatic way**: This device measures the critical dynamics of the tool, generating the stability charts and providing automatically the best process parameters to guarantee optimal machining and chatter free cutting conditions.
- New **smart fixturing devices have been developed in the project based on an active damper and clamping system**. The damping is implemented with magnetorheological elastomers and eddy currents which will be able to adapt to the dynamics of different large and flexible work pieces.
- To reinforce the self-sufficiency, portability and plug-and-produce features of the components described above the **project will focus on energy harvester devices and wireless communication bridges**. The energy harvesting functionality will allow locating numerous monitoring sensors in positions extremely close to the points where the action takes place during a machining operation: the interior of the head and the clamps of the fixture. The wireless bridge will be used to transmit the information monitored by these sensors to the control units of each of the components, but also to link the new plug-and-produce devices to the machine's control.

During these the project the following achievements have been reached in each one of the around the new mechatronic components:

Roughing 5F Head:

Soraluce and Ideko defined and selected the spindle head for roughing operations. The main dynamic problems affecting the spindle (chatter regeneration), the cutting forces, critical modes, dynamic variations and vibration levels were identified for describing the problem. Besides that, a study about the actuator location was made using FEM analysis. The requirements of the actuator in terms of main specifications, communication protocols, power electronics and signals processing were also identified. A demonstrator based on hardware on the loop was set up to prove different control laws.

Later on, 5 functionalities new roughing spindle head was designed, manufactured, assembled and validated in a SORALUCE machine. Using this spindle head, a good knowledge of the dynamic behavior of the machine could be obtained, and different maintenance and dynamic problems could be detected and solved.

An inertial actuator was introduced in this new spindle head, so first, the new MICA inertial drive was tested independently for the validation of the spindle head. Once the new spindle head and all control equipment were mounted on the SORALUCEs milling machine, the first four functions were tested, demonstrating their good performance and the fulfillment of the objectives.

Figure 1: New 5F Roughing Spindle head.

Nowadays there are two principal problems in order to implement the Advanced Control Loop Function in the machine with Heidenhain CNC. On one hand, motor-drives control loops of Heidenhain CNC are not 100% configurable. On the other hand, it is not possible to read accelerometer signals on real-time in Heidenhain CNC. Therefore, this function could not be implemented on the machine and has been developed over only the test bench, with excellent results.

Remarkable exploitation results have been obtained in this component. First of all, SORALUCEs active inertial spindle head has been patented to protect its exploitation. MICA inertial drive has also been introduced in CEDRAT actuator's catalogue. Finally, industrial pilot experiences of two of 5 functionalities have been started last year over two beta users.

Finishing 5F High Speed Head:

Tekniker and Goi-Alde beneficiaries described in the beginning of the project the spindle head requirements (mechanical, communication, installation and cables), as well as the problem of regenerative chatter to be solved and the 5 main Functions to be implemented on the spindle (monitoring, dynamic calibration, stability prediction, damping and advanced control).

Active Magnetic Bearings 5F Spindle Head was designed manufactured and tested in a Bizkor machine located in IK4-Tekniker facilities.

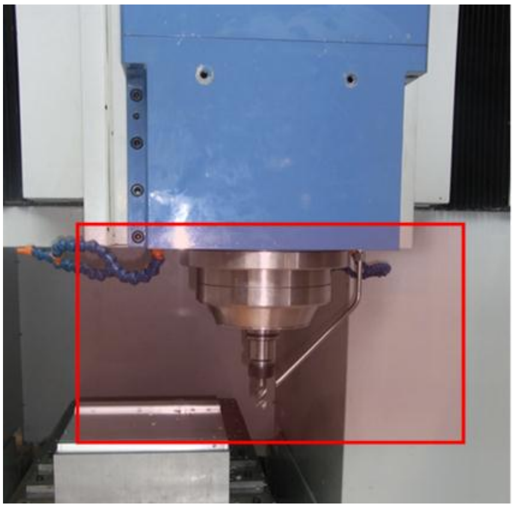


Figure 2: Active Magnetic Bearings HSM Head installed

As the 5F roughing spindle head, a good knowledge of the dynamic behavior of the machine can be obtained, and different problems can be detected and solved, when this spindle head is used.

It is remarkable the result obtained with the active damping function, where the chip-flow can be increased more than 5 times. Without active damping, the active magnetic bearings spindle head has a very small damping and this way, it would not be valid for cutting due to chatter vibration problems in many cases. By means of the active damping function, the damping is increased and the productivity can be increased clearly.

As exploitation result can be commented that a workshop was organized for aerospace parts manufacturers showing the possibilities of a 5F high spindle head to improve the productivity in aluminum roughing.

Adaptive damping fixturing devices with smart materials

Dr Matzat and Nice University partners proceeded with the description of the requirements of fixtures for vertical and horizontal machining centres, as well as for large dimension workpieces. In all the 3 cases, the theoretical modal analysis was performed. Besides that, during the first months of the project the milling force excitation range were defined for cutting tools with low and high number of flutes.

Three different damper prototypes have been designed and built, based on different working principles, and adapted to different applications. The working principles applied have been MR fluids, MR elastomers and eddy currents. In all of them the possibility of changing the dynamic characteristics with simple control signals has been demonstrated.

Machining tests with the MRF and eddy current prototypes have shown the possibility to remove chatter in two different test benches. The best results have been obtained with eddy current dampers, due to its linearity. Furthermore, this effect decouples the damping from the stiffness and it is a great advantage for the tuning of the actuator.

Figure 3: Self-tunable eddy current damper.

Using eddy current actuator, a novel control algorithm and system has been built for self-tuning capability and its effectiveness has been demonstrated.

On another hand, an adaptive clamping fixture has been built and approved, which has two working modes. The first one is a damping mode without blocked MR fluid and the second is an aligning mode with blocked MR fluid. Both modes have provided a significant better damping with respect to a reference clamping.

In this way, a patent about the eddy current actuator has been submitted, while another patent about the MATZAT fixture has been scheduled.

Adaptive solutions for chatter free machining

Fidia and RWTH companies defined the system architecture and requirements for the dynamic calibrator hardware as well as the AD/DA interfaces, base units and I/O cards. The metrological units, the software for the stability chart calculation and their interface with the CNC from Fidia were also defined during these first months of the project. Two dynamic calibrators have been built and tested in different machines. These calibration units have the potential to enable an increase in machining performance in industrial applications, since they allow an automatic measurement of the dynamic behavior of the machine tool and come along with easy-to-handle measurement and calculation software.

Figure 4: HPC (left) and HSC (right) dynamics calibrators.

The exemplary application of the HSC calibrator for the calibration of a milling process was successful. The predicted stability diagram is in good agreement with the results of cutting tests. Furthermore, it was proven and demonstrated that the HPC calibrator can be used for an efficient characterization of the position dependent dynamic behavior of machine tools. A patent about the HPC calibrator is under study.

Energy harvesting and wireless communication

RWTH, Fidia and Cedrat companies defined the specifications for the wireless communications and the employed sensors, the concepts for the acquisition of the data and processing units. The general requirements for the energy harvesting devices were also defined.

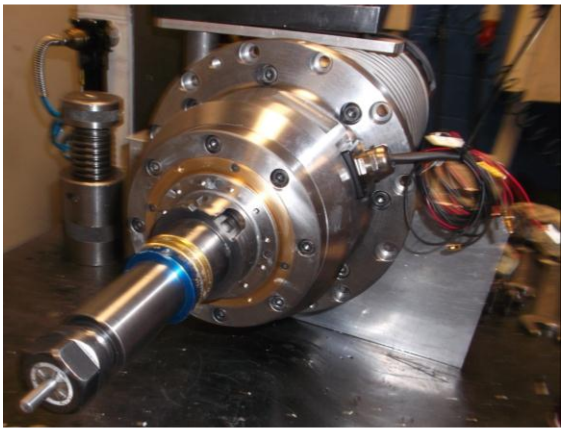


Figure 5: Spindle with assembled generator on GOIALDE test stand.

A spindle has been instrumented with a generator that provides energy for a wireless communication system The wireless communication system may be used as a platform for machine tool condition and process monitoring. Furthermore, a test stand has been modified as a carrier for the demonstration of the prototype. For this purpose a FIDIA NC has been connected to the test stand to simulate a real machine setting.

It has been shown that the generator assembly inside the spindle is able to provide energy. The only restriction has been a problem with the conditioning electronics. Furthermore the integrated ECS Sensors could not be tested because of this restriction.

The wireless communication is able to provide data that may be used for condition monitoring and is able to communicate the data over a range of about 10 m, which is well suited for the application in machine tools. The sensor attachment may be further improved to get better results from the acceleration sensors. The system has been realized using COTS-Components and is therefore easy to adapt to specific needs and inexpensive which suits well for the application in machine tools.

More information about the project objectives, activities and companies involved can be found through the project's web site http://www.dynxperts.eu and the performance of these devices can be seen in our youtube channel http://www.youtube.com/channel/UC65-m6BdQixvK7KXl-ibLIA.

3. Description of the main S & T results/foregrounds

In the DYNXPERTS project six new plug & produce machine tool components have been developed during the last three years. In the next pages, the main scientific and technological results are going to be reviewed analyzing one by one all this new components:

<u>Roughing 5F Head</u>:

In current machine tools, the measurement systems and drives are usually far from the cutting zone and the bandwidth is not wide enough to avoid self-excited vibrations and other dynamical problems. Therefore, the main objective was to introduce sensors and active devices close to the cutting point by means of a brand new design of an active spindle head with an integrated accelerometer and an electromagnetic actuator. During the project this active inertial spindle head has been manufactured and validated.

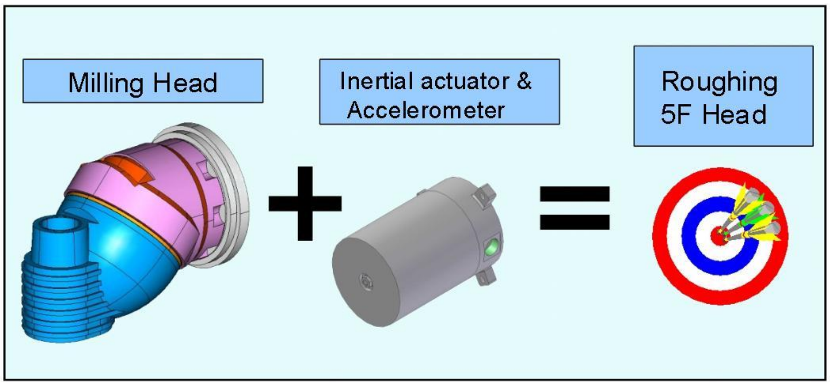


Figure 6: The active 5F roughing spindle head concept

A new high force MICA inertial drive was designed customized for the new spindle head and its performance was validated. The integration of the equipment on the SORALUCE FL6000 milling machine was performed and finally, different tests on real working conditions were done.

The behavior of the inertial actuator has been tested by means of three different tests. In the first test, the dynamic response of the actuator was obtained. This test provided the position of the natural frequency of the suspension mode, which is very important for the proper tuning of the controller.

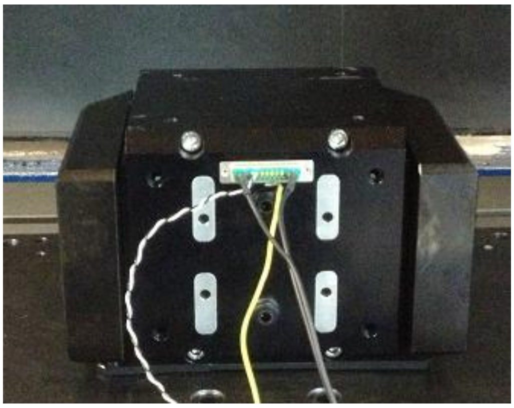


Figure 7: MICA 800L inertial drive

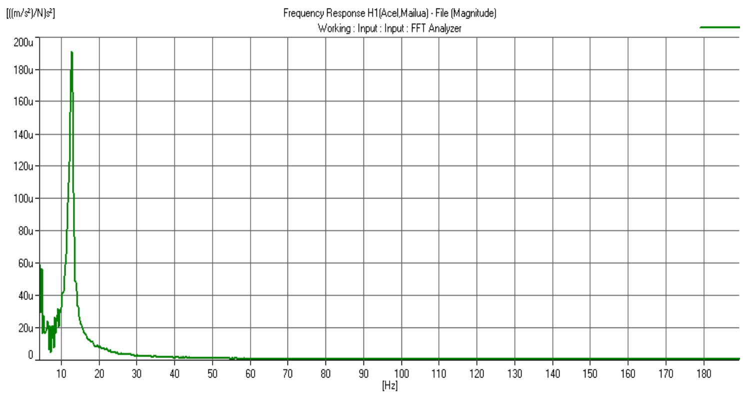


Figure 8: Frequency response function of the actuator.

In the second tests, in order to analyze the ratio between input voltage and output force, an excitation signal is commanded to the MICA actuator and force is measured by means of a dynamometric plate. In this way, changing the amplitude of the excitation input, the linearity of the actuator was analyzed.

The frequency response function (FRF) between the generated force measured by the dynamometric plate and the applied chirp excitation input shows that actuator is very linear from its suspension mode frequency.

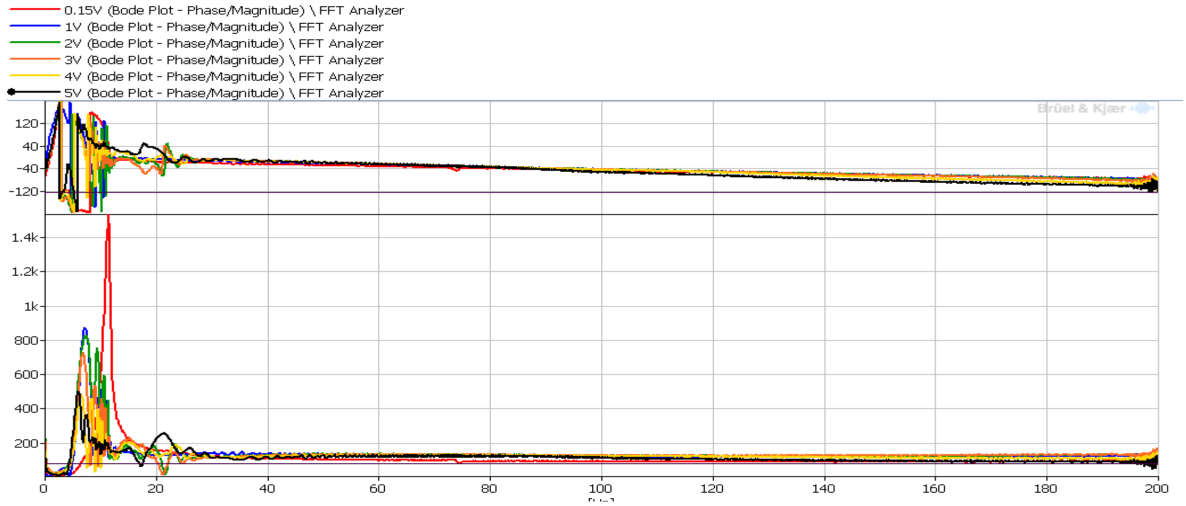


Figure 9: Voltage-force ratio when a chirp excitation is applied

In the third test, force done by the actuator with different input amplitudes was measured. A sinusoidal excitation was introduced and the force has been measured again by means of the dynamometric plate. In these tests, two frequencies close to typical chatter frequencies have been selected. Forces above 1200N can be achieved by means of this actuator, obtaining a very good ratio between force and the volume.

Once it was tested, the actuator, the control and all cables were integrated on the Soraluce FL 6000 machining center. The actuator was located in the new spindle head designed by Soraluce, while the control, consisting of the servo amplifier Elmo Tuba and the real time controller NI CompactRIO, has been located in the cabinet. In this way, no cables are visible since all of them are integrated inside the machine.

Figure 10: Integration of the actuator and the control system on the FL6000 milling machine.

In this new head, 5 new functions has been implemented and validated: monitoring, calibration, stability, damping and advance control loop functions.

Milling head is a complex mechanical system that contains elements such as bearings and gears. The kind of elements inside the head may have failures over the time, so the objective of the **monitoring** function is to detect and analyze these failures.

Once that the description of bearings and gears inside the spindle head are introduced in the database, the user has to rotate the spindle and start the acquisition. The system will acquire acceleration signals and a CNC internal signal that captures spindle's speed on real time. In this way the system indicates automatically if there are failures or not.

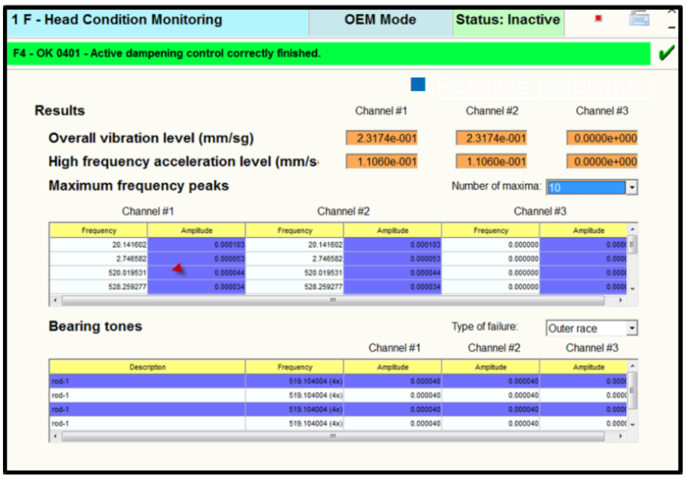


Figure 11: Interface of 1F Monitoring function without any failure.

The objective of the **calibration** function is to obtain the dynamic characteristics of the machine in the whole workspace in a fast and accurate way. This characterization of the machine is performed measuring frequency response functions (FRF) in different points of the workspace. The FRFs are obtained shaking the structure using the inertial actuator and measuring the response with the accelerometers located in the mobile part and fixed part of the actuator located in the spindle head. Once the FRF of one position is obtained the machine goes automatically to the next position. In the validation of his function, a calibration of the complete workspace was performed and results were satisfactorily correlated.

The **stability** function measures, avoids and controls self-excited vibrations. In the first step, the vibrations during cutting process are measured by means of an accelerometer located in the spindle head. Once the accelerometer signals are stored in the control system, an algorithm processes them and offers solutions to avoid self-excited vibrations.

The solutions offered by the system are based on stability lobes diagram and there are two types of possible solutions depending on which unstable conditions works the machine:

- DARDO solution: the solution consists on selecting a constant stable spindle speed, locating it around a resonance frequency.
- MUTE or CSSV solution: the solution consists on working with a variable sinusoidal spindle speed, disturbing the regenerative effect.

Therefore, in order to validate this function the totally different machining operations have been selected: a drilling operation and a rough milling operation.

A drilling operation has been selected, in this way, the algorithm proposes a constant new spindle speed. The tool used is a Walter indexable. The algorithm has detected chatter at 35.6Hz when a drilling operation at 1200 rpm has been selected, and it has suggested a spindle speed of 1068rpm to avoid low frequency chatter. The chatter disappears when the operation is performed with the spindle speed proposed by the system.

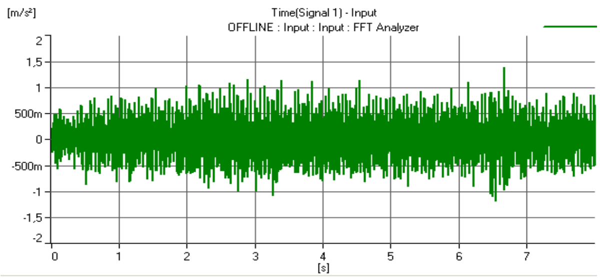
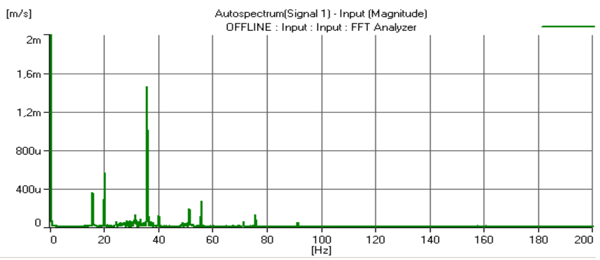
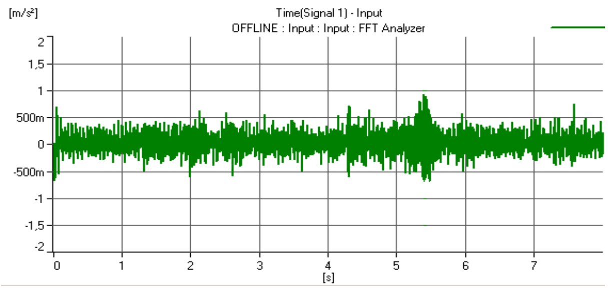
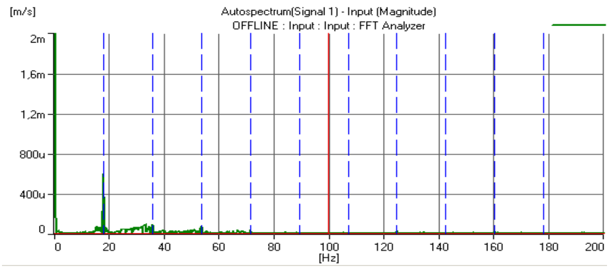
INITIAL CUTTING CONDITIONS	FINAL CUTTING CONDITIONS
 	 
Material: Steel F1140	**Material:** Steel F1140
Cutting conditions: N=1200rpm,az=0.1mm/z	**Cutting conditions:** N=1068rpm, az=0.1mm/z

Figure 12: Initial cutting conditions and solutions proposed by the algorithm.

A second case was selected where the algorithm proposes to use the spindle speed variation. The tool used in this test is a Sandvik milling tool.

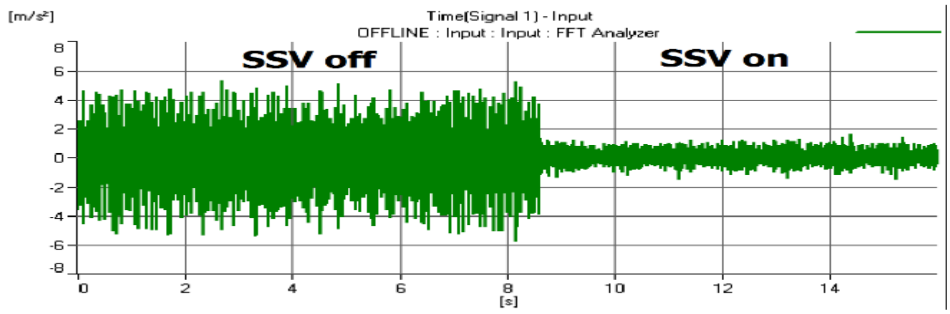
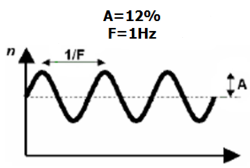
INITIAL CUTTING CONDITIONS	FINAL CUTTING CONDITIONS
	
Material: Steel F1140	**Material:** Steel F1140
Cutting conditions: N=186rpm az=0.2mm/z ae=100mm ap=3.5mm	**Cutting conditions:** Same conditions but with variable spindle speed. 

Figure 13: Initial cutting conditions and solutions proposed by the algorithm.

With the initial conditions chatter appears with 1mm depth of cut. However, if Mute is applied this depth of cut can be increased to 4mm with chatter free conditions, and the material removal rate (MRR) is increased four times.

The objective of the **damping** function is to eliminate chatter vibrations using an active damping strategy using the inertial actuator located in the spindle head. When this function is switched on, vibrations are measured by an accelerometer and an algorithm applies a control technique to calculate the force that the actuator should introduce in the machine to introduce damping.

On the validation test of this function, the tool used in the second case of the stability function was selected introducing 8 teeth.

In this way, different ram overhangs have been tested. The tests show that the chatter free depth of cut can be doubled in whole workspace without chatter vibrations introducing active damping.

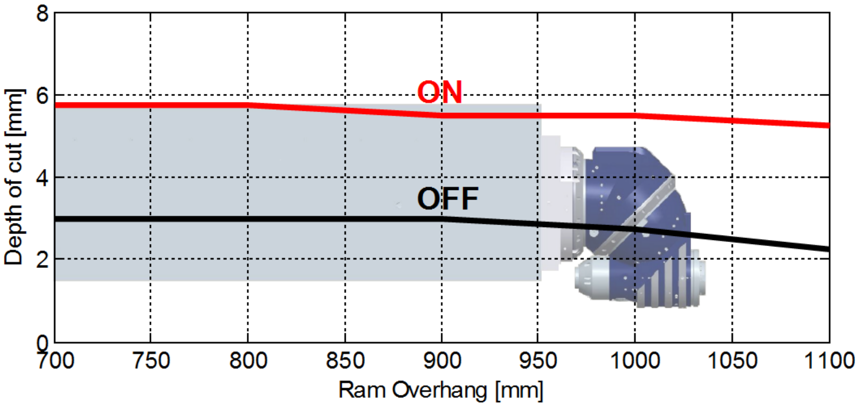


Figure 14: Active damping test results

In this project IK4-Ideko has built a two axis test bench in its prototype workshop with a LabVIEW control system to validate the **advance control loop** function. In this way it is possible to measure the status of the vibrating structure using an accelerometer, which is the simplest and most direct way to measure vibrations in mechanical structures, and introduce a force on the system directly proportional to the acceleration of the vibrating component. The immediate result that is obtained with the use of this technique is a significant increase on the damping coefficient of the vibrating mode, which means that after an excitation the vibration will disappear much faster.

The force is introduced on the mechanical system using the ordinary motors of the machine. However, an important difficulty is that commercial CNCs do not provide the necessary customization options to introduce the required algorithms on their control core. After the proper adjustment of the new control loops on the control bench, a huge increase in the damping coefficient was achieved. The comparison of the acceleration response of the tool center point to viscous step command with or without advance control loop shows clearly the magnitude of the improvement.

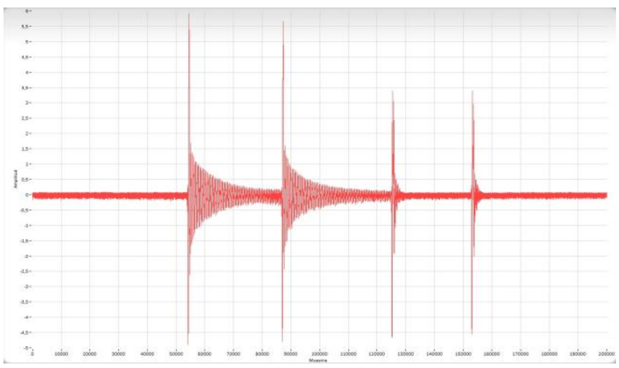


Figure 15: Comparison between Acceleration Feedbacks ON/OFF

Finishing 5F High Speed Head:

One of the main purposes has been to improve the machining capabilities of the Active Magnetic Bearing (AMB) Spindle Head, in order to get closer to a finite product for GOIALDE HS. Actually, the machining capability of the spindle has been increased almost 7 times during the project, which is a great result. The demonstrator has been located inside a spindle machine called Bizkor, placed at IK4-Tekniker facilities. The demonstration showed clearly the interest of each one of the 5 functionalities implemented during the project.

Figure 16: S Bizkor machine inside IK4-Tekniker facilities.

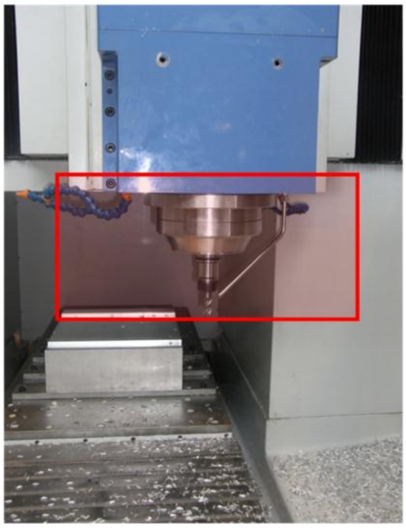


Figure 17: 5F Active Magnetic Bearings High Speed Spindle Head

The **monitoring** function is a utility that allows modifying and analyzing the state of the spindle head, in order to modify its behavior or to get a diagnostic of the AMB head.

Dynamic **calibration** function deals with the identification of the first natural frequency of the shaft of the spindle head. For that, a chirp form force is used to excite the system using magnetic bearings, and the Frequency Response Function (FRF) is computed. The computed FRF is shown on the Monitoring Software. A spindle speed dependent identification demonstration can also be done, where FRF functions are obtained for several speeds.

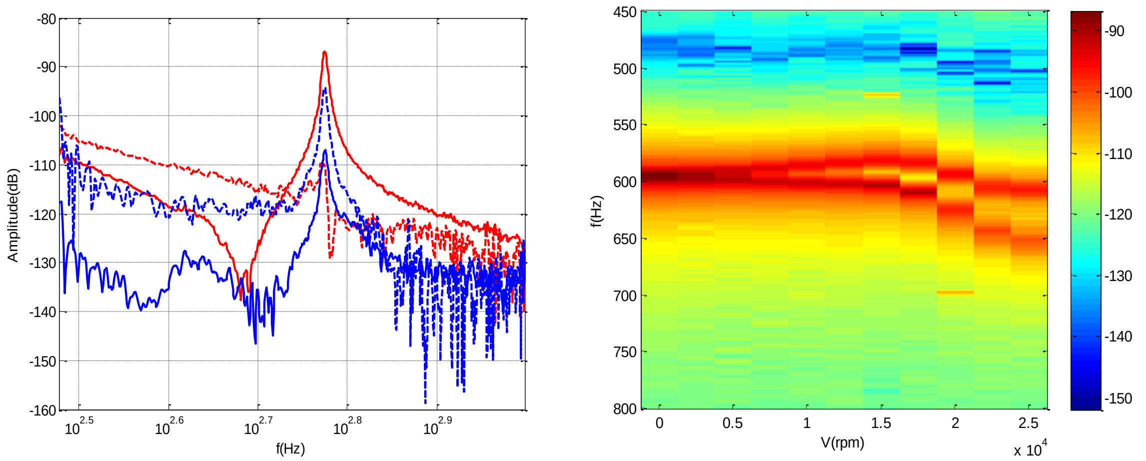


Figure 18: Identification of the first natural frequency of the 5F spindle shaft. On the left hand, at 0rpm, using several bearing-sensor combinations. On the right hand, at several speeds.

Stability function detects that chatter is happening, and it modifies the spindle speed in order to go to a more stable machining region, following stability diagram computed using the previously identified natural frequency.

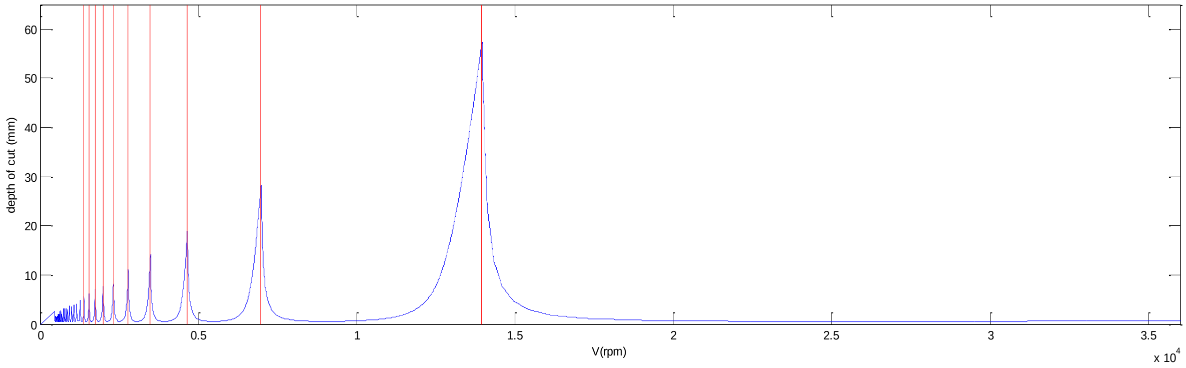


Figure 19: Stability diagram of the beam-based modeled shaft. Horizontal red lines are places at spindle speeds

$$V_k = f_n * 60 / Z / k$$

During the demonstration the algorithm is applied fulfilling several steps:

- The machine starts machining at 18000 rpm, and almost instantaneously chatter happens.
- The algorithm detects chatter and modifies the speed command to around 12000 rpm.
- There is a quite long transitory till the final speed is reached. Chatter continues.
- When the final speed is reached, chatter disappears, and the last part of the machining process is chatter free.

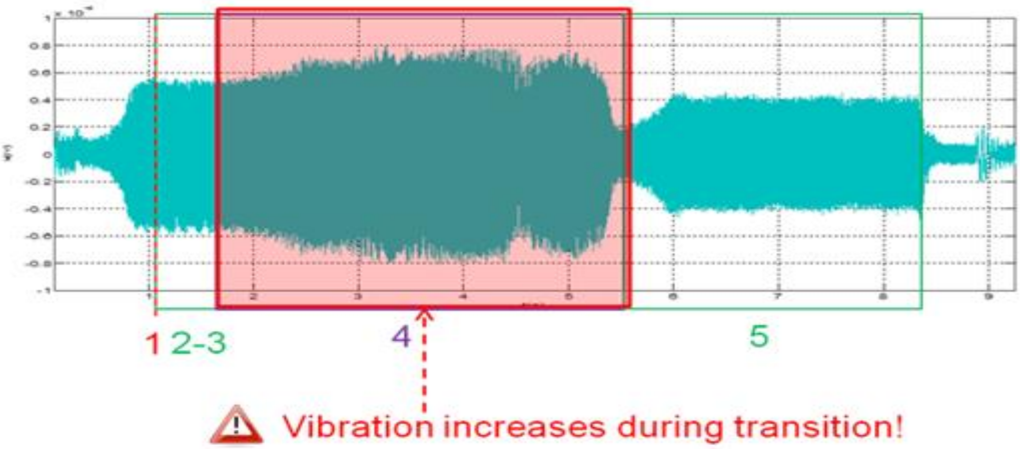


Figure 20: Vibration measurements during Stability function demonstration

At the end of the demonstration, vibration signal is shown on the Monitoring Software, and the difference between chatter free machining and machining with chatter is clear in the surface of the work piece. If the stability function is applied on line the results are not so good, because transition between speeds is quite low and vibration increases during the transition. However, the function offers the best spindle speed if it is used off line.

Damping algorithm is a basic function to introduce magnetic bearings in metal cutting spindle. One of the main drawbacks of the magnetic levitation is the lack of damping due to absence of contact. When the active damping function is activated during machining, and clear decrease of the noise is observed at the same moment. Vibration measurements are shown on the Monitoring software, where a reduction of 33% is measured when the algorithm is activated.

The difference between using damping algorithm and not using it is also very well observed on the surface leaved by the tool on the workpiece.

At the previous demonstration, the potential of damping function was shown, but the productivity remained small. On this second Damping demonstration, two machining are performed independently using all the power of the damping function. **The material removal rate increased more than 5 times using the active damping function**

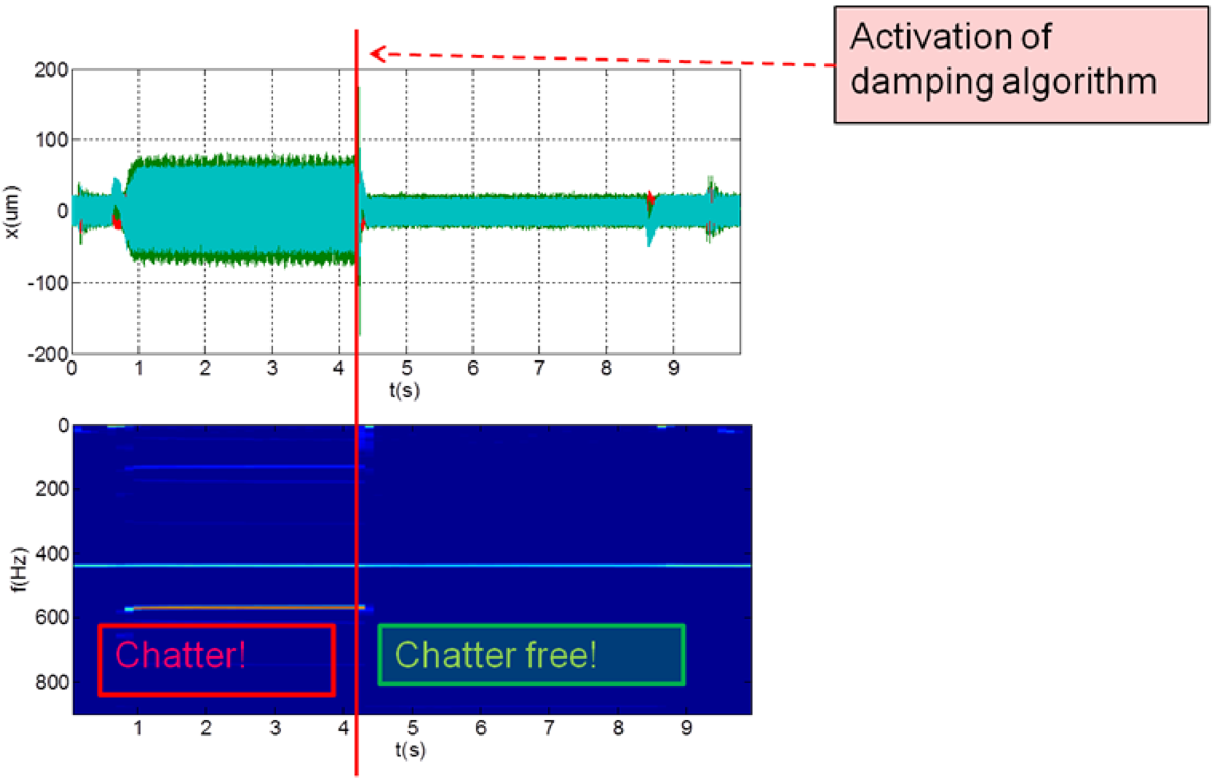


Figure 21: Vibration measurements during Damping function demonstration. Machining starts around 0.75 s and finished around 8.75 s.

	Without damping	**With damping**
Depth of cut	5mm	15mm
Width of cut	10mm	10mm
Feed-rate	3.5m/min	6m/min
Chip-flow	175cm^3/min	900cm^3/min

Table 1: Maximum machining conditions without and with damping algorithm.

Together with the increase of productivity, a new limitation appeared when using damping algorithm, and vibration measurements are shown to show the new limitation. Machining productivity is not more limited by vibrations produced by chatter, but by the deviations produced by the impact between tool and workpiece at the start and at the end of the machining process.

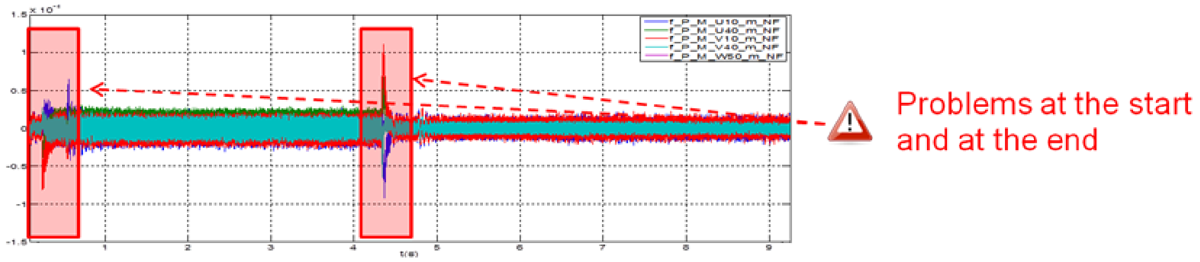


Figure 22: Vibration measurements using damping function at maximum productivity conditions.

An improvement of the behavior at start and end points of the machining process is provided by **Advanced Control Loop** (ACL) function, and that is what is shown during the demonstration. For that, the same machining process is repeated with ACL inactive and with ACL active, and vibration signals at transitions are compared. It is seen that ACL function makes the deviation smaller (deviation decreased to the 60% of the initial deviation).

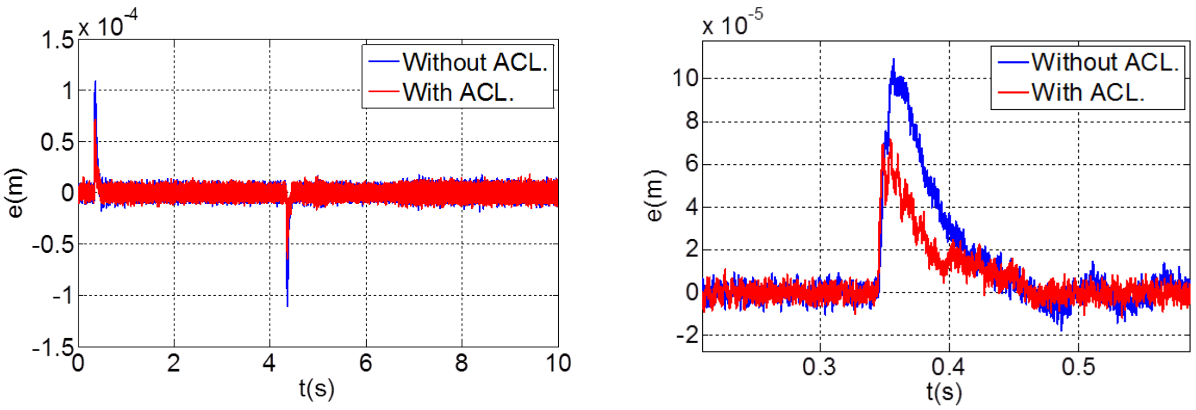


Figure 23: Comparison of deviations on transitions without and with ACL.

Then, if are able to make better at same conditions, we are also able to increase the productivity. The last demonstration of the ACL function consisted of two machining process at maximum capability without and with ACL (in both cases with damping function activated).

	Without ACL	**With ACL.**
Depth of cut	15mm	15mm
Width of cut	10mm	10mm
Feed-rate	6m/min	7.5m/min
Chip-flow	900cm^3/min	1125cm^3/min

Table 2: Maximum machining conditions without and with ACL (with damping function activated).

The productivity (the chip-flow) is again increased %25 from the initial productivity that can be slightly appreciated during machining.

Combining the damping function and the advance control loop function the material removal rate (MRR) was increased 6 times.

	Before DYNXPERTS	After DYNXPERTS
Depth of cut	5mm	15mm
Width of cut	10mm	10mm
Feed-rate	3.5m/min	7.5m/min
Chip-flow	$175cm^3$/min	1125cm3/min

Table 3: Maximum machining conditions before and after Dynxperts.

Smart dampers:

Since chatter is closely related to a lack of damping, we must increase the damping to reduce the vibration amplitudes. Furthermore, the vibrations appear at frequencies related to the system resonance frequencies, which are likely to vary during the process and will change when another workpiece will be used.

Two different technological approaches have been adopted. In the first one, magnetorheological materials have been used to change the dynamic characteristics of the dampers. In the second one, a controlled rotating spring has been used to tune the frequency, and eddy current effect has been used for generating the damping. Control hardware and software has been developed to allow automatic tuning during machining operations.

The demonstration of these systems has been done by means of cutting experiments on a SORALUCE milling machine located at IK4-IDEKO's facilities. For the MR damper tests, a fixture provided by MATZAT has been used.

Tunable dampers based on **MR fluids and elastomers** have been developed during the project. As final demonstration, MATZAT provided a fixture which suffered from chatter problems in certain demanding conditions. The design and tests of the two dampers is described next:

During the machining process, the fixture's plate can be modeled by the oscillating system with a natural frequency f_{res}. The DVA is modeled by a mass m_{DVA} attached to the primary mass M through a spring and a dashpot.

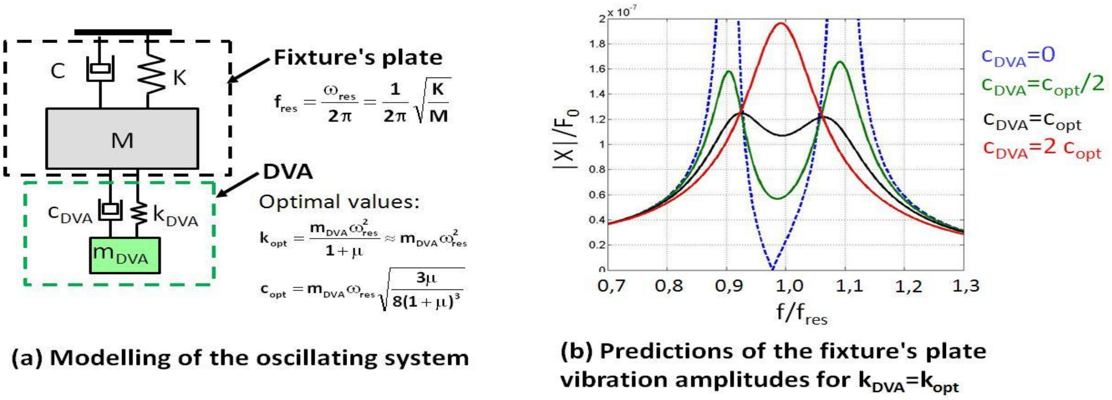


Figure 24: Modeling of the DVA

The DVA is efficient only when its natural frequency is close to the natural frequency f_{res} of the original system. When the natural frequency f_{res} changes, it is important to be able to change the DVA stiffness and damping factor. This is the reason why we used smart concepts in our prototypes.

We conceived a damper for a fixture's plate modal mass. On this drawing, the outer part is attached to the fixture's plate. The internal part, the electromagnet, is the moving mass of the DVA which is attached to a disk of steel which plays the role of a spring and will provides the required stiffness.

A reservoir was dug in the moving mass to receive the MR fluid. Without magnetic field, the MR fluid does not provide contribution; so the damping factor of the DVA is low and its stiffness is brought only by the disk in steel so it is equal to k_{disk}. But when the natural frequency of the fixture's plate becomes higher, we must increase the damping and the stiffness of the DVA. This is done by applying a current in the electromagnet to generate a magnetic field so that the MR fluid introduces extra damping and stiffness in the DVA. IDEKO did the characterization of this prototype by measuring its natural frequency with respect to the current generated in the electromagnet and for several forces applied on the DVA's moving mass. Finally the damper was mounted below the plate for damping its vertical bending model.

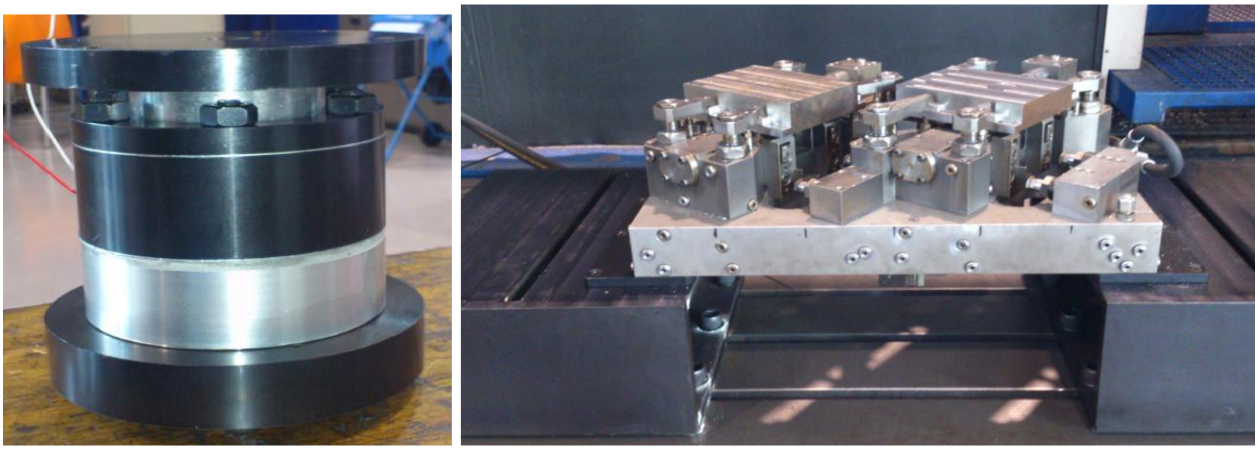


Figure 25: Modified MRF prototype and MATZAT workpiece fixture

With this modification, it was possible to tune the damper to the resonance frequency of the fixture and effectively damp it. With an appropriate tuning, the resonance peak of bending of fixture will be split in two peaks with lower amplitude and thus higher damping.

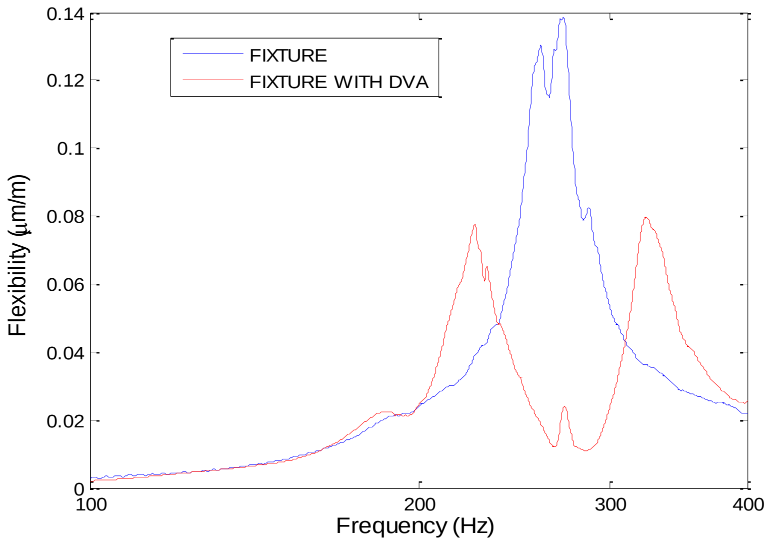


Figure 26: FRF of MATZAT fixture with and without MRF DVA

Some cutting tests were performed comparing the result with and without the DVA. The damper managed to eliminate chatter and obtain nice surface quality in a wide range of cutting conditions.

Tool: Hitachi ASR4050M-4 HAH047 (D50 Z4)

Inserts: EDNW13T4TN-15 R15 CY250

Slotting (ae=100%)

N=800rpm

fz= 0,3 mm/z

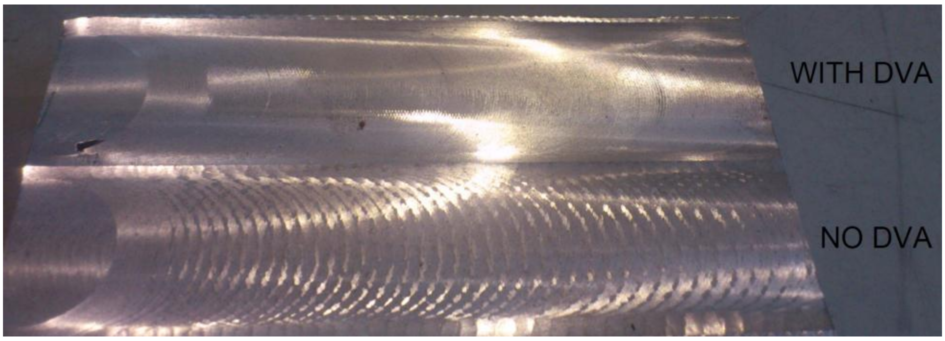


Figure 27: Cutting conditions and workpiece surface after machining, with and without DVA

An alternative way to achieve tunable dampers for machine tool chatter has been explored. We have looked for ways of being able to decouple stiffness and damping effects in the damper. A first prototype was built for proof of concept. Following the positive results a second prototype has been built which can be applied for a variety of industrial cases.

Tunable stiffness has been implemented by designing a rotary spring with variable stiffness in function of its orientation. Controlling this spring with a motor, the stiffness of the damper can be tuned within a certain range. In the prototype used in the demonstration, this rotation can change the resonance frequency between 20 and 40 Hz.

This spring generates almost no damping. **Eddy current effect** is used for producing the damping. A combination of magnets and copper plates produce this effect by their relative vibration. This effect produces no stiffness, so that the goal of decoupling stiffness and damping is achieved.

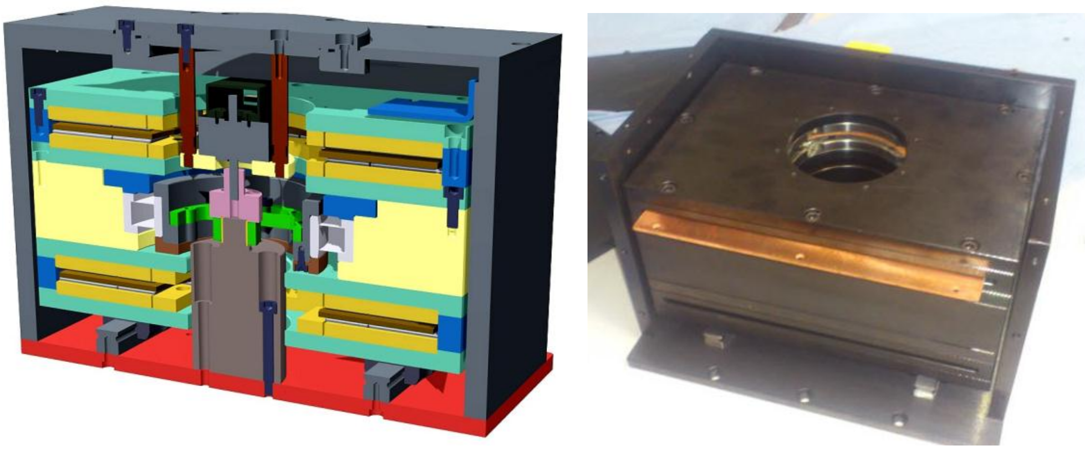


Figure 28: Design of tunable eddy current damper

A dynamic analysis of the damper was performed, which showed how the resonance frequency changed with the angular position of the spring, controlled by the motor.

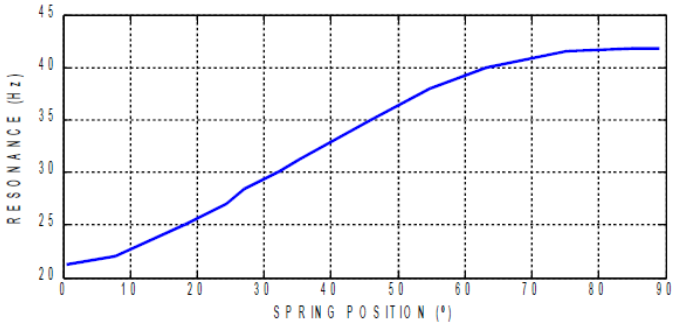


Figure 29: Resonance frequency variation with spring angular position

For the demonstration, the damper was placed on a vertical fixture in a SORALUCE milling machine. By means of the damper the amplitude of the resonance frequency in the FRF decreases significantly, therefore succeeding in adding damping to the system.

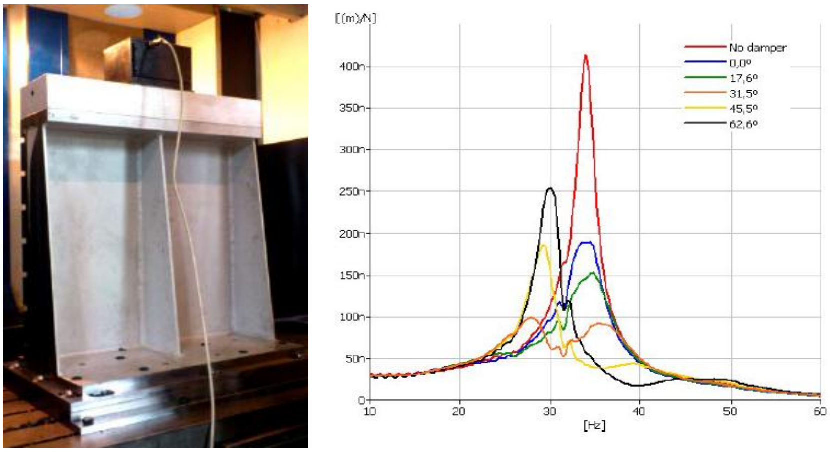


Figure 30: Demonstration setup and dynamic response with damper

The damper was designed not only to be tunable, but also self-tuning. The damper incorporates an accelerometer that read the vibration level at the fixture. A real time processing controller has been developed, which reads this vibration level, and automatically detects whether chatter is being produced or not. When it is, it calculates the chatter frequency, and sends a signal to the motor in the damper that tunes the spring, therefore setting the damper in the optimal conditions for eliminating chatter.

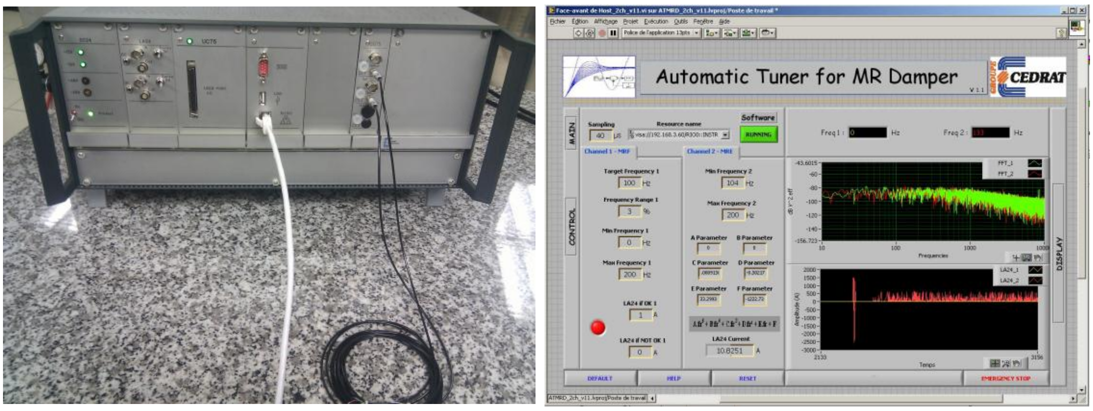
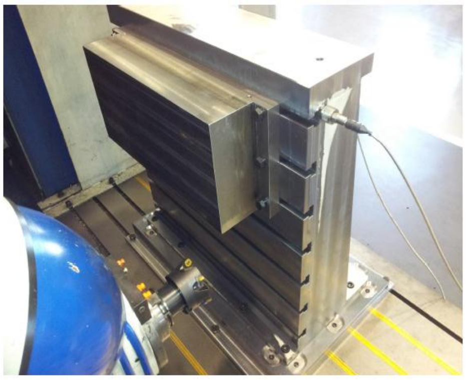


Figure 31: Control hardware and software for damper tuning

Several cutting tests were performed on the SORALUCE machine to check and demonstrate the functionality of the damper. Cutting tests were performed at three different heights in the workpiece, and the stability at each height with and without damper was checked for different cutting depths. The damper was able to increase 5 times the depth of cut and the material removal rate (MRR).



Cutting parameters:

- Tool: Hitachi GFH476 ASF5125RM (D125 Z6)
- Inserts: TB6045 SDNW-1505ZDTNR
- Face milling
- ae=70%, Up-milling
- N=255r/min, fz=0,3mm/z

Figure 32: Machining setup and cutting conditions

- P1 position
- N=255r/min
- ap=1mm
- f=0,3mm/z

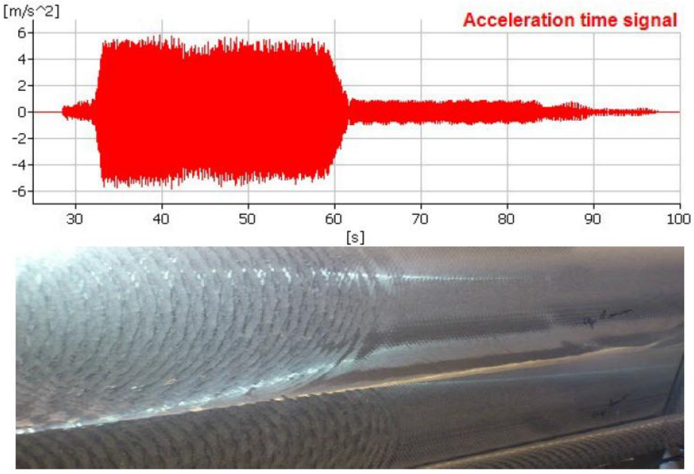


Figure 33: Acceleration and workpiece surface during cutting process. Initially controller is off, then

<u>Adaptive fixturing device</u>:

Workholding is very important for the performance of any machine tool. Fixtures affect the precision and integrity of the workpiece and are one of the biggest limitations of machine tools with regard to their productive flexibility.

Manufacturers are aware of limitations of their fixtures caused by many reasons. Two of the limitations are:

- Different shapes, dimensions and materials of the workpieces. This issues demand usually a lot of different components e.g. clamping jaws to adapt fixtures to a new workpiece.
- The appearance of self exited vibrations (chatter) during the chip removal. These vibrations are closely linked to the damping of the structure of the fixture and the workpiece.

Due to the wide range of workpieces and machine tools there are a lot of different designs and technical versions of fixtures. The aim of the demonstrator is to show the functionality and validity of the adaptive fixturing device under real working conditions in a machining center.

The main idea is to align, clamp or damp different workpieces in a machining process using moveable rods to adapt the fixture to the shape of the workpiece. In the adapted position the position of the rods can be locked (to align the workpiece) or not (for only providing damping in the machining process). For the locking of the rods a magnetic field will be applied the block the magnetorheological fluid (MRF) inside the adaptive clamping device.

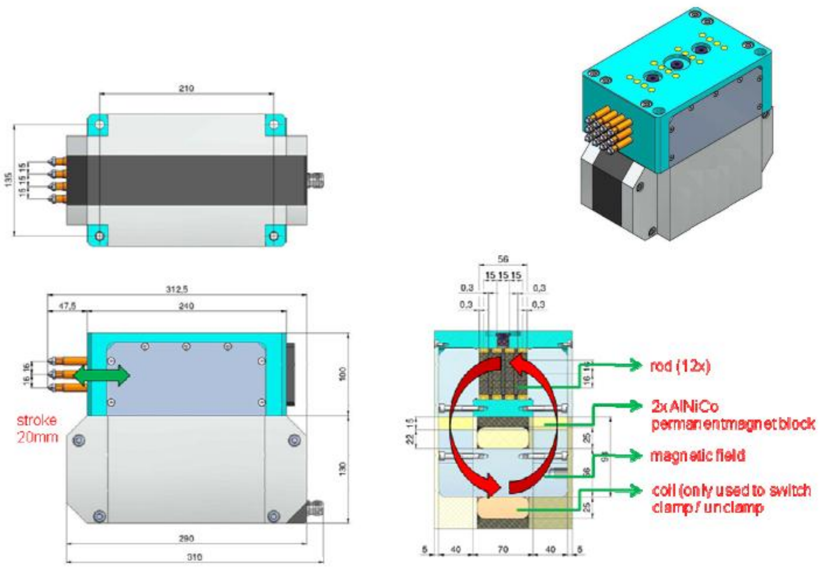


Figure 34: Designs of the final prototypes.

An important advantage in comparison with former prototypes is the use of an electropermanent magnet system. The version of the adaptive fixturing includes magnetizable magnets in AlNiCo. In order to magnetize the two AlNiCo magnets, we apply a pulse of current in the coil which generates a pulse of magnetic field. Once magnetized, the magnets generate a permanent magnetic field so that the MR fluid behaves as a solid and blocks the rods during the machining process. This way, we do not need to apply any current in the coil during the machining process to block the rods, which is good for power saving. After machining, when we need to slide the rods, we apply a smaller current in the opposite direction to cancel the field generated by the magnets and the MR fluid goes back to the liquid state.
For testing the adaptive clamping device and for the demonstrator a control unit was developed and manufactured. The control unit is foreseen for applying two adaptive clamping devices in two different channels.

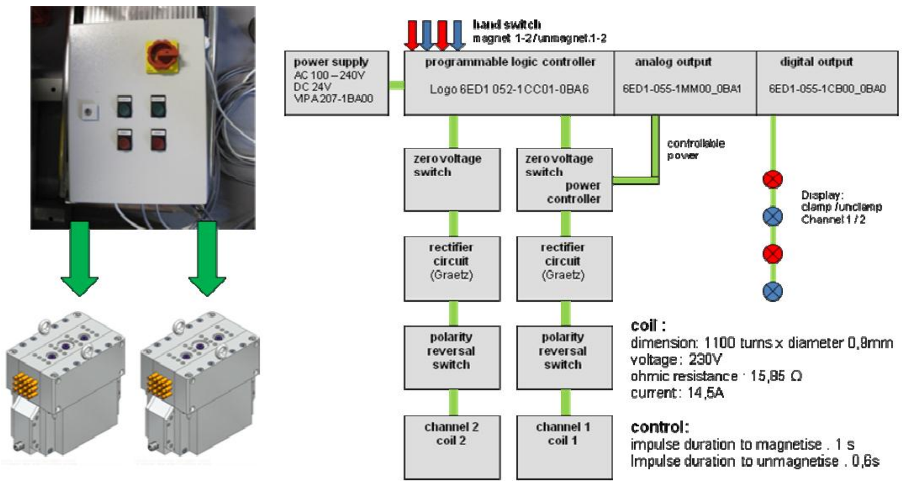


Figure 35: Control unit functionality.

For testing the adaptive clamping device a demonstrator for use under real milling conditions was developed. The demonstrator is designed using for milling aluminum rods on a Fidia machining center, but the system is transferable to any kind of similar machining centers and workpieces.

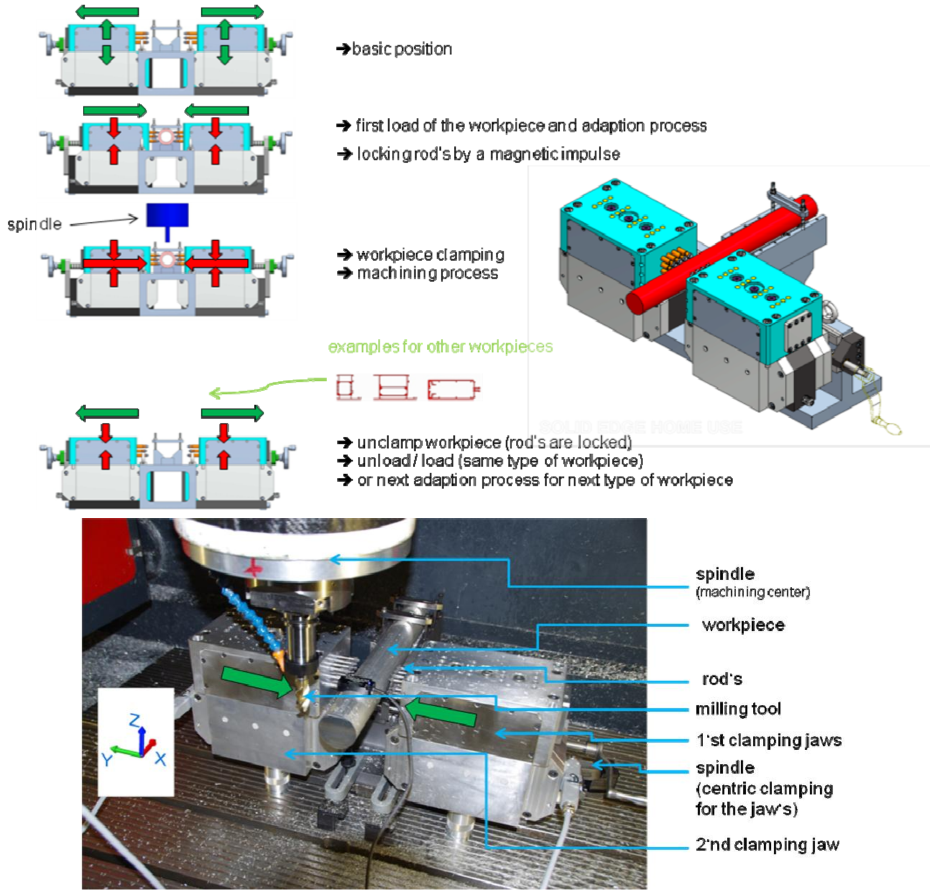


Figure 36: Demonstrator picture.

The tests were executed in three different versions with the same overhanging length of the workpiece as a milling operating on the front face:

- Milling without the adaptive clamping device as a reference.
- Milling with the adaptive clamping device and without blocking the MRF.
- Milling with the adaptive clamping device and with blocked MRF. Without using the adaptive clamping device the amplitude increases during the cut. With using the adaptive clamping device the clamping dampens the vibration during the cut.

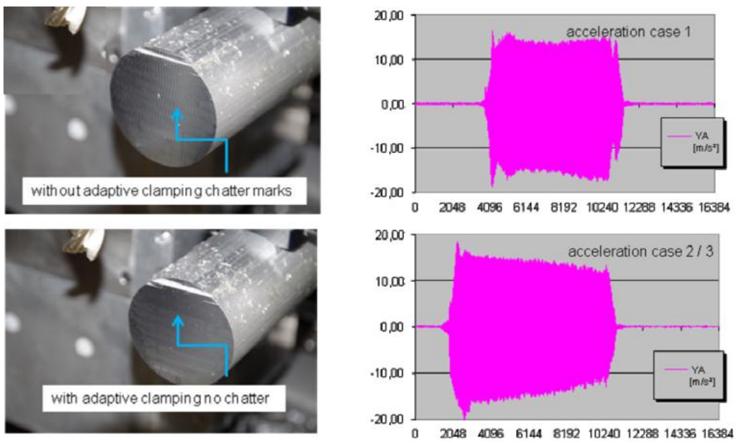


Figure 37: Results obtained.

Summary acceleration		**Case 1**	**Case 2**	**Case 3**
		Reference without adaptive clamping device	With adaptive clamping device	With adaptive clamping device and blocked MRF
Runout frequency	171 Hz	2.6 m/s^2	2.4 m/s^2	1.5 m/s^2
2nd runout frequency	343 Hz	5.56 m/s^2	3.71 m/s^2	2.07 m/s^2
Tooth impact frequency	515 Hz	14.71 m/s^2	5.1 m/s^2	1.09 m/s^2

Table 4: Detailed information about results obtained.

The easily adaptability to different shapes workpiece is another important point of this new device.

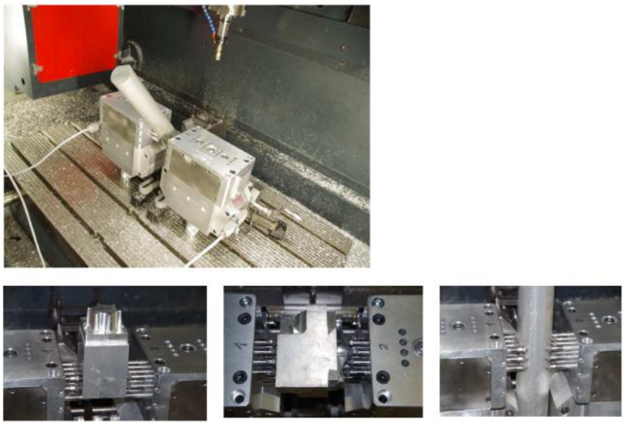


Figure 38: Adaptability to different shapes.

Adaptive solutions for chatter free machining

An adaptive system to select the optimal conditions for chatter free machining has been developed using dynamic calibrators. Here the different components of the system are listed and described.
First of all two measurement heads are included: the High Performance Cutting (HPC) measurement head and the High Speed Cutting (HSC) one. Next, the control of the measurement and calibration procedure requires a software component and a computer on which the calibration software is installed. The last components are the –DA/AD converter and the Signal Conditioning Unit.

Figure 39: Components of dynamics calibrator.

The **HSC measurement head** is fixed to a ferromagnetic surface by a magnetic interface, while the interface to the tool is a prismatic tip. The HSC measurement head has a robust and waterproof housing, which protects the integrated sensors and the integrated piezo element from cooling fluid and chips.

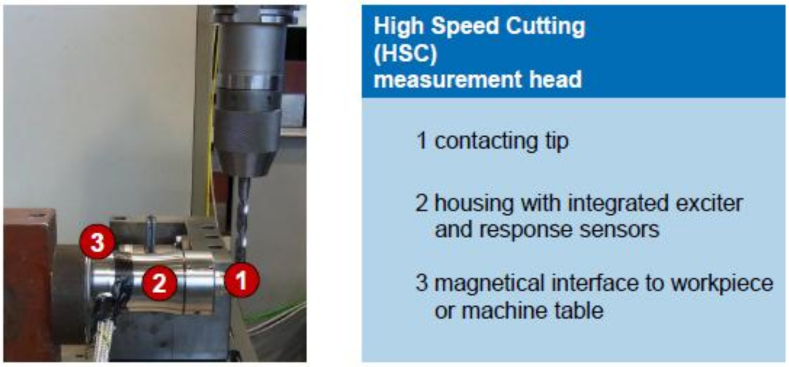


Figure 40: HSC measurement head.

As soon as the exciter is fixed to the work piece or the machine table, the tool must be driven against the contacting tip before the excitation itself can be started. By measuring the preload it is possible to verify that the contact has been established. It is important to ensure a proper contact between the prismatic tip and the tool. Depending on the shape of the tool, it could be necessary to change the angular position of the tool's cutting edges.

The procedure starts with the setup of the tool, then the work piece and finally the machine. After the setup the FRF measurement is performed using one of the new measurement heads.

The process of FRF measurement can be divided in several steps. First of all the selected measurement head has to be clamped in the right measurement position and only when every cable is connected in the right way the first measurement can be done. It can be useful to check different exciter locations keeping in mind that at least two orthogonal directions are needed for the stability calculation. In a post-processing of the FRFs, it is possible to integrate the FRFs, shift the phase and save the measured data. As soon as the FRFs are available the stability can be calculated by starting the stability module. Several boundary conditions have to be given by the user, such as the process parameters (important for the stability calculation). When the stability of the cutting process is calculated, a stability chart is displayed. It can be used to search the optimum process parameters that allow a stable and productive cut.

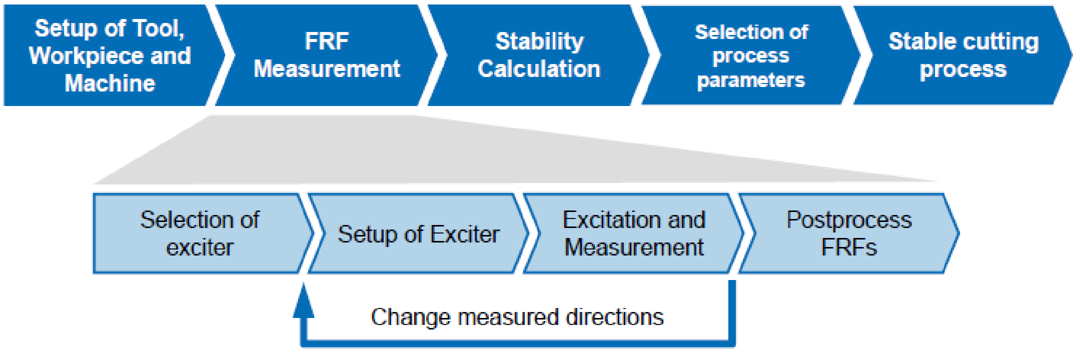


Figure 41: Calibration workflow.

Before the measurements can be performed, an excitation signal must be defined, which controls the force generated by the measuring head. So far, the **calibration software** allows the specification of a sine sweep - or a noise signal. The sine sweep signal indicates a continuous change in frequency with time. With the help of a digital equalizer, arbitrary reference points (frequency and amplitude) can be set for this signal.

Once the measurement is completed, the frequency response is loaded into the software module for the stability calculation. Besides the machine model, information about the process- and material model and the tool geometry is added. As soon as stability calculation has finished, optimal process parameters can be chosen in the stable - region of the stability chart.

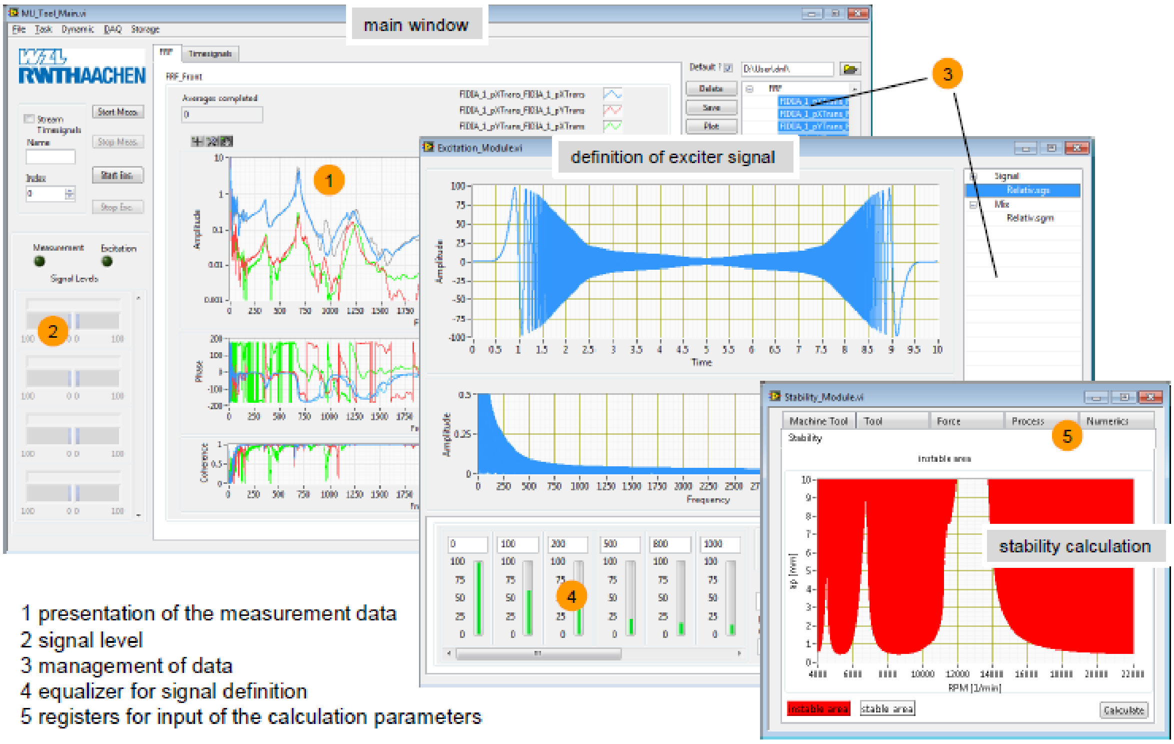


Figure 42: HSC measurement and stability calculation software.

The **stability calculation** adopted by the calibration software, is based on two different approaches: the Semi-Discretization Method (SDM) and the Extended Multi Frequency Solution (EMFS). The SDM is a time-domain technique, which requires the modal parameters as input using a fitted FRF. The EMFS is a frequency-domain method and it uses directly the raw FRF data eliminating this way the errors originated from the FRF fitting algorithm. The operator can chose between the two methods.
For verification of the calibration unit, a three-axis milling machine (FIDIA, type DL155) was available.
First, the machine dynamics of the tool side are measured in different directions. The dynamic measurements are executed with the tool, which will be used for the cutting tests.

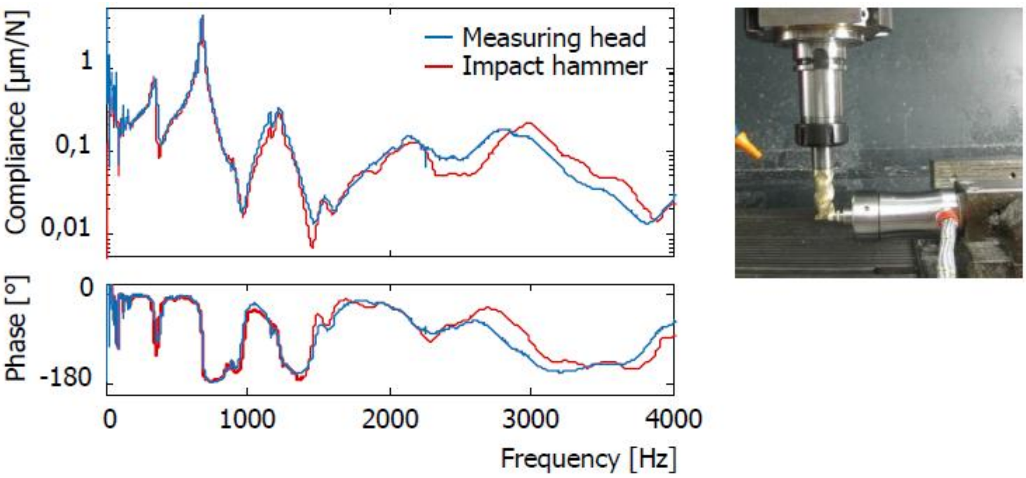


Figure 43: Comparison of the measured FRF using an impact hammer and HSC measurement head.

The first process with n=9000r/min and depth of cut a_p=4 mm was unstable under remarkable chatter vibrations. The milled surface had significant chatter mark. In order to make the machining more productive and stable, a stability diagram is determined with the help of the calibration unit.

In addition to the specifications of the process, the measured frequency responses are used for stability analysis. In order to confirm this prediction further milling operations are carried out with different parameters. Overall, there is a good agreement between prediction and experiment. In the considered case the material removal rate can be increased by 212% by changing the initial parameters to n=12500min-1 and ap=9mm. The MRR has increased 3 times using this system.

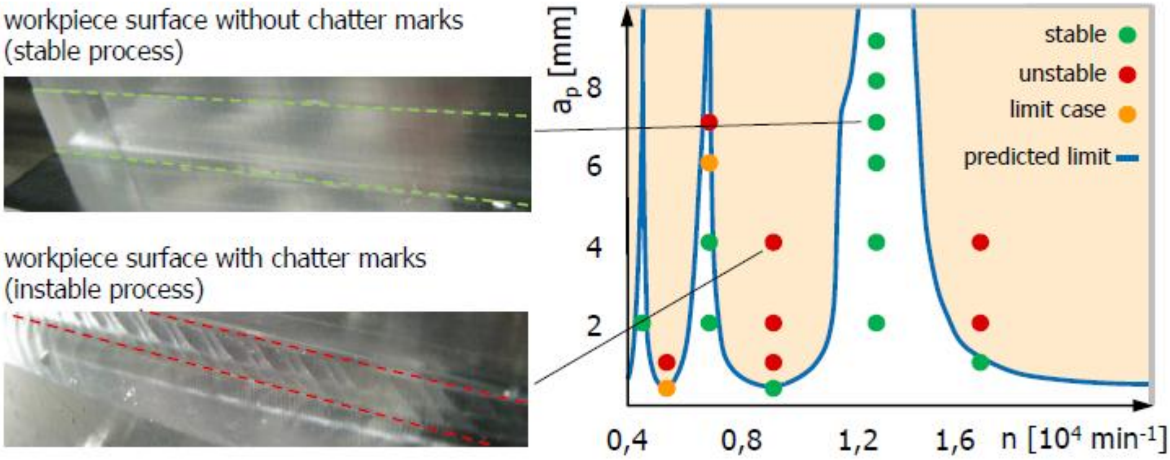


Figure 44: Calibration of milling process in aluminum.

Energy Harvesting and Wireless Communication

In this way, the aim was to integrate on high speed spindle head a magnetic harvester, the process monitoring sensors, and the electronics for the wireless communication. On the CNC side, the system features a receiving wireless electronics with processing module and, after integration of all the devices, the spindle is integrated on a dedicated test bench to verify its functionality.

A **magnetic harvester** was designed to supply the process monitoring sensors and the wireless electronics. The magnetic harvester was optimized to increase the available power and fit in the spindle head. Additionally, the magnetic harvester integrates three position sensors, to sense the shaft position. This solution is very effective since it only needs to integrate one device to get two functionalities of generator and sensor.

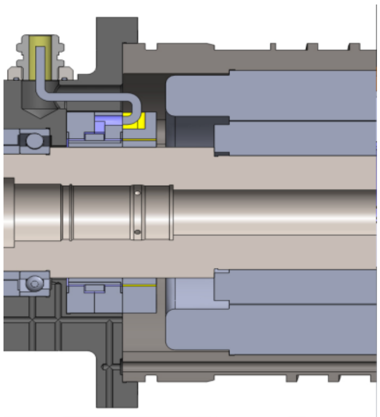


Figure 45: Design of the spindle with integrated harvester behind the front bearings

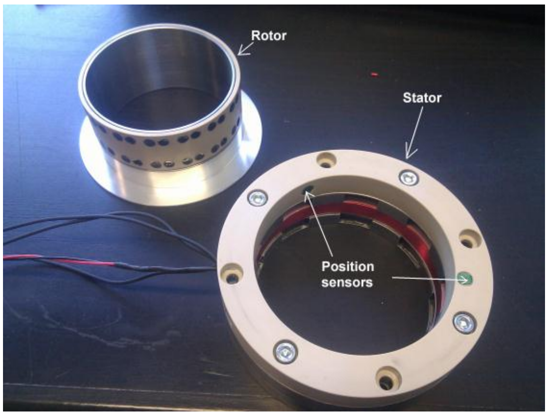


Figure 46: Generator Components

The prototype of magnetic harvester is composed of a rotor attached to the spindle shaft, and a stator, attached to the stator of the spindle. In order to harvest the energy from the generator, dedicated supply electronics was built. This electronics rectifies the voltage out of the generator, and performs DC/DC conversion and buffering for supplying the sensors and wireless communication. This electronics also feature the conditioners for the sensors:

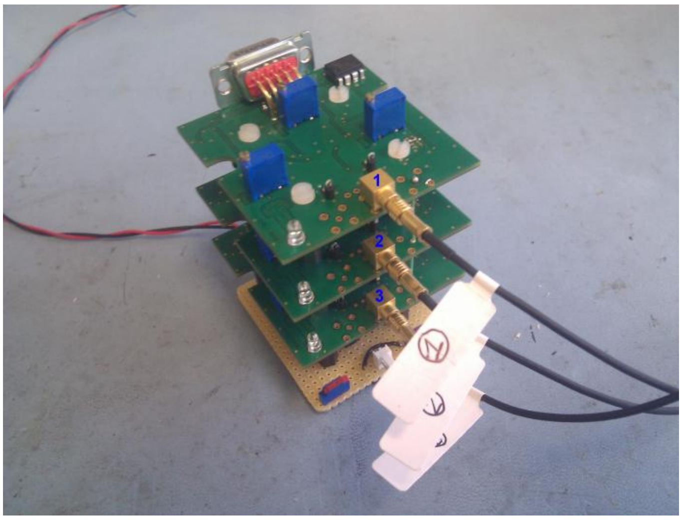


Figure 47: Generator electronics with integrated ECS conditioning

Before delivery for the integration inside the spindle head, the generator was tested. The harvester is capable of supplying the position sensors, and there remains power for the wireless electronics and other sensors. The generator being validated, it was integrated on the GOILADE spindle head.

The objective of the instrumented wireless spindle head is to be able to monitor the state of the spindle and cutting process over the wireless link. There were three different **sensor** types chosen to instrument the spindle: temperature, acceleration sensors and position sensors.

The temperature sensors are PT100 temperature sensors, which are used to monitor the temperature of the spindle's bearings.

Figure 48: PT100 Sensors

Figure 49: ADIS16220 Sensor

The acceleration sensors are off-the-shelf MEMS accelerometers ADIS16220 with integrated ADCs that directly digitalize the acceleration data. Those sensors are used to monitor the axial and radial acceleration on the spindle's bearings. The position sensors are Eddy Current Sensors (ECS) developed by CEDRAT. These position sensors are sensing the displacement of the shaft in the axial and radial direction.

Figure 50: Eddy Current Sensors (ECS) integrated into the Generator

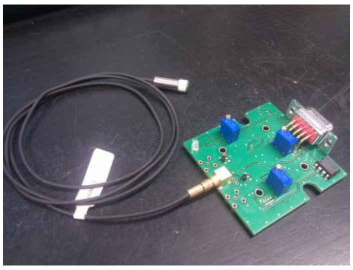


Figure 51: ECSu10 modified ECS conditioner

A dedicated conditioner ECSu10 was developed for DYNXPERTS, in order to have a compact solution, with low power consumption. The ECS probes are integrated inside the generator, thus there is no specific requirement for their integration.

For the **Wireless Communication** a ZigBee based solution was implemented on the instrumented spindle head. The solution is based on a Texas Instruments MSP430 Controller (MSP430F5529) for the application level and a CC2530, also manufactured by Texas Instruments, as the Radio section of the solution.

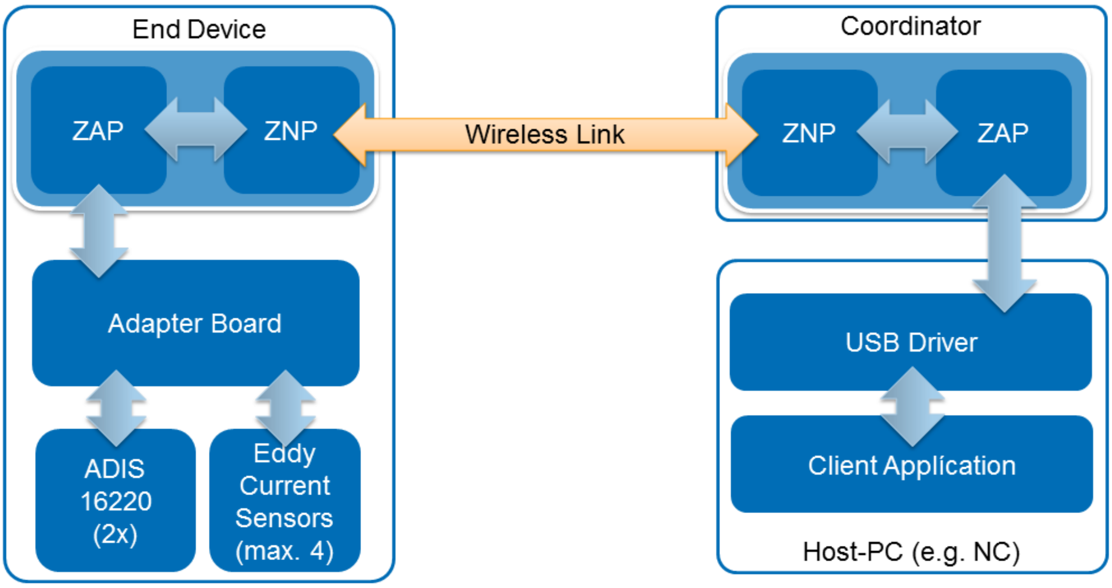


Figure 52: System components and connections

The system consists of a coordinator node which is connected to the Fidia Numerical Control Unit and one or more sensor nodes which read the sensor values and transmit them to the Coordinator Node. The Coordinator Node communicates with the NC via a USB Connection. The data is displayed in a standard windows application which is running under .NET-Framework 4.5 and is developed in C#.

The Sensors attached are ADIS 16220 MEMS Accelerometers which are Systems-on-Chip with integrated AD-Converters for the accelerometer values. Furthermore the integrated displacement sensors are sampled with the integrated AD-Converters of the employed MSP430 Processor.

The basis for the firmware employed on the single nodes is formed by the TI provided Z-Stack ZigBee Pro 2007 Implementation. Furthermore an USB-Library provided by TI was used. On top of these frameworks the individual applications need to be built.

The client application is the front-end for the ZigBee communication system that was developed. It displays the data and allows for communication with the network through the USB connection to the coordinator.

The main area is used for displaying the results of the sensor read-out. The data is always displayed for a single sensor node at a time. The sensor node that shall be displayed is selectable through a drop-down box at the top of the main area. There are three possible views for the gathered data. The first one displays the sensor values graphically in a chart display. The options for the time that shall be shown in the chart are expandable on the bottom of the chart. The second option is a tabular view for all data received from the sensor node. And the third one shows the condition associated with a certain value on a scale from green to red.

GOIALDE has worked on the **redesign of the spindle**. Particularly, the integration of the magnetic harvester was complex, and required a deep redesign work. Especially, there needed to by wire outlet, so that the sensor and power cables could go out of the spindle. From the outside, the only thing that can be noticed is the cable outlet from the generator and the accelerometers:

Figure 53: Assembly steps for the generator integrator

The test bench was located at WZL facilities and is usually used for testing spindles under load conditions. To get to a realistic situation in an industrial setting the test stand was modified so that the Fidia NC controls the PLC. In this way the setting is the same as in a machine tool, except that there are no axes moving.

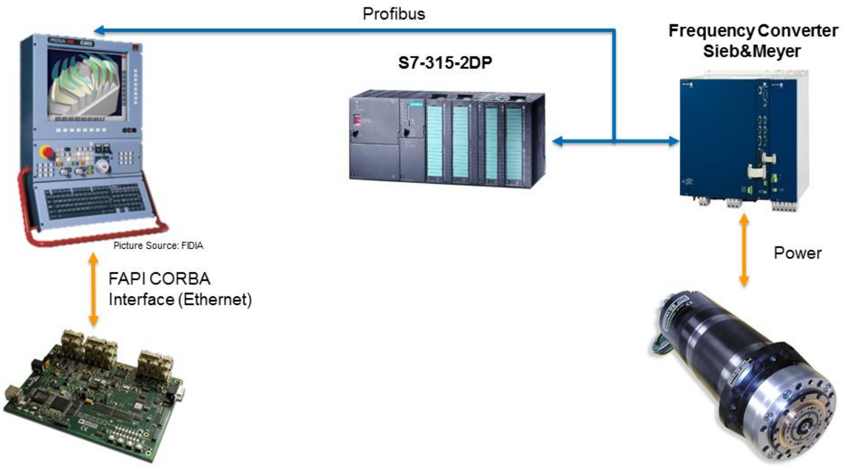


Figure 54: Connections of the test stand

A stand-alone **FIDIA CNC NC15** has been interfaced with the Processing Module and with the test bench control (Siemens PLC based), effectively acting as a real time bridge between the two systems. The FIDIA CNC NC15 architecture has two separate processors, one for the operator interface and one for the CPU (running on a dedicated board on PCI bus), enabling high milling performance in terms of quality and speed to be achieved. Moreover, thanks to Windows XP operative system, any application software can be installed including the most powerful 3D CAM systems.

A dedicated Graphical User Interface (GUI) has been implemented on the FIDIA CNC to show (in Real Time) the status and value of the exchanged variables.

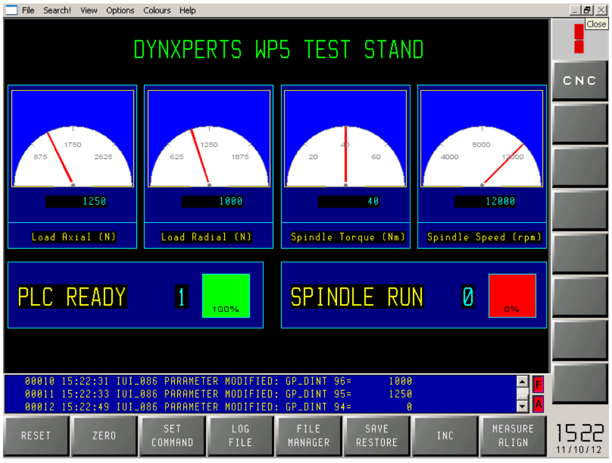


Figure 55: Screenshot of the control application running on FIDIA NC

For friendliness purposes the two variables with Boolean meaning (PLC ready and Spindle Run) have been depicted with a color code (green for 1 and red for 0) while gauges indices have been selected for the other 4 variables. For all variables the numeric value is also available.

On the PLC side a simple Interface was implemented which allows the external control to be switched on and off and shows the values communicated via Profibus to the user.

For testing the components were mounted on the **test stand** and the sensor was attached to the Spindle using Brackets.

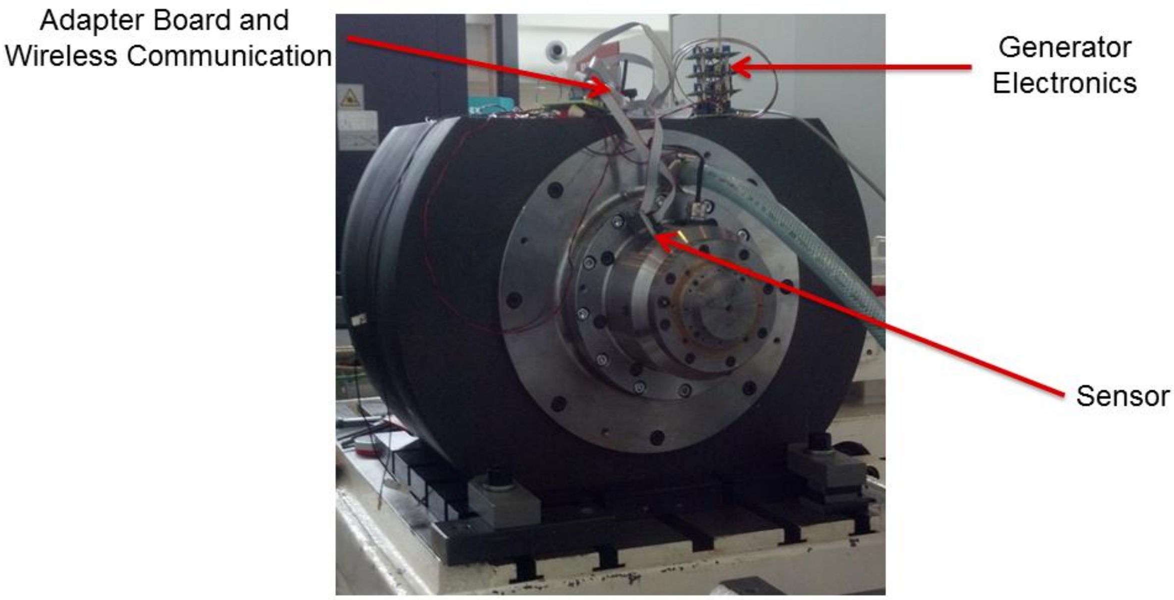


Figure 56: Spindle mounted on the test stand

The Generator was tested at the WZL in all configurations provided by the Generator Electronics. For testing purposes the load on the Generator output was simulated by means of externally applied resistors on the output of the generator electronics. The available configuration modes are Resonant or Standard Rectification and ECS Conditioning switched on or off. The ECS Conditioning Electronics are supplied by a DC/DC-Converter providing stabilized Voltage output needed by the system.

For testing the Wireless Communication System the spindle was driven up to 10.000 rpm in 1.000 rpm steps, while the sensors were measuring successfully the acceleration occurring at the spindle.

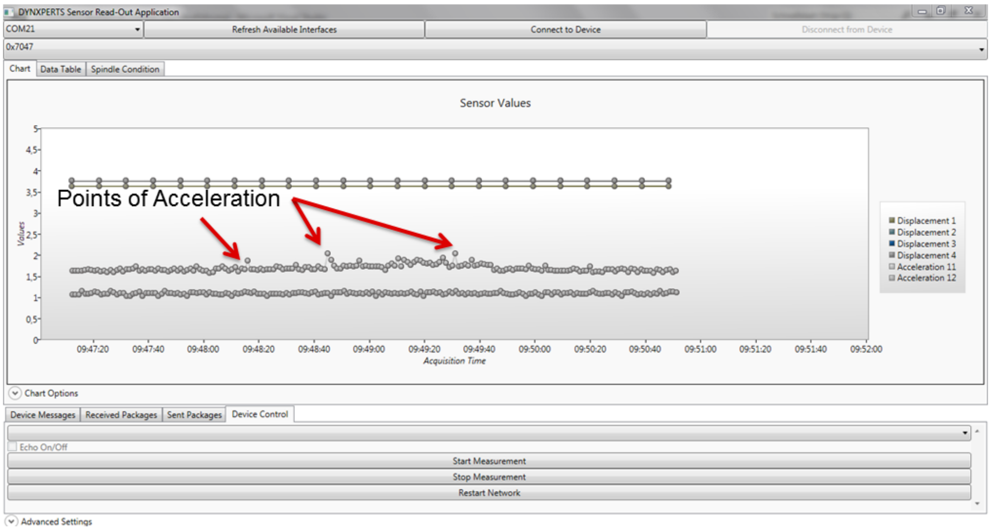


Figure 57: Screenshot of the Application with a real measurement example

4. Description of the potential impact.

In order to keep a leading position and stop the loose of market share, the transition from a cost-based competitive industry to a knowledge-based industry is becoming essential. The Plug and Produce components developed in the DYNXPERTS project are aligned with this objective and will allow European machine tool developers to stay ahead of the competition in the global economy.

A new generation of advanced production instruments has been developed and are a reality: a roughing 5F high torque spindle head, finishing 5F High Speed Spindle Heads, smart MR and eddy current dampers, advanced fixturing units, chatter free machining adaptive solutions and wireless monitored high speed spindle are available after the end of the DYNXPERTS project.

Individual technical impact of each plug and produce component:

The technical impact of each new component is going to review in the next lines:

- 5F Roughing Spindle Head: the system has been able to remove chatter using different smart functions with a reduction of vibration severity decrease between 39-94%. The introduction of this head supposes an improvement of the dynamic behavior of the milling machine. In fact, the dynamic stiffness and the damping have increased 150% in some positions. Therefore, the material removal rate (MRR) has been increased between 200-420% depending of the roughing operation. The new system offers the possibility of automatic head failure detection and a wizard to define the best cutting conditions.
- 5F Finishing Spindle Head: during this project the machining capability measured by means of material removal rate (MRR) has increased 543%. A reduction of 68% on surface roughness has been achieved using the new features developed in this project. The new system offers also in this case the possibility of automatic head failure detection and a program to define the best cutting conditions.
- Smart dampers and adaptive fixturing: an improvement of fixture damping in the range of 330% has been obtained using the new systems. Due to this improvement the MRR has increased between 380% and 633%. A reduction of 94% in the surface roughness has been measured.
- Adaptive solutions for chatter free machining: The system has permitted an improvement of 312% in material removal rate (MRR). A reduction of 55% on surface roughness has been achieved using the new features developed in this project.
- Energy harvesting and wireless communication: a high speed spindle has been monitored using accelerometer, temperature and displacement eddy current sensors. Eddy current sensors have been developed during the project and magnetic harvesting device has been used.

	Technical description	Target	Achieved
WP1. Roughing 5F Head	Chatter removal, with vibration severity decrease of	90%	94%
	Dynamic stiffness and damping increase of	20%	150%
	Material removal rate (MRR) increase of	300%	420%
	Automatic head failure detection	OK	OK
	Automatic cutting conditions selection	OK	OK
WP2. Finishing 5F Head	Machining capability improvement in high power conditions	30%	543%
	Improvement on surface roughness in finishing operations	50%	68%
	Automatic head failure detection	OK	OK

	Automatic cutting conditions selection	OK	OK
WP3. Adaptive fixturing with smart materials	Increase of fixturing damping of	20-80%	330%
	Material removal rate (MRR) increase	OK	632%
	Surface roughness decrease	OK	94%
WP4. Adaptive solutions for chatter free	Increase of material removal rate (MRR)	100%	212%
	Surface roughness improvement of	10-30%	55%
WP5. Energy harvesting and wireless communication	Wireless sensoring in all the plug and produce components	OK	Only sensors of WP2 have a wireless link
	Self-supplied sensoring	OK	OK
	Vibration and magnetic harvesting	OK	Only magnetic harvesting

Table 5: Technical impact

Economic and social impact for manufacturing industry:

End users of cutting machine tool systems are a conglomerate of industrial sectors. This could be by large the industrial sector that would bring the largest economic impact of a successful completion of the project.

Machine tools are used for production purposes where metal cutting could represent 10% of their turnover. Many of these industries are SMEs, with a reduced investment capacity, to which the use of the Plug and Produce Components would present a number of benefits:

- Lower investment in productive equipment
- Generic solutions for different problems (the same Plug and Produce Component can solve different specific problems).
- Increased flexibility allowing tackling complementary production orders, especially for the production of single parts or reducing batches
- Produce high accuracy parts right first time, with a high level of productivity

Big impact is expected in production sectors producing high added value parts, as the aerospace sector, molds and dies sector, railway sector, energy sector… which employ more than 1 million people high quality direct jobs in production tasks, and which are moreover key sectors for European competitiveness.

The economic and social impact that has been achieved for end users with the development of the DYNXPERTS project is summarized:

- 5F Roughing Spindle Head: this device has been developed for general machining but it has a special impact in wind turbine sector and large part machining (naval motors, earth moving machinery,…). The introduction of this head supposes a reduction between 50-76% in some face milling operations. The dynamic calibration process has been improved thank to the new calibration feature. This way the required time has been reduced in 6 hours and a repetitive and uncomfortable work has been automatized. The preventive maintenance is performed automatically by the machine and the special measurements have been eliminated.
- 5F Finishing Spindle Head: The natural field of this head is the aerospace structural parts manufactures. This spindle offers high energy efficiency at high speed due to the absence of losses at the bearing. In the other side, this head supposes a reduction in machine stops and improvement in the reliability of the spindle. This improvement has not quantified yet.
- Smart dampers and adaptive fixturing: These systems cover a wide range of applications from aerospace thin wall machining to heavy duty machining of naval engines, construction machinery and

wind mill manufacturing. A reduction of 94% in the surface roughness has been measured and material waste decrease is obtained.

- Adaptive solutions for chatter free machining: this system is focused on high speed machining of light alloys especially in aerospace sector. The system has permitted an improvement of 312% in material removal rate (MRR) and 68% reduction in machining time of some roughing operations. An improvement of 21% in machine availability has been simulated.
- Energy harvesting and wireless communication: a high speed spindle has been monitored and therefore the aerospace sector is the first target sector for these devices. However, the system has application in other fields. Autonomy increase, energy saving and portability are some of the positive impacts of this device.

	Economic and social impact	Target	Achieved
WP1. Roughing 5F Head	Reduction of machining time	OK	80%
	Dynamic calibration of the area with saved time of	2-3 hours	6 hours
	Preventive maintenance elimination	OK	OK
	Spare component waste reduction	OK	OK
	Noise reduction	75dB(A)	To be measured
WP2. Finishing 5F Head	Higher Energy efficiency due to absence of losses at bearings	OK	OK
	Higher reliability due to their contactless nature	OK	To be measured
	Improvement of the life of the spindles	OK	To be measured
	Less time needed for control adaptation in tool change	60% less	To be measured
WP3. Adaptive fixturing with smart materials	Material waste decrease due to the great safety against spoiling the part due to vibrations	OK	OK
WP4. Adaptive solutions for chatter free	Machining time decrease of	50%	68%
	Increase of machine availability of	10%	To be measured
	Reduction of the dynamic calibration set-up time	OK	OK
WP5. Energy harvesting and wireless communication	Autonomy increase	OK	OK
	Energy saving	OK	OK
	Portability	OK	OK

Table 6: Economic impact

Apart from the general economic and social benefits for the end users of the plug and produce components developed in the DYNXPERTS project, which have been pointed out before, the machine tool manufacturers that exploit these new concept components will also take advantage with an important turnover increase. FIDIA and SORALUCE, as machine tool builders, expect to wide their customer portfolio, enlarging the offer of flexible and re-configurable machines.

SORALUCE expects an increase in the market share in technology demanding countries, especially in Asia, which will bring an annual turnover increase of around 10%. SORALUCE has installed in two beta users technology developed in this project. The idea is to check the reliability of the technology in production conditions to improve the product considering the faults and the feedback of the customer. This way the first reference is obtained and the product can be launched to the market.

FIDIA, with the breakthrough in CNC achieved in this project, consisting in offering products that are ready to interface in an easy and fast way smart components, foresees to have a 5% average increment in machine tool-turnover for the three years following the end of the project and a 7% average increment in CNC related turnover as well.

Dissemination of the results:

The dissemination of the project results have been performed in two different dimensions: scientific dissemination related to the generation of knowledge in academic terms, and industrial dissemination trying to show the results of the new generation of plug and produce machine tool components to possible customers.

Part of the knowledge created has been published in SCI journals. Eleven publications have been performed based on knowledge acquired by the consortium in the field of the stability calculation, characterization of MR materials and the development of 5 functions. These publications do not interfere with the protection and the exploitation of the results.

Seventeen oral presentations have been performed during the project in reference congresses in the field of machining and dynamics. In the European conferences the hardware and the machine tool components developed in the DYNXPERTS project were shown. In the other conferences the presentations were centered in the prediction of the stability of the milling process.

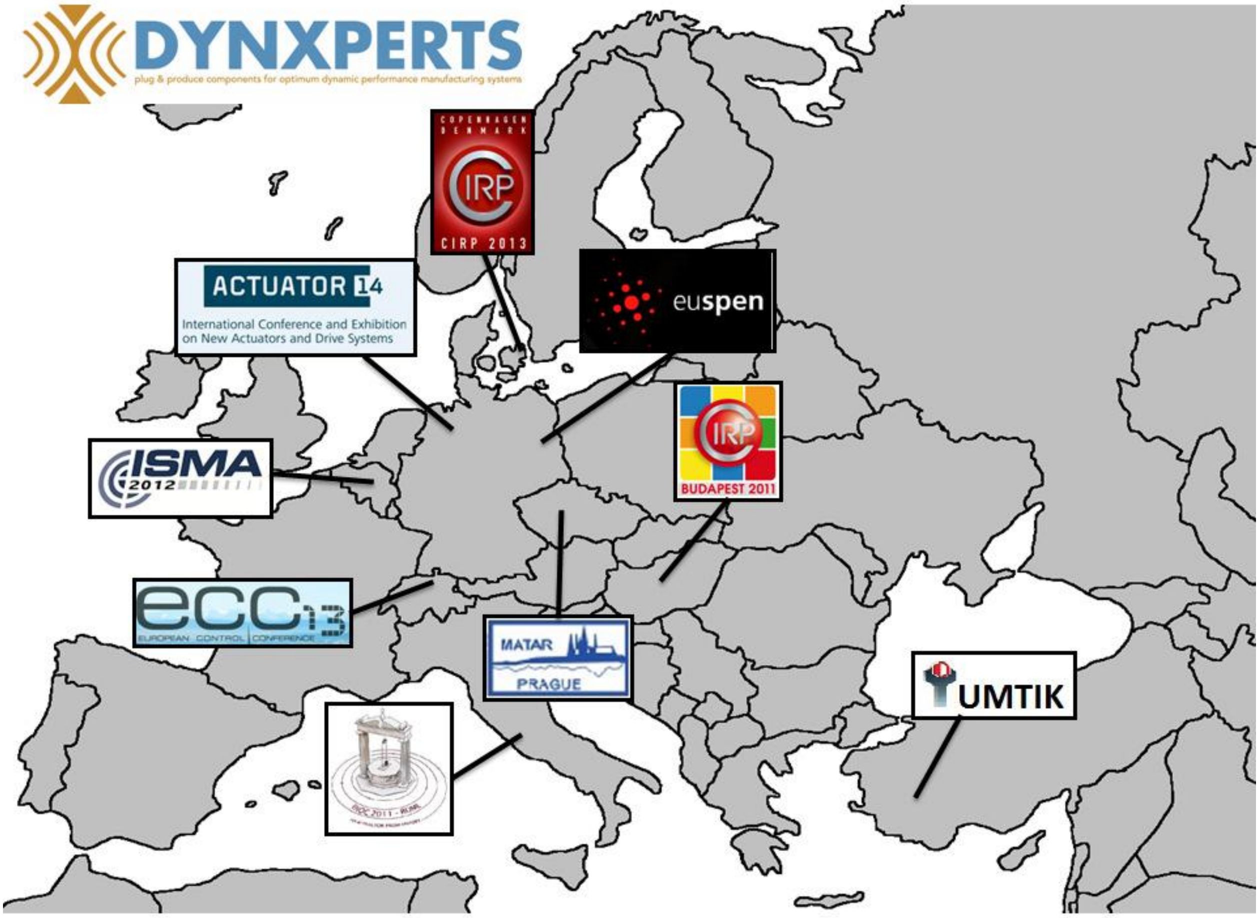


Figure 58: Conferences

The objective of the industrial dissemination is to contact machine tool builders and end users to show the new plug & produce components developed in the project. The results were presented in two important machine tool fairs in Germany and Spain with a total assistance of 55400 visitants related to machine tool. Three workshops (SORALUCE 50th anniversary, demonstration of 5F magnetically levitated high speed spindle and DYNXPERTS final workshop) were organized to show the possibilities of the new components to possible customers using the commercial network of SORALUCE and GOIALDE. The consortium has participated in three technological fairs showing the main achievements to possible customers and investors.

Four articles have been published in important machine tool industrial magazines (Interempresas, IMHE, Empresa XXI, and ZWF) to present the results of the project to machine tool community. The newsletters of IDEKO, CEDRAT and IMHE have been used to inform about the benefits of the new devices.

A webpage (www.dynxperts.eu) and a YouTube channel (https://www.youtube.com/channel/UC65-m6BdQixvK7KXl-ibLIA) were launched to inform about the project and to show the performance of the new components. Six different webpages related to machine tool world have published reports about the DYNXPERTS project.

Finally, part of the knowledge has been disseminated using the academic activity of BME and EHU-UPV, and internal curses prepared by IDEKO for the DANOBATGROUP, the biggest machine tool manufacturer of Spain.

Exploitation of the results:

During the project 28 exploitable results were identified and classified in three groups: plug and produce machine tool components, hardware products (mainly sensors and actuators) and software products.

Two new machine tool components have been patented to protect the results of the project: the antichatter spindle head based in the 5F heavy duty spindle head and the inertial damper of the adaptive fixturing system.

- Inertia damper for suppressing vibrations in machine tool (EP 12380046). This damper permits controlling and changing the tuning of the damper using the position of a cylindrical spring. A new chatter suppression algorithm has been proposed as well.
- Antichatter Spindle Head (P201330810). This is the main head developed in this project to perform de 5 smart features in heavy duty operations.

Two products designed and manufactured by CEDRAT TECHNOLOGIES for the DYNXPERTS product are already in the market using the sales network of CEDRAT:

Figure 59: The new MICA actuator

Figure 60: UC65 Controller

- High Force MICA Actuator: They provide with a controllable force on several millimeters of stroke. The optimized design offers a very high energy density, several times better than moving coil actuators. With strokes that reach 10mm for the MICA L family and 5mm for the MICA M family, these actuators perfectly complete well known CEDRAT's APA® actuators. MICA is controllable, high force, highly dynamic actuator. The MICA M actuators have a stroke of 5 mm and nominal forces range from 110N up to 440N.The MICA L actuators have a stroke of 10 mm and nominal forces range from 530 up to 1600N.
- UC65 Controller: The new UC65 is a board that can be plugged in the 75 family racks. It is based on a powerful DSP core and can control several independent or coupled channels. It can implement a very fast control loop with sampling rates up to 60khz for 1 channel. Include A/D and D/A converters to implement digital controls up to three independent channels with 16 bits Resolution. Sampling rate 60kSamples/s – Plugged with standard HDPM GUI to set your optimum control law (Proportional Integral Derivate parameters + Additional filters selected among standard low pass or stop band filters with orders up to 4). Texas Instrument Powerful DSP core able to control fast control loops

The machine tool sector is a really conservative market where the introduction of new devices and systems is not easy. The transfer from the laboratory to the production facility is a difficult process full of technological and mental barriers. One of the most important factors is the reliability. The possible customers are suspicious of the long term behavior of the new device or system. In this point, it is very important to have references or industrial pilot experiences to open the door of the production facilities. In this project, the dissemination activities and the network of SORALUCE have permitted to contact companies interested to test industrially results of the DYNXPERTS project. This way two of the smart features are being tested in industrial conditions and in general terms the feedback is really positive.