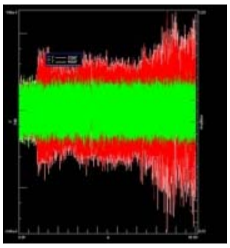
FFI Robust machining



Project within FFI Sustainable production technology

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2013-02-13

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Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

For more information: www.vinnova.se/ffi

1. Executive summary

New generations of environmentally friendly and safe vehicles require manufacturing of light weight materials with higher strength and as a consequence tougher machining conditions and increased machining robustness. High precision components like CGI engine blocks, injection nozzles, shafts and gears have to be machined at extremely narrow tolerances – dimensional as well as surface roughness. This puts very high capability demands on machining systems – both as new as well as to be maintained during the operational phase.

There is a need for practical, fast and reliable methods and tools to evaluate and control the capability for robust machining with respect to product properties and with competitive manufacturing cost.

The very complex system of machine tool, fixture and cutting tools during machining of a part is almost impossible to model analytically with enough accuracy. To be able to do this it is necessary to monitor and analyze the real system at the factory floor in full production.

Design and measured data could then be put together to make a realistic digital model of a physical machine system individual, that could be used as input in machining simulation software to find the root causes of stability problems.

Another issue is to leverage the use of knowledge and manufacturing experiences gained when defining new products and processes. The problem with bringing back experience from dispersed company IT systems to the earlier phases of product development includes both the issues of searching and accessing relevant data as well as the ability to present the data in the recipient's context.

The new concepts and technologies should be further developed and tested in typical industrial cases. In an iterative process the results from industrial case studies should trigger improvements.

The project was organized in four workpackages:

- WP1 Project coordination and result dissemination
- WP2 Machining system condition testing and monitoring
- WP3 Machining system modeling and reuse of manufacturing experience
- WP4 Machining system design – high damping interface (HDI) system.

Important results obtained are:

- Demonstrators for preloaded double ball bar (LDBB).
- System for static and dynamic testing of rotating tools.
- Characteristics and parameters that are most relevant to integrate in digital models of machining systems to be able to analyze machining robustness from dynamic point of

view of machine tool components. Dynamic characteristics are defined in terms of mass, damping and stiffness.

- Methods and systems for the test cases to collect and communicate the needed characteristics and parameters.
- Extended STEP AP 214 machine tool models including static and dynamic stiffness to be used to generate input data in available commercial machining simulation software: The characteristics of joint interfaces between machine tool components are defined in terms of damping and stiffness.
- Appropriate software to study the interaction between machine tool structure and machining process for evaluation of machining robustness. Available software at the project partners was used.
- A methodology for experience reuse.
  Methods and work procedures for mapping, analyzing and improving the flow of experiences from manufacturing to development of new products to reduce manufacturing disturbances due to inadequate design solutions from a producability point of view.
- Demonstration of a system support to improve the reuse of the experience gained from the production process.
  The methodology has been used to improve existing design support system to better utilize experiences from manufacturing for development of new products. In addition, a video-based approach is proposed to lower the effort in capturing and disseminating lessons learned from production and other downstream phases to design practices. The results encompass methodology, guidelines, process description and technological enablers for continuous experience feedback to the design practices.
- Descriptions of the week points in the test cases.
- Demonstrators, machine tool components based on high damping interface (HDI) concept in relevant test cases.
- Generic advice and suggestions how to specify/design new machine tool systems to be improved by HDI.

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2. Background

New generations of environmentally friendly and safe vehicles require manufacturing of light weight materials with higher strength and as a consequence tougher machining conditions and increased machining robustness. High precision components like CGI engine blocks, injection nozzles, shafts and gears have to be machined at extremely narrow tolerances – dimensional as well as surface roughness. This puts very high capability demands on machining systems – both as new as well as to be maintained during the operational phase.

Sustainable manufacturing is a ‘compound’ concept. One factor is economic sustainability. In short, the ability to manufacture the kind of advanced components mentioned above more profitable than the global competitors.

The Swedish national research agenda 2008 for production by the Association of Swedish Engineering Industries, the Swedish Production Academy and Swerea IVF pointed out ‘robust and reliable manufacturing systems’ as a prioritized research area. The European ManuFuture technology platform suggests ‘intelligence for enhanced processes’ as one important research topic within adaptive manufacturing.

There is a need for practical, fast and reliable methods and tools to evaluate and control the capability for robust machining with respect to product properties and with competitive manufacturing cost.

The very complex system of machine tool, fixture and cutting tools during machining of a part is almost impossible to model analytically with enough accuracy. To be able to do this it is necessary to monitor and analyze the real system at the factory floor in full production.

Design and measured data could then be put together to make a realistic digital model of a physical machine system individual, that could be used as input in machining simulation software to find the root causes of stability problems.

Another issue is to leverage the use of knowledge and manufacturing experiences gained when defining new products and processes. The problem with bringing back experience from dispersed company IT systems to the earlier phases of product development includes both the issues of searching and accessing relevant data as well as the ability to present the data in the recipient's context.

Figure 1 Members of the FFI Robust machining team involved in machine testing at Scania's transmission workshop in Södertälje.

3. Objective

The new concepts and technologies should be further developed and tested in typical industrial cases. In an iterative process the results from industrial case studies should trigger improvements. To start with, a gear cutting machine at Scania in Södertälje, a 5-axis machining center at Saab, Linköping, a machining center at PTC in Trollhättan and a turning center at Leax Falun in Falun were to be studied.

For each industrial case study a proposal of industrial test and analyze procedure should be developed. Further on actions and measures should be proposed and implemented to increase the stiffness and robustness of the system. Generic advices and suggestions how to specify stiffness and acceptance test methods for new machine tool systems as well as techniques to reuse manufacturing experiences in several contexts was to be developed.

4. Project realization

The project was divided into four work packages:

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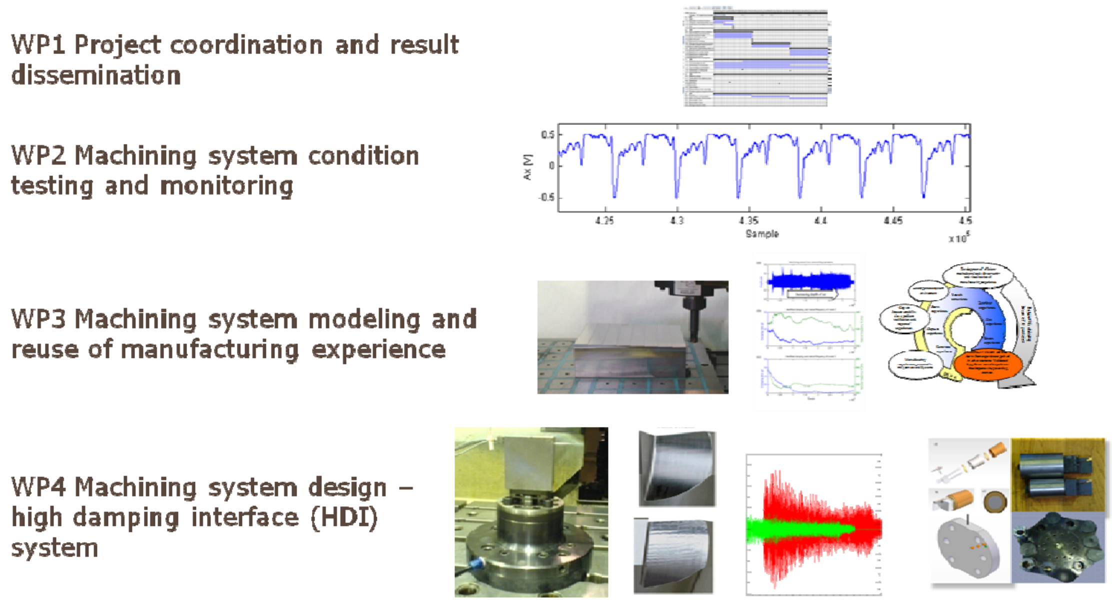

Figure 2 Work packages.

5. Results and deliverables

5.1 Delivery to FFI-goals

Use of tools for virtual production planning in order to perform fast and thorough impact and optimization studies has increased rapidly.

WP3 Machining system modeling and reuse of manufacturing experience

Machining system modeling – for model driven operation planning

Machine tool accuracy depends on kinematic error and stiffness properties. For accurate simulation and compensation it is important to model and characterize these properties. A prerequisite is measuring and modeling kinematic error under operation-like conditions. Enabling integration with other data in production engineering is an important requirement to be fulfilled. The proposed modeling approach is based on the ISO 10303 STEP generic data model augmented with machine tool characterization terminology *e.g.* for kinematic error defined in ISO 230. This modeling approach is applicable for any kind of machine tool or product mechanism.

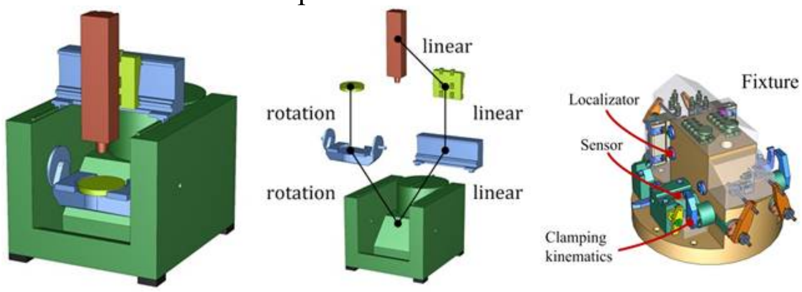

Figure 3 ISO 10303 STEP kinematics augmented with terminology.

Models of manufacturing resources as machine tools, fixtures and cutting tools contribute to efficient and simplified operation planning. With operation planning domain concept, defined in ontology and used during modeling of coherent ISO 10303-214 conforming data models of manufacturing resources, stable implementation solutions are ensured while capable of representing current manufacturing resources and resources developed in the future. Using similarities between different types of resources, a unified modeling approach may be applied independent of the type of object. Information classes as interfaces, kinematics, performance and behavior are identified and related to corresponding construct of the standardized product generic schema. With the common representation of shared information between applications domains as operation planning, maintenance and factory layout design, presented result contributes to set the basis for a digital factory used in virtual manufacturing to continuously improve the production system.

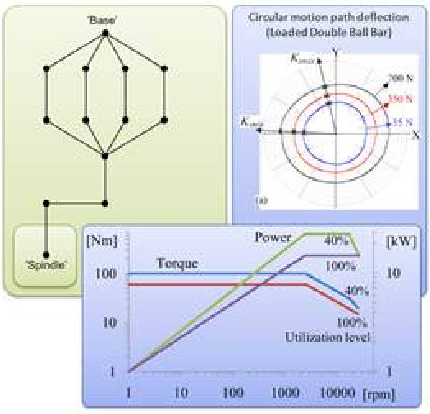

Figure 4 Kinematic structure as context for loaded double ball bar (LDBB) result and spindle motor properties.

A demonstrator is realized using a 3-axis Mazak VQC20 machine tool at KTH. The machine tool 3D-shape and kinematics (degree of freedom and geometry for axes position and configuration) were created in a commercial CAD system and exported to ISO 10303-242 STEP using a plug-in developed by KTH. Then were measured characteristics integrated with the nominal machine tool model. The machine tool model describing kinematic error was uses for calculating (by NIST) total error in the kinematic structure loop i.e. from workpiece, to cutting tool via the machine axes and machine tool base. Stiffness of the machine tool was measured using loaded double ball bar (LDBB). Machining of a Scania crown wheel was done. Simulated cutting force (by Boeing) was used to calculate deflection from nominal tool path to predict shape deviation on machined crown wheel. Predicted and measured shape had good qualitative correlation.

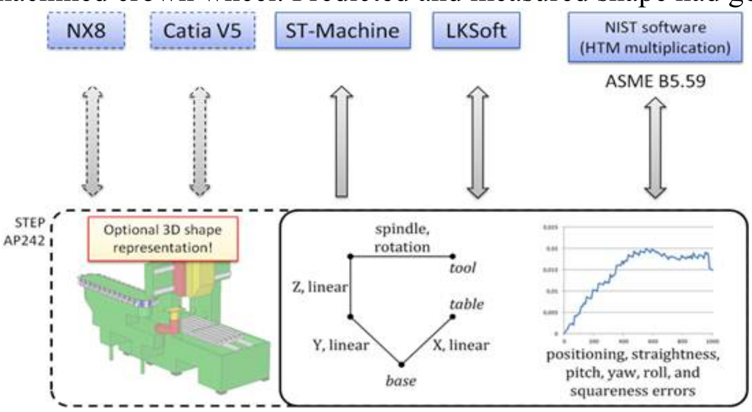

Figure 5 System integration via data consolidation.

An ISO TC184 SC4 WG3 T24 STEP-manufacturing conference was arranged at KTH on 14th June 2012. There was 34 participating international expertise on model based machining (from 17 organizations in 9 countries e.g. Boeing, Sandvik Coromant, NIST, ISCAR).

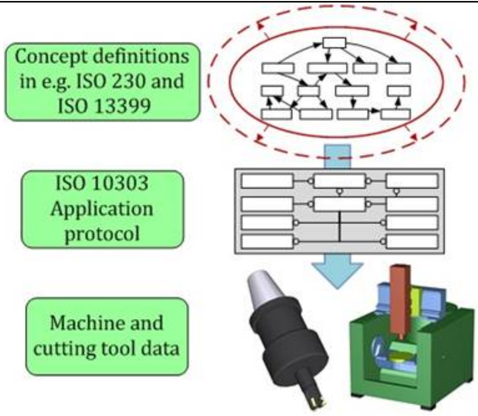

Figure 6 Modeling approach combining extendable terminology with STEP data model.

With the presented approach to apply established concepts and terminology conventions it is possible to unambiguously represent manufacturing resource requirements, functional description and behavior. This data model then constitute a powerful information repository to retrieve data from, which can be used to populate other models optimized for e.g. real-time computing or visualization purposes. While the data model is based on the integrated resources of ISO 10303, data easily can be shared between other application protocols of this standard. For operation planning AP238 provides capability to represent information for model driven NC using machining features. Such mutual interaction between AP214 and AP238 enhances model driven operation planning. For other applications as maintenance and factory layout design this approach is also applicable and will take benefits of the shared model representation. Presented research result contributes to create building blocks for the digital factory used in virtual manufacturing with the objective to continuously improve the production system.

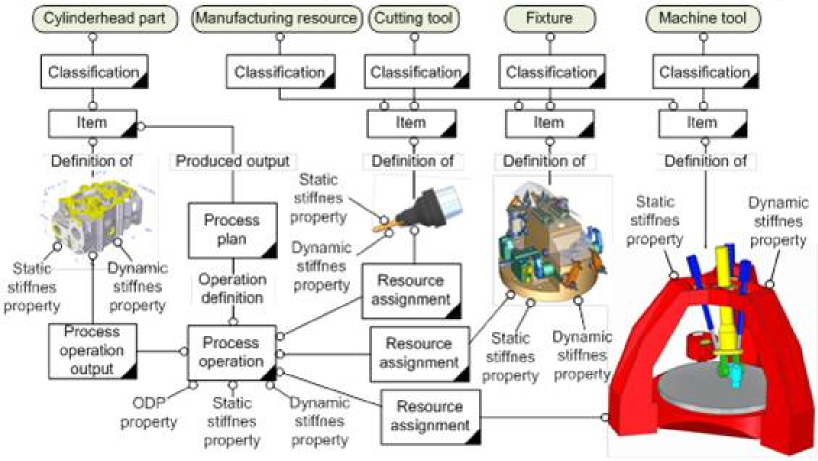

Figure 7 Coherent industrial data based on ISO 10303.

WP3 Machining system modeling and reuse of manufacturing experience
Machining system modeling – process-machine interaction (PMI)

In intermittent machining operations, the time-varying and discontinuous nature of the cutting process represents a challenge in terms of cutting parameter selection, control and optimization. To investigate physical phenomena and for thorough validation of parametric identification approach of the operational module, a virtual machining system engine (VMSE) has been developed.

The VMSE is based on a FE computation. As the engine represents both the structure and cutting process it can generate a response of known damping ratio and frequencies of the machining system.

The term ´engine´ indicates that the virtual machining system is capable of emulating the physical interaction that occurs in a real machining system under operational condition. The two subsystems, machine tool elastic structure and cutting process dynamics, are represented by physical relations and their mutual interaction is described by physical processes.

The FE-modeling of the intermittent cutting process has the purpose of being accountable for:

- Thorough modal parameter estimation (mass, stiffness, damping) of the elastic structure.
- Parametric identification of the dynamic response resulting from the interaction between the elastic structure and the cutting process.
- Use the above results to optimize the model structure in recursive identification of operational machining systems.
- To provide a good physical insight into the phenomena investigated.

The relative motion between the tool and workpiece represents the sum of all individual relative displacements in the machine tool elastic structure and those generated during cutting process. The machine tool structural system is represented by two orthogonal bending modes and one torsion mode. The X-Y coordinate system is fixed with respect to the machine tool structure, and its axes are aligned with the principal modes of oscillation. As will be described later in this section, another coordinate system, tempo-spatial X-Y is used to represent the delay process and is transformed to temporal and spatial coordinates with respect to the reference system. To represent the cutting process, five dynamic force types are generated at each cutting edge. For the purpose of representing the regenerative effect that is characteristic for unstable machining, two different computational techniques have been employed. For the regenerative effect between two consecutive teeth an "extrusion" technique was implemented. The oscillations along x and y, respectively, calculated on the cutting edge of *i-1* tooth are projected to the *i* tooth and subtracted from the corresponding oscillation.

For simulation of the regenerative effect at every revolution, the arbitrary Lagrangian-Eulerian (ALE) method has been used.

At the tooth passing frequencies close to the natural frequencies of the elastic structure, resonance occurs. In the example in Figure 8a the spindle speed is 326 rev/sec so that the tooth passing frequency is close to the 980 Hz bending mode. The damping is only insignificantly changed, thus correctly representing a stable system. Meantime, the amplitude increases by two orders of magnitude.

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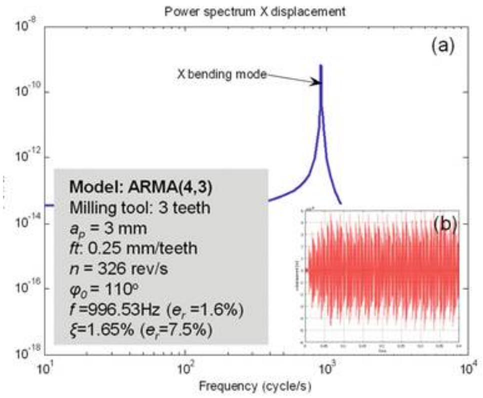


Figure 8 Power spectrum of a ARMA (4, 3) at tooth passing frequency close to 980 Hz. (b) time domain stable vibration in X direction.

The vibration pattern for the stable machining operation that undergoes resonant vibrations has quite evenly distributed amplitude. The response of an unstable PMI when the tool is in full immersion ($\varphi_0 = 180°$) is shown in figure 8.7a. The regenerative effect is produced by the chip thickness variation between consecutive teeth and between tool revolutions. The estimated damping ratio identified in an ARMA (4, 3) model drops to a very low level (0.07%), correctly identifying an unstable process.

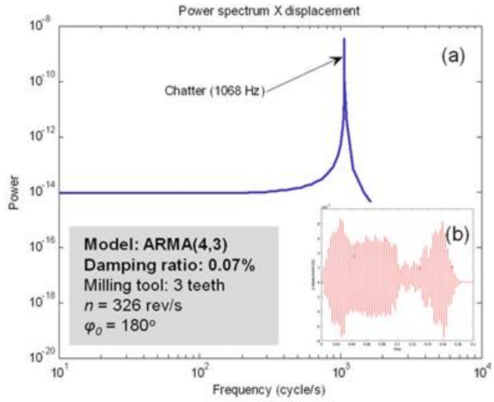


Figure 9 Parametric identification: power spectrum for unstable machining system, (b) time domain chatter as a regenerative phenomenon between consecutive teeth, vibration in X direction. The nonlinear effect due to the loss of contact between tool and work is apparent.

WP3 Machining system modeling and reuse of manufacturing experience
Reuse of manufacturing experience

Digital machine tools could allow realistic digital manufacturing simulations. 3D CAD models of parts and tools are already available in many companies today. Swedish manufacturing industry and in particular Swedish automotive industry needs access to reliable and complex information from real machining in order to model, build and validate machining systems.

Managing experience is a multifaceted challenge. Experience can be fact-based, explicitly defined as data or information, or knowledge-based with tacit dimensions. To approach this challenge a framework was developed that decomposes the versatile task of experience management. The framework identifies typical activities involved in the feedback process and recognizing barriers within the activities and in the transition between them. Entities of the “experience” and the relationship between these entities are explained. The framework can be used for improvement efforts to analyse gaps and search for corrective actions. Another application of the framework is for educational purposes, providing a common view of the feedback process and indicating important aspects in the transition of knowledge through the process.

In aero-space companies, issues regarding product modeling (smooth surfaces, geometric tolerances and modeling techniques) are a central part of the product definitions updating activities. Hence, a KBE application has been developed to support the engineer in the definition of aero blade design. Blade design is a multidisciplinary engineering design activity involving optimization within the disciplines of aero-thermal, mechanical and manufacturing. The application supports the design engineer by providing rapid generative CAD model. The figure below illustrates the user interface provided with options to include specific design tasks and change parameters within a certain design space.

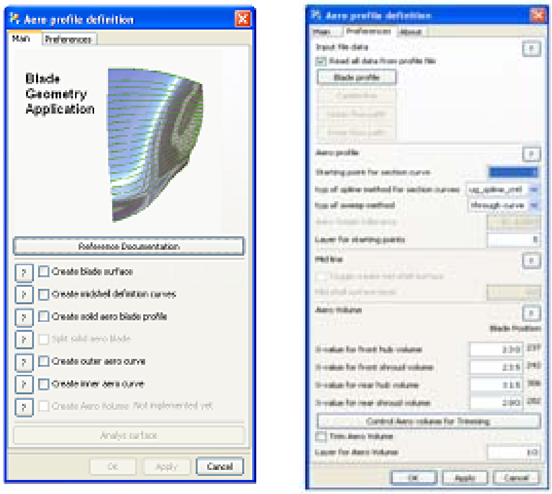


Figure 10 User interface of aero-blade application.

By adopting the framework described earlier each step was evaluated from a re-use perspective to identify weaknesses.

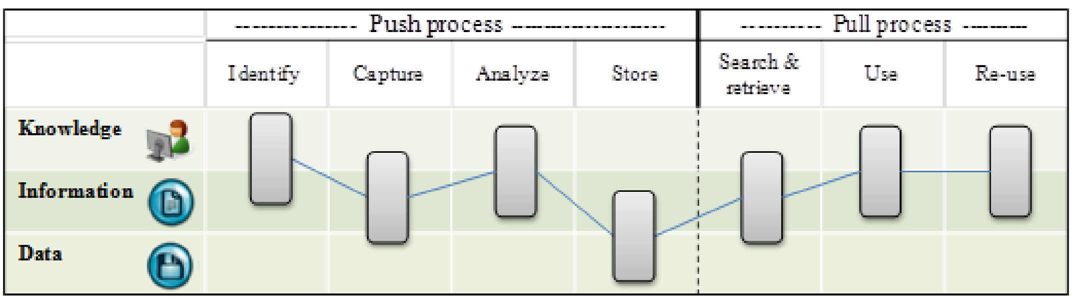


Figure 11 A document centered knowledge-information-data pattern.

Weaknesses were identified relating to the activities to “Store” as well as “Search & Retrieve”. It was found that the aero-blade application was not fully implemented (stored) in the CAD environment leading to limitations in accessing (Search & Retrieve) the application. The aero-blade application is not available in the standard CAD design engineering environment and the designer has to request for access to be able to install the application. Although there were no explicit routines for continuous improvements, a number of enhancement requests from different stakeholders in the design process have resulted in new versions of the KBE application. However, the occasions when the KBE tool failed to accomplish requested results did not always lead to a request for an update of the tool, instead informal routines were adopted to accomplish the design task and considered best practice.

40% higher productivity in production planning.

WP3 Machining system modeling and reuse of manufacturing experience
Experience feedback using social media: from the production to the design process
High-quality precision products demand tougher machining conditions and increased machining robustness. When selecting particular machining processes, designers must carefully consider a large number of factors that relate directly to the nature of the machining problem. Designers should therefore take the advantage of experience feedback (aka lessons learned) from production, which could help them in understanding the complexity in the manufacturing operations in the early phases, thereby allowing them to avoid costly mistakes. New methods and tools are required to continuously aid the designer in making decisions regarding process selection, manufacturability and reliability.

Social media tools, with their dynamic ways of interaction and sharing capabilities, represent a new way for capturing the context, tacit and experiential knowledge, enabling networking around the lessons learned. The case study has been conducted on Design Practice System at GKN Aerospace (former Volvo Aero Corporation) in order to identify solution alternatives to fostering a more continuous approach for leveraging lessons learned from production and other downstream phases. Empirical data has been collected through observations at the company and interviews with Design Practice System and product lifecycle stakeholders.

A video-based approach is proposed to lower the effort in capturing and disseminating lessons learned from production and other downstream phases to design practices. The results encompass methodology, guidelines, process description and technological enablers for continuous experience feedback to the design practices.

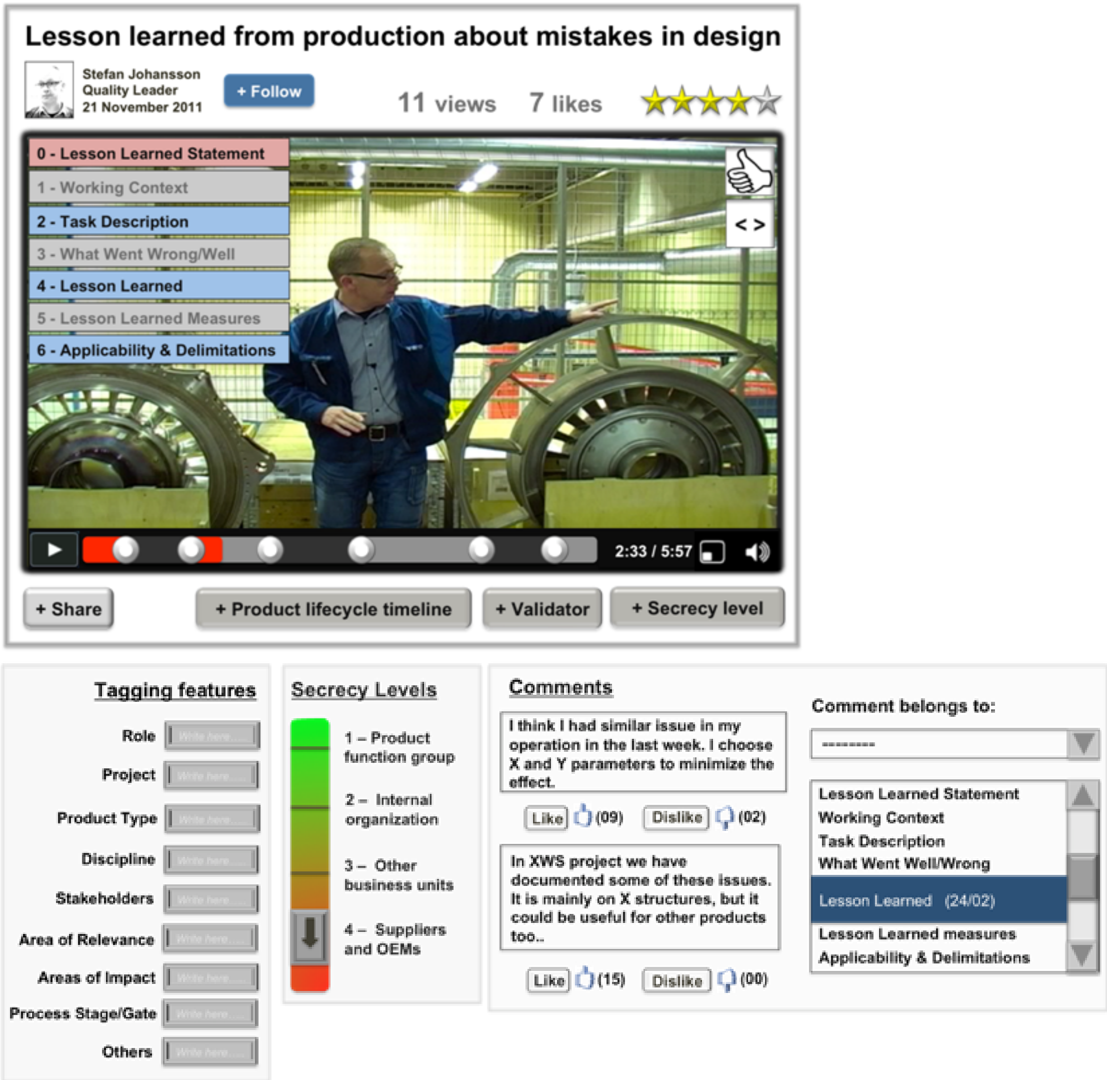


Figure 12 Video-based LL sharing prototype platform with functional interfaces of tagging, commenting and secrecy levels for enabling cross-functional knowledge sharing.

30% higher productivity in production processes.

WP2 Machining system condition testing and monitoring

Machining system condition testing

The work presented in this part of the work package deals with the static and dynamic capability of machining systems. The main focus is on the operational stability of the machining system and structural behavior of only the machine tool as well, by introducing the concept of operational dynamic parameters (ODP). In contrast to the traditional theory, this methodology allows to determine the machining system's dynamic stability, in real time under operating conditions. This framework also includes an evaluation of the static deformations of a machine tool.

Figure 13 Closed-loop dynamic machining system. The machining system represented as the interdependence of two subsystems, the elastic structure and the cutting process dynamics. The machine tool elastic structure forms the primary loop of the machining system, while the cutting process dynamics is represented as a subsystem in the feedback loop.

Within the computational framework for off-operational stability the novel concept of elastically linked system (ELS) is introduced to account for the representation of the cutting force trough an elastic link that closes the force loop. The ELS is evaluated trough a computational model based on finite element (FE). Distribution of deformations corresponding to the static stiffness can be obtained for different magnitudes and orientations of the elastic link. For evaluation of static stiffness/deformations of a machine tool a novel type of double ball bar (DBB) which has the ability to create a preload between machine tool table/workpiece and tool/spindle is introduced. The device is called loaded double ball bar abbreviated LDBB.
Recursive model-based identification is used to identify the modal parameters of the machine tool structure. From a technical point of view, the effect of the spindle rotational speed on system damping ratio is of interest. For this purpose a special contactless excitation and response system (CERS), in combination with an especially developed milling cutter, has been developed.
Summary of results:

- Operational stability of machining systems
  The stability of machining systems is operational dependent. By using parametric identification models in a recursive implementation, qualitative criteria can be used. Such a criterion is operational damping ratio (ODR). A non-conservative mechanical system with positive ODR is said to be dynamically stable, whereas one with negative ODR is said to be unstable. This gives a robust criterion for discrimination between forced and self-excited vibrations, which is not related to the vibration amplitude criterion.
- Implementation and demonstration – DSP multiprocessor system
  The recursive model identification system consists in four main modules implemented in various DSPs:
  - signal acquisition and conditioning module
  - parameter estimation module
  - ARMA power spectrum module
  - ODP estimation module.

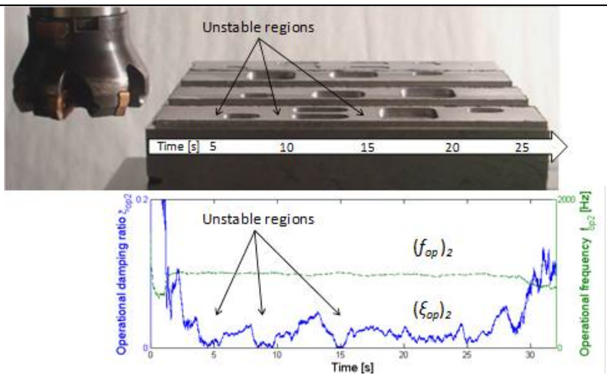


Figure 14 RARMA identification of ODP in face milling. Top, the experimental setup in which the workpiece is prepared with holes and pockets to replicate time-varying cutting condition, and bottom, tracking the variation of the second identified ODR and frequency.

- Off-operational stability of machining systems
  The ELS is configured according to two concepts; one where the cutting process is represented with an elastic element (LDBB) and the other where the cutting process is replaced by a non-contact dynamic link.
- Implementation and demonstration – loaded double ball bar (LDBB)

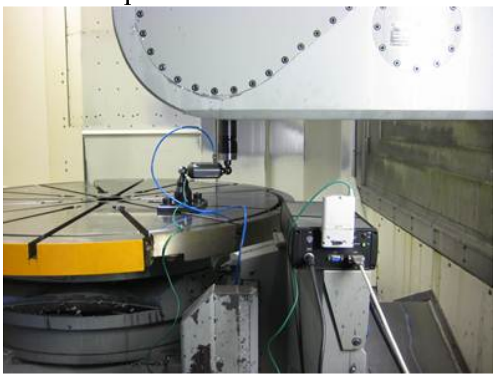


Figure 15 The loaded double ball bar system (LDBB). The LDBB is a result of a collaborative development by the two Swedish companies Scania CV AB and CE Johansson AB and KTH Royal Institute of Technology.

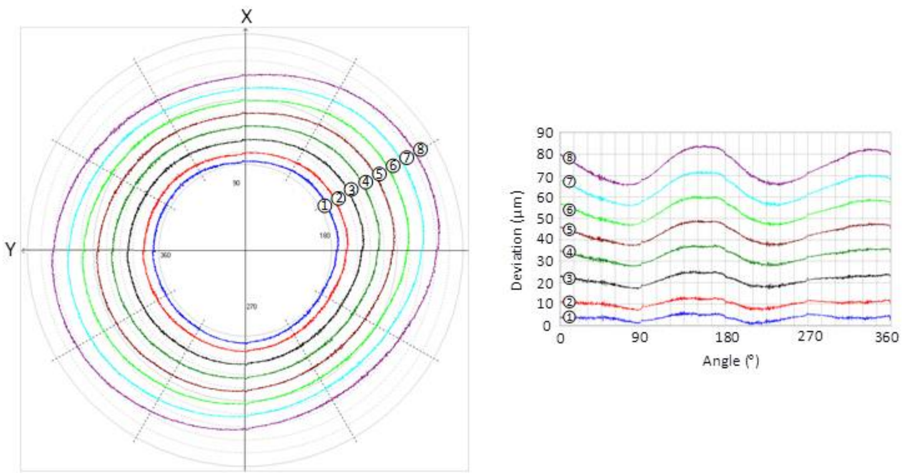


Figure 16 Deflection diagrams in X-Y plane. Deflection diagram as function of applied load P_{force}(1-8)= {36; 112;

238; 364; 490; 616; 742; 868} N, (10µm/div).

- Implementation and demonstration – contactless excitation and response system (CERS)

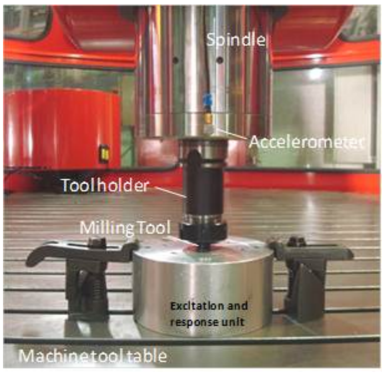


Figure 17 Contactless excitation and response system (CERS). The actuator hardware with on-board displacement sensors is clamped on the machine tool table. The specially developed cutting tool is inserted in actuator unit. The contactless excitation is done with inductive coils and the response measurements are done via displacement sensors placed 90º apart.

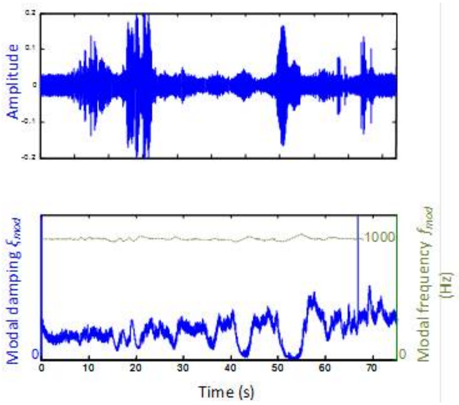


Figure 18 Damping ratio and natural frequency. RARMA-modal estimation on accelerometer signal in Y direction. Contactless random excitation.

WP2 Machining system condition testing and monitoring

Machining system condition monitoring

In this part of the work package the possibility of using a machine's internal sensors for monitoring the condition of a machine tool in operation was examined. Condition monitoring involves not only measuring as well as processing and analysis of signals, but also extracting and classifying the characteristics of the signals to be correlated with the machining process.
Research on condition monitoring of a 5-axis machining center is based on observations made from practical experiments by measuring the machine response from the angle sensor on the main spindle and from linear position sensors on both active and "passive" machine axes. Initially, a number of possible ways of measuring signals in a reliable and accurate manner were tested to reduce interference in the measured signals and avoid disturbances in the machine's internal signals. The realized measuring method and

measuring system has been developed during the project.
The main focus has been to study the responses from all the sensors positioned in forced periodic excitation of the machine system. The measured responses thus show the small displacements (vibrations) in the directions of the sensors. The fundamental characteristics of the measured signals were initially unknown. A thorough investigation of the signals occurring at different load situations was therefore necessary before a more comprehensive analysis of the signals could be implemented. The focus of the initial experiments was to investigate the response of simple load situations, such as imbalance tests on the machine's rotary table and milling of simple geometries. The experiments were systematic and repeatable. From these initial experiments a methodology to extract the essential information from the signals could then be developed.
The latter part of the work focused more on the sensitivity of the measurement method, i.e. how small changes in the process that can be detected. The impact of the tool wear on the response was considered to be particularly interesting to investigate as this tends to limit the process. Much of the work was to find a suitable methodology for characterizing the process dynamics and quantify tool wear.
Summary of results:

- Measurement of encoder signals
  Position sensors are of the type sin/cos that provides continuous interpolatable quadrature signals (90° phase shifted). Differential measurements of the signal pairs (A+, A-) (B+, B-) and (R +, R-) via the parallel bus from encoder outputs were used to avoid signal distortion.

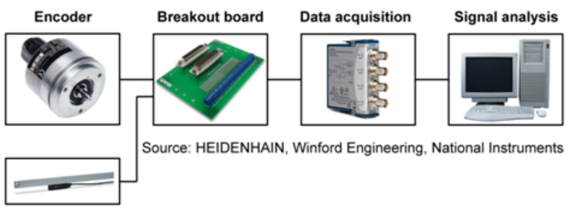


Figure 19 Measurement chain from the encoder output to the measurement computer.

- Imbalance test on turntable
  As a first step it was shown that the generated vibrations are transmitted through the encoders. This was done by an imbalance test on the turntable where an unbalance weight was placed on three different radial distances from the center of the table, whereafter the table was ramped up was from 0 to 400 rpm and the outputs of the XY axes were measured. The experiment showed that the vibration amplitude is proportional to the angle of the Lissajous figure of A and B signals. One could now realize that the position for a passive feed axis could be determined by the same method as for an active feed axis. The test also showed that the movement was greatest along the Y axis due to the machine structure. Only a small vibration amplitude was observed along the rigid X axis indicating a negligible crosstalk between these axes. The imbalance test was done with two turntables and one could see the differences in the patterns of Poincaré sections.

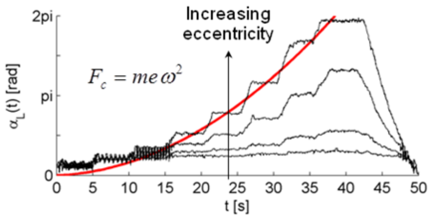


Figure 20 Measured angle in Lissajous figure with increasing eccentricity of the unbalanced weight. Increasing the table speed of 50 rpm every 5 seconds.

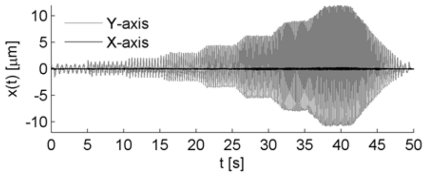


Figure 21 Calculated vibration amplitudes. Increasing the table speed of 50 rpm every 5 seconds.

- Torsional vibrations of the spindle
  The demodulation technique applied to the response of the rotary angle sensor made it possible to study the torsional oscillations of the spindle.

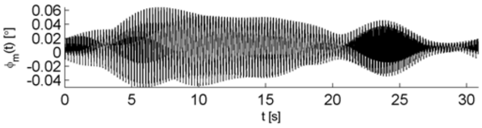


Figure 22 Torsional oscillations in the time domain for 5-toothed milling based on measurement of the encoder signals.

- Poincaré section of process dynamics
  A Poincare section is a mathematical tool for analyzing the dynamic system and is well suited for the study of dynamic systems that exhibit a periodic sequence. The major advantage is that an *n*-dimensional state space can be studied in *n-1* dimensions. The method thus provides a reduction of the dimension of *-1*. By applying non-linear analysis, a 3-dimensional state space can be created.

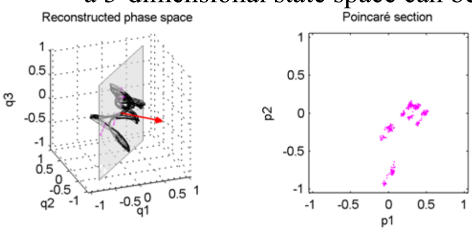


Figure 23 3-dimensional state space with a flat Poincaré plane (left) and the corresponding 2-dimensional Poincaré section (right).

- Detection of tool wear in milling
  Being able to detect tool wear during machining is very important to achieve a more robust and economical manufacturing process. The project has investigated the possibility to achieve this without connecting additional sensors. This is advantageous from an industrial perspective as this method does not involve any restrictions on the machining

process. Another great advantage is that you do not need to buy expensive sensors and avoid the cost of maintenance and calibration of sensors. The experiments have been performed on a modern 5-axis machining center. The measurement method is generic as the type of signals used can be found in all modern machine tools. By performing a blind test, where the wear rate and the position of the worn insert was unknown, with multi-teeth milling it could be demonstrated that it is possible to determine the current level of wear and identify which tooth was worn. To enable this, information on the individual inserts' angle in relation to current feed direction. In conjunction with this identification, a method (RD2P, a 2-point method with reflective sensor) to determine the position of the inserts relative to the internal reference angle of the spindle was developed. By creating so-called state spaces from the measured response during machining with different levels of tool wear it can clearly be seen that the process dynamics change with the wear level.

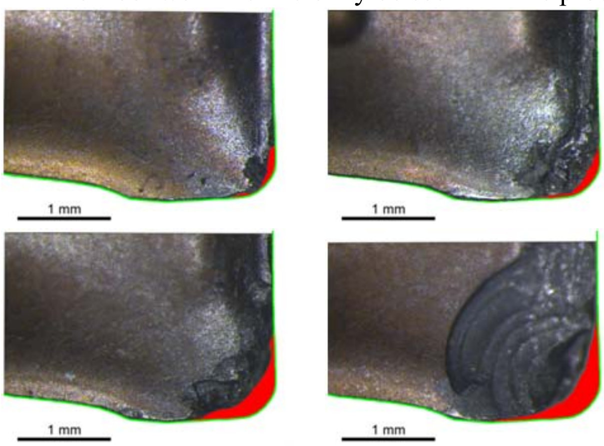


Figure 24 Different levels of tool wear.

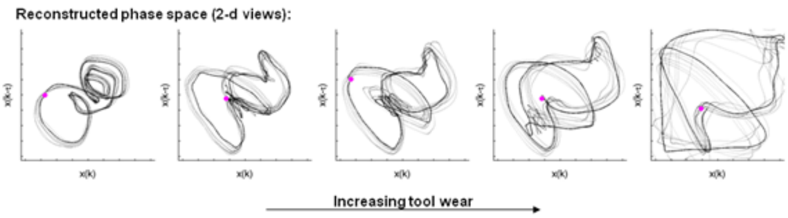


Figure 25 2-dimensional images from the state space at different levels of tool wear.

WP2 Machining system condition testing and monitoring
Reduction of vibrations during horizontal milling of aluminum parts

This work has been conducted at SAAB Aerospace, Linköping. The research aimed at vibration problem during milling operation. Vibration sets in at tool- workpiece interface if certain conditions are achieved. Research has been carried out with the purpose to reduce or eliminate chatter. Chatter decreases the dimensional accuracy and surface finish of workpiece.

Figure 26 Poor surface finish after machining.

The goal was to identify the source of vibration, then to find solution for the problem to remove or reduce the vibration. Further scope includes giving suggestions for future work in this area and also to facilitate employees to understand the issue at SAAB.
In the first step the identification of source and nature of vibration was performed. This required two experimental methods:

1) Experimental modal analysis (EMA) on aluminum parts with different thicknesses; one analysis at the thickness before machining and second analysis at the final thickness. This was done using impact test off-machining.
2) Online machining test, to identify the source of vibration.

Then finite element analysis (FEA) was done on the CAD models of workpiece to simulate the natural modes of vibrations under different circumstances. Both EMA and FEA were then correlated to be able to find a method that will utilize minimum amount of resources.
A Matlab program is also developed in meantime to calculate stability lobe diagram. This is only useful if the source of vibration turns out to be of self-excited nature.

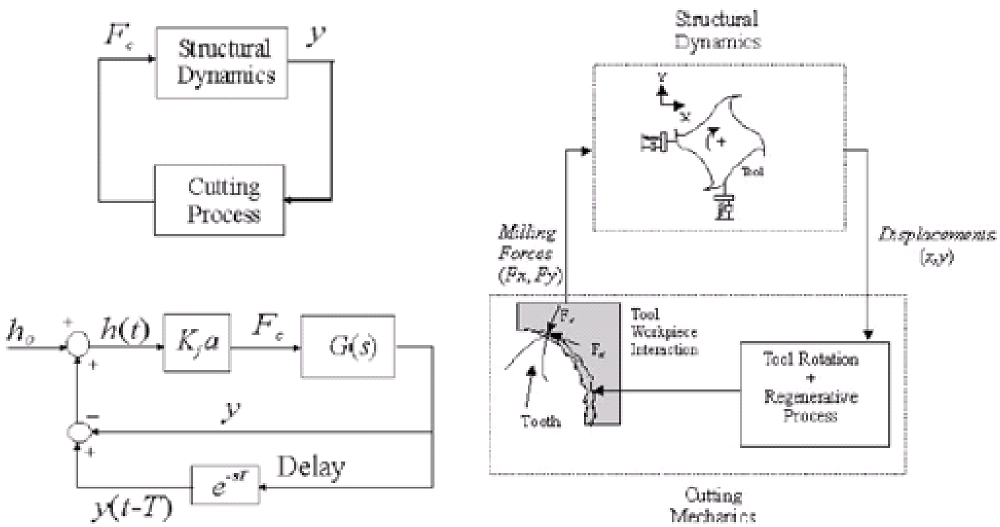


Figure 27 Dynamics of orthogonal milling operation.

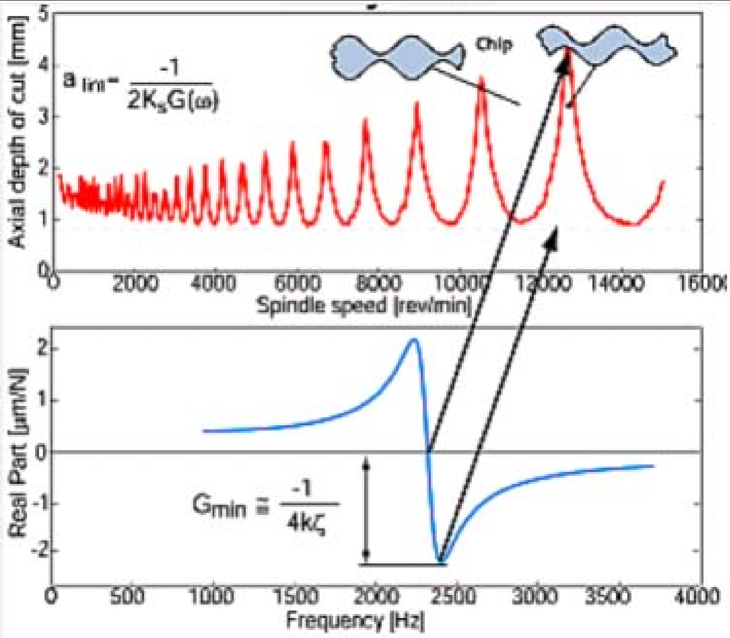


Figure 28 Stability lobe diagram.

The workpiece is made of aluminum Al-7075. Due to unavailability of exact material properties, nearest standard alloy has been used. Workpiece is mounted on solid steel revolvable fixture. Hemispherical balls are used as location devices. 10 clamps are used to fix the workpiece in place with the help of bolts to apply torque. No damping material is used in clamping.

The following steps have been done in order to perform finite element analysis:

1) Import the part geometry in Comsol 4.2a interface. Universal file format *.stp is used. Define the units of linear measurement (mm selected).
2) Select the material for the workpiece. Right selection of material is the key for acquiring optimum results. If the material selected is not available, approximate material properties can be used.
3) Next step is to apply loads and constraints on the workpiece. The 10 clamping locations on the workpiece at each side are constraints, *i.e.* $x=y=z=0$.

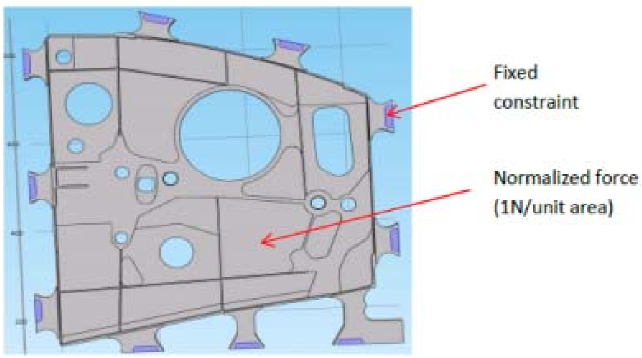
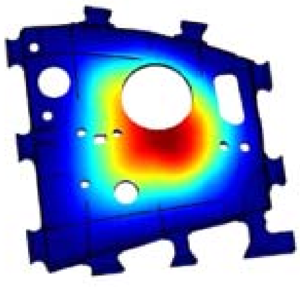


Figure 29 Load on and constraints for the workpiece.

In Comsol 4.2a (FEA) the eigen frequency study reveals the natural modes of vibrations at which the structure shows resonances if excited. Similarly in Test Lab rev 11a (EMA) the natural vibration modes are selected by viewing FRF and indicating the stable regions which shows concentration of chatter amplitude.



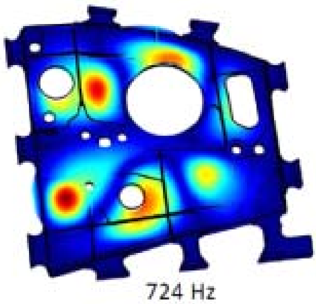


Figure 30Simulation of modes of vibration.

Results have shown strong similarities between experimental and simulation analysis. The simulation has revealed certain natural frequencies at which resonance can occur and large amplitudes can set in. Surprisingly, the same higher amplitudes are also been observed during impact testing and online machining test. This proves that the simulation could be a time saving and more efficient alternative to lengthy equipment testing procedures. Thus saving time, cost and improving overall machining process by pre-simulating the workpiece.

As shown in experiments, the frequencies with maximum amplitude are same. The first mode of vibration occurs at 147 Hz in EMA and 189 Hz in simulation. The maximum amplitude occurs at natural frequency of 726 Hz from EMA and 724 Hz with FEA simulation. These results are very close to each other, which will eventually help to find an appropriate solution.

There are two methods to control vibration in machining operations:

- changing cutting data
- introducing damping in the system.

In our case as the problem is due to resonance at tooth pass frequency, therefore adding damping will not help at all. The only solution is to move away the tooth passing frequency by changing cutting data.

Three parameters that can be controlled during machining:

- spindle speed
- feed rate
- depth of cut (DOC).

Selecting optimum spindle speed, which in turn does not excite any of the natural frequencies, is important. The FEA results from Comsol are sufficient to give a preview of the response of the workpiece, which could be used to select tooth passing frequency. The tooth passing frequency is directly proportional to spindle speed, i.e. tooth pass frequency=Nz/60.

In the future EMA will be avoided to save time and resources. Selection of spindle speeds will be done using results from FEA. As shown below, there are certain regions represented in at which there, theoretically, will be no resonance. Three stable tooth pass

frequencies should be selected and then corresponding spindle speeds should be calculated.
One way to keep material removal rate (MRR) same is by increasing the chip load while decreasing spindle speed.

RPM	No. of teeth	Tool Dia (mm)	TPF (Hz)	Feed rate (mm/min)	Cutting speed (m/min)	Chip Load (mm)
22000	2	20	733	7000	1381.6	0.159
20100	2	20	670	7000	1262.28	0.174
18000	2	20	600	7000	1130.4	0.194
15000	2	20	500	7000	942	0.233

Table 1 Constant MRR (cycle time 89 min).

Another way is to decrease the MRR thus increasing the overall cycle time. Calculations show that there will be 7.7 min increase in cycle time if we reduce the spindle speed to 20100 from 22000. And almost 16 min increase if we drop spindle speed to 18000.

RPM	No. of teeth	Tool Dia (mm)	TPF (Hz)	Feed rate (mm/min)	Extra Time (Min)	cycle time (min)
22000	2	20	733	7000	0	89.0
20100	2	20	670	7000	7.7	96.7
18000	2	20	600	7000	16.2	105.2
15000	2	20	500	7000	28.3	117.3

Table 2 Constant chip load (0.159 mm).

According to the findings as described in previous sections, the vibration source is forced excitation (tooth pass frequency) which can be eliminated by changing the spindle speed optimally.
As shown earlier there are two ways in which spindle speed will affect the MRR. An easy way is to keep MRR constant by increasing chip load (within safe zone), thus keeping same overall productivity.
It is recommended to change the spindle speed to either 20100 rpm or to 18000 rpm as both speeds are in stable cutting zone theoretically.

WP4 Improvement of dynamic stability in machine tool system and process interaction – high damping interface (HDI) system

This work package dealt with the design of machine tool components with enhanced damping capability. The ultimate objective when designing machine tool components capable of withstanding cutting instability in a passive manner is to enhance both stiffness and damping. On the other hand, these two properties are intrinsically linked to one another and the enhancement of one usually compromises the other. It is in fact well known that for the majority of machining operations it is the product of stiffness (K) and damping (δ) that determines the vibratory conditions in the system. Another aspect to take in consideration is that the overall damping ability of a complex structure, such as a machine tool, not only depends on the individual components' damping capacity but also, and more considerably, on the damping associated with joints between the very components. Thus the necessity to make use of different components of the machine tool for enhancing both K and δ.

To maintain a high level of static stiffness, it was chosen to adapt hydrostatic clamping systems to the tools. The effect of this kind of clamping system on the tool deflection is well recognized. It is common knowledge that the effective overhang of a tool has to be considered from the outmost fixed point, which is the first screw on the conventional screw clamp, and the outmost face on the hydrostatic clamp.

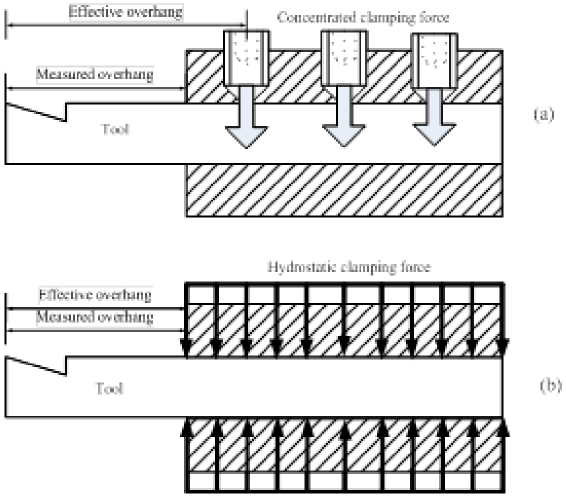


Figure 31 Comparison between conventional screw clamp (a) and hydrostatic clamp (b).

Thus the measured overhang of a tool mounted in a screw clamp does not correspond to the effective overhang. The effect of the hydrostatic clamp can be easily quantified. As the screw is usually positioned 12 mm from the end of the clamp, the effective overhang of the tool mounted in the screw clamp will be 12 mm longer than the one of the tool clamped in the hydrostatic clamp. If, for instance, a boring bar is mounted with a measured overhang of 120 mm, its deflection can be reduced by 25% by employing a hydrostatic clamp instead of a conventional screw clamp. This solution does indeed help to minimize vibration amplitude but it does not create any vibration dissipation; what is achieved with such clamping technique is an enhancement of the static stiffness. This means that it is more difficult to excite the system tool-clamp at its natural frequency but when this occurs the system will not oppose resistance. In fact, the stiffness obtained solely using such clamping system for vibration control purposes could actually result in an excessive reduction of damping ratio, defeating the purpose of reducing vibration. Therefore, it is important to be aware of it and exploit it by accompanying the clamping system to a properly designed damping system.

Interface damping is a well-known phenomenon – having been studied first by Da Vinci and later by Coulomb. Friction arises whenever two, or more, surfaces are in contact and participating to a vibratory movement and this friction eventually translates into damping. High damping interfaces (HDI) are intentionally introduced interfaces where the damping ratio is enhanced by introduction of viscoelastic (VE) polymer metal composites between the two metallic surfaces composing the interface. As every vibratory mode is characterized by its own damping ratio (and natural frequency), the HDI is effective in those modes where the mode shape involves the HDI, i.e. when the VE polymer composite experience shear strain. Therefore the positioning of such interface is of vital importance.

Another important issue to consider when designing a HDI is the mechanical impedance between coupled structural elements which control the energy flow path through the structure. It is important that most of the energy flows through the damper. If the energy has an alternative path of propagation with lower mechanical impedance, the energy will by-pass the damper. For this reason, the damping interface should be the only structural component in the energy flow path.

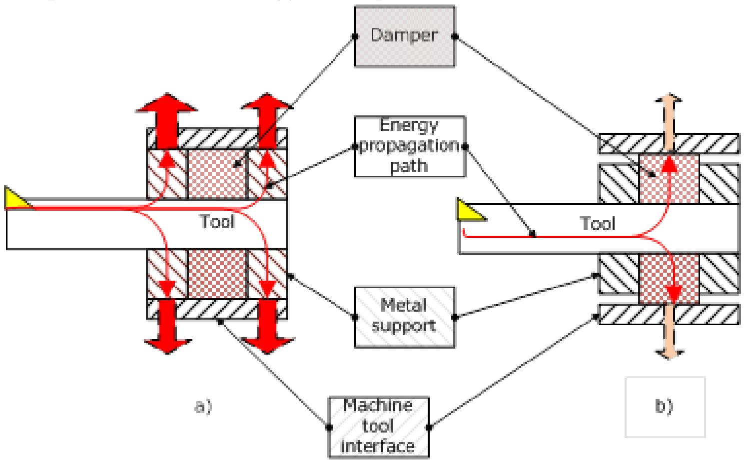


Figure 32 Energy propagation paths. (a) Bypass through metal-to-metal contact. (b) No bypass, energy flows through damping material.

The figures below shows the joints treated in the CNC-lathe structure and the concept adopted for implementing the HDI in the turning tool holders.

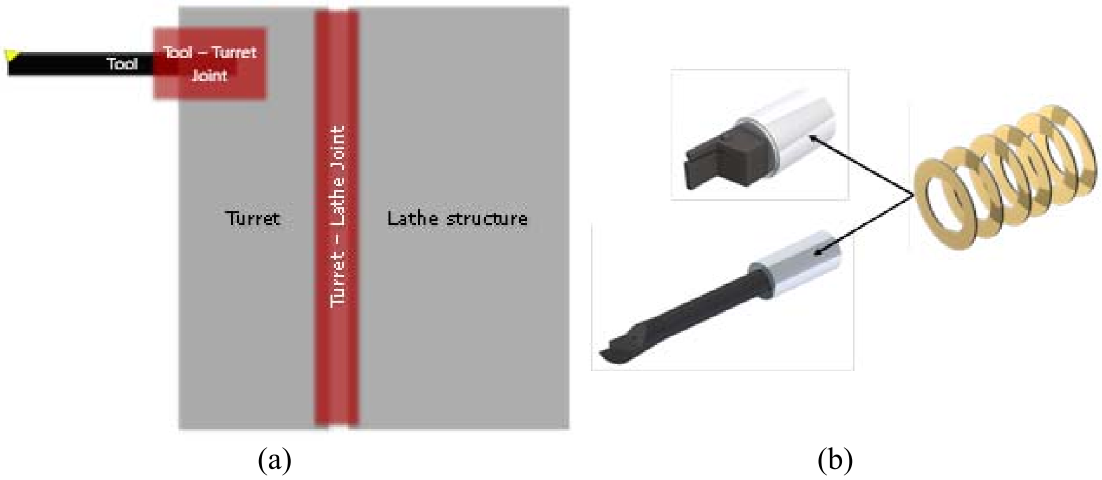


Figure 33 (a) Joints treated in the CNC-turning centre. (b) Multiple layers of VE polymer metal composite plates implemented in the parting-off tool and in the boring bar.

The adoption of the HDI concept allows to machine in stable conditions at three times higher depth of cut than a conventional system, as illustrated in the figure below.

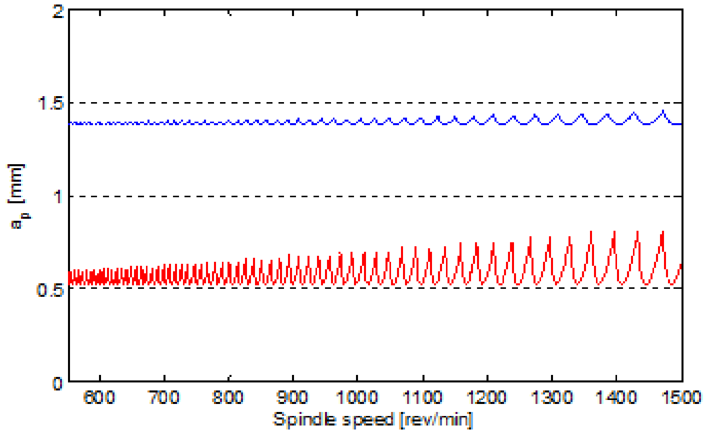


Figure 34 Stability limit diagram for conventional tool (red) and HDI-tool (blue).

The figure below shows that the HDI concept is able to produce an impeccable surface roughness at any of the tested cutting parameters. From the industrial application point of view, the presented concept allows the end user to select the most suitable parameters in terms of productivity avoiding the hassle of tuning the devices, having to acquire a deep knowledge in structural dynamics or having to use additional control systems. In addition to this, the enhanced machine tool system becomes less sensitive to stability issues provoked by difficult-to-machine materials or even fluctuations of the work material properties that might occur in everyday production processes. This solution enables higher removal rates with unchanged or even improved machining performance, reducing energy and material waste at the same time, as one might carry out grossing and finishing in only one pass.

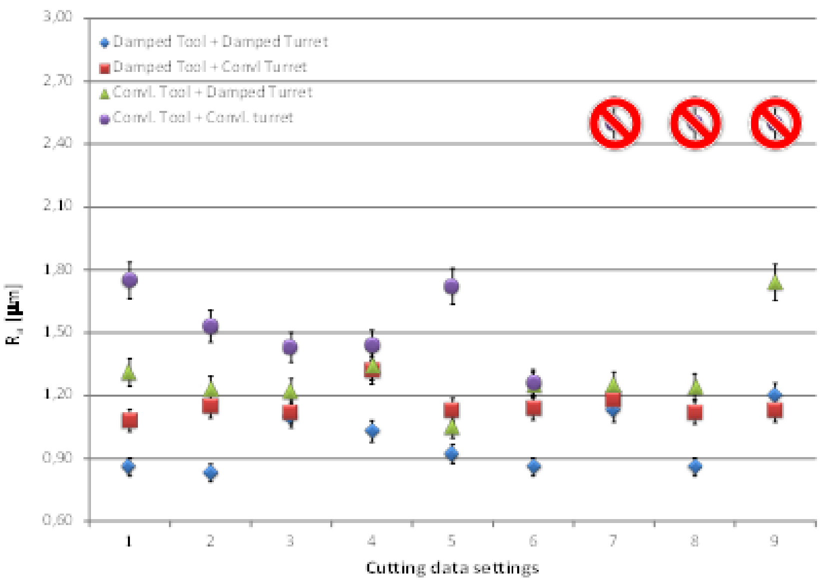


Figure 35 Machining test results, surface roughness. Comparison between the conventional tool clamped in conventional turret and in the damped turret, as well as the damped tool clamped in the conventional turret and in the damped one. The conventional tool clamped in the conventional turret could not perform at setting 7, 8 and 9 due to excessive instability.

6. Dissemination and publications

6.1 Knowledge and results dissemination

Inspired by the gear project, FFI Sustainable gear transmission realization and the gear network, a new two day concept was introduced for the last robust meeting:

- Day 1 late afternoon and evening: steering group meeting followed by a robust dinner.
- Day 2 morning and early afternoon: plenary robust meeting with presentations from researchers in the project and company partners as well as invited speakers from both Swedish and international research organizations and companies.
- Day 2 afternoon: company tour or lab visit.

This new robust meeting concept is intended to be a tradition and is considered as an important networking as well as knowledge and experience transfer activity. Hopefully, it will be maintained in the new FFI COMPIT project as well as in FAV – Forum för användare av verktygsmaskiner (http://www.kth.se/itm/fav).

The project results are also reported in a wiki: http://130.237.56.41/mediawiki/index.php/FFI_Robust_machining.

6.2 Publications

Andersson, P, 2011, Support for re-use of manufacturing experience in product development: from an aerospace perspective, doctoral dissertation, Luleå University of Technology, Luleå, Sweden, ISBN (print) 978-91-7439-257-9

Andersson, P, Larsson, T & Isaksson, O, 2011, A case study of how knowledge based engineering tools support experience re-use, Research into Design: Supporting Sustainable Product Development, Research Publishing Services, Bangalore, India

Andersson, P, Isaksson, O, 2010, Reuse of manufacturing experience to support development of product/service systems, Industrial product-service systems (IPS²): proceedings of the 2nd CIRP IPS² Conference, Linköping University, Linköping, Sweden

Alsyouf, A M, 2010, Dynamic Characterization of Turrets with Enhanced Damping Capability, student paper, KTH Royal Institute of Technology

Archenti A, Nicolescu, C M, Casterman G, Hjelm S, 2012, A new method for circular testing of machine tools under loaded condition, 5th CIRP Conference on High Performance Cutting, Zurich, Switzerland

Archenti A, Nicolescu C M, Lundholm T, 2012, Virtual Machining System Engine for Simulation of Process Machine Interaction, Modern Machinery Science Journal, March 2012, pp 310-314

Archenti, A, 2011, A Computational Framework for Control of Machining systems Capability – From Formulation to Implementation, doctoral dissertation, KTH Royal Institute of Technology, Stockholm, Sweden, ISBN 978-91-7501-162-2

Archenti, A, 2011, Projektrapport, utböjningsmätning samt beräkning av statiska styvheten i DyE – Saab Aerostructures, Linköping, Sweden

Archenti, A, Daghini, L, Österlind, T, Lundholm, T, 2011, Projektrapport, Testning av kuggbearbetningssystems dynamiska egenskaper – Scania CV AB, Avdelning DX, Södertälje, Sweden

Archenti, A, Nicolescu, C M, Lundholm, T, 2011, Virtual machining system engine for validation of real-time identification schemes, Proceedings of the 2nd International conference Newtech on Advance manufacturing engineering, pp 189-194, Brno, Czech Republic, ISBN 978-80-214-4267-2

Archenti, A, Nicolescu, C M, Lundholm, T, 2011, Finite element modelling and analysis of time-varying dynamic stability in milling system, 4th International Swedish production symposium, Lund, Sweden

Archenti, A, Österlind ,T, Nicolescu, C M, 2011, Evaluation and representation of machine tool deformations, Journal of Machine Engineering, vol 11, no 4, pp 105-117

Archenti, A, 2010, Preliminära resultat från bearbetningsexperiment i DYE: bearbetning av kompositstrukturer, SAAB Aerostructures, Linköping

Archenti, A, Daghini, L, Nicolescu, C M, 2010, Recursive estimation of machine tool structure dynamic properties, CIRP 4th International Conference on High Performance Cutting, Gifu, Japan, , ISBN 978-4-915698-03-3

Archenti, A, Nicolescu, C M, 2010, Recursive estimation of operational dynamic parameters in milling using acoustic signals, CIRP 2nd International Conference on Process Machine Interactions, Vancouver, Canada, ISBN:978-0- 9866331-0-2

Archenti, A, Nicolescu C M, 2009, Model-based identification of manufacturing processes operational dynamic parameters, International Conference on New Technologies in manufacturing NewTech, Galati, Romania

Bertoni, M, Larsson, A, Ericsson, Å, Chirumalla, K, Larsson, T, Isaksson, O, Randall, D, 2012, The Rise of Social Product Development, International Journal of Networking and Virtual Organisations (IJNVO), vol 11, issue 2, pp 188-207

Chirumalla, K, Bertoni, A, Ericsson, Å, Isaksson, O, 2012, Knowledge Sharing Network for Product-Service System Development: Is it atypical?, 4th CIRP International Conference on Industrial Product-Service Systems (IPS2), Tokyo, Japan, pp 109-114

Chirumalla, K, Johansson, C, Bertoni, M, Isaksson, O, 2012, Capturing and Sharing Lessons Learned across Boundaries: A Video-based Approach, 20th European Conference on Information Systems, Barcelona, Spain, Paper 236. http://aisel.aisnet.org/ecis2012/236

Daghini, L, 2012, Improving Machining System Performance through Designed-in Damping, doctoral dissertation, KTH Royal Institute of Technology, Stockholm, Sweden

Daghini, L, Archenti, A, Nicolescu, C M, 2010, Design and dynamic characterization of composite material dampers for parting-off tools, XXI CIRP Knowledge Based Manufacturing Conference, 15-18 mars 2010, Karpaz, Poland and Journal of Machine Engineering, vol 10, no 2, pp 57-70

Daghini L, Nicolescu C M, 2010, Influence of the join system turret-boring bar on machining performance of the cutting process, CIRP 2nd International Conference on Process Machine Interactions, Vancouver, Canada, ISBN:978-0-9866331-0-2

Dong, H D, 2011, Characterization of machine tool components for drilling operations with intergrated damping system, degree project in production engineering management, second level, KTH Royal Institute of Technology

Hedlind M, Klein L, Li Y, Kjellberg T, 2011, Kinematic structure representation of products and manufacturing resources, Proceedings of the 7th CIRP-Sponsored International Conference on Digital Enterprise Technology, Athens, Greece, 2011, ISBN 978-960-88104-2-6

Hedlind, M, Lundgren, M, Archenti, A, Kjellberg, T, Nicolescu, C M, 2010, Manufacturing resource modeling for model driven operation planning, CIRP 2nd International Conference on Process Machine Interactions, Vancouver, Canada, ISBN:978-0-9866331-0-2

Krajnik, P, Archenti, A, Pusavec, F, Nicolescu, C M, Kopac, J, 2010, Investigation of Cryogenic Cooling Lubrication Effect on Machining System Operational Damping Ratio using Acoustic Signal, CIRP 4th International Conference on High Performance Cutting, Gifu, Japan

Krogstie, L, Andersson, P, 2012, A case study on reuse of manufacturing knowledge: comparing defence practices with automotive & aerospace practices, 45th CIRP

Conference on Manufacturing Systems: Innovation: the challenge for the manufacturing of the future, Elsevier, Procedia CIRP, vol 3, pp 330-335

Li Y, Hedlind M, Kjellberg T, 2012, Kinematic error modeling based on STEP AP242, 1st CIRP Sponsored Conference on Virtual Machining Process Technology, Canada

Li Y, Hedlind M, Kjellberg T, 2011, Implementation of kinematic mechanism data exchange based on STEP, Proceedings of the 7th CIRP-Sponsored International Conference on Digital Enterprise Technology, Athens, Greece, 2011, ISBN 978-960-88104-2-6

Repo, J, 2012, Condition Monitoring in Machining Using Internal Sensor Signals, doctoral dissertation, KTH Royal Institute of Technology, Stockholm, Sweden, ISBN 978-91-7501-128-8

Repo, J, Pejryd, L, Beno, T, 2012, Measurement method for the identification of individual teeth in milling operations. CIRP Journal of Manufacturing Science and Technology, volume 5, issue 1, pp 26–32

Repo, J, 2010, Condition monitoring of machine tools and machining processes using internal sensor signals, licentiate thesis, KTH Royal Institute of Technology, Stockholm, Sweden

Sandberg, M, Tyapin, I, Kokkolaras, M, Isaksson, O, Aidanpää, J-O, Larsson, T, 2011, A knowledge-based master-model approach with application to rotating machinery design, Concurrent Engineering: Research and Applications, vol 19(4), pp 295-305

Österlind T, 2011, Investigation of Vibrations During International Turning – An Experimental and Numerical Study, examensarbete inom industriell produktion, avancerad nivå, KTH Royal Institute of Technology

Österlind, T, Archenti, A, Nicolescu, C M, 2012, Improvement of gear cutter dynamics by use of acoustic imaging and high damping interface, CIRP 3nd International Conference on Process Machine Interactions, Nagoya, Japan

Submitted:

Bertoni, M, Chirumalla, K, Johansson, C, 2012, Improving knowledge sharing practices in product design: Where do social media matter the most?, Journal of Enterprise Information Management, submitted September 2012

Chirumalla, K, 2012, Managing Knowledge across Boundaries: Connecting the Web 2.0 Approach to Product-Service System Innovation, Research-Technology Management Journal, submitted June 2012

Chirumalla, K, Bertoni, M, Johansson, C, 2012, Experience feedback using social media: from the product lifecycle phases to the design practices, 5th CIRP Conference on Industrial Product-Service Systems, submitted

Repo, J, Pejryd, L, Beno, T, 2011. Detection of tool wear in milling using internal encoders of machine tool, Part II – Phase space methods, CIRP Journal of Manufacturing Science and Technology, submitted 2011-09-20

Repo, J, Pejryd, L, Beno, T, 2011, Detection of tool wear in milling using internal encoders of machine tool, Part I – Spectral methods, CIRP Journal of Manufacturing Science and Technology, submitted 2011-09-15

Repo, J, Pejryd, L, Beno, T, 2011, Detection of tool wear in milling using internal encoders of machine tool, Part I - Spectral methods, International Journal of Machine Tools and Manufacture, submitted 2011-04-01

7. Conclusions and future research

The knowledge and the experiences obtained from the project in parallel with new industrial demands have laid the foundation for formulating new challenges in the new project FFI COMPIT (Characterization of machining systems and performance improvement technologies). The main goal for FFI COMPIT is to provide Swedish automotive industry with innovative methodologies and industrial tools to assess and control the capability of machining systems that are the building blocks of all manufacturing systems. The ultimate objectives of these developments are both to increase the throughput of existing production lines and enable the industry to machine new high strength materials which form the basis of the next generation high performance automotive vehicles.

8. Participating parties and contact person

The project partners are listed below.
Academic: KTH Royal Institute of Technology, University West and Luleå University of Technology
Automotive: Scania and Volvo (Volvo Aero Corporation/GKN Aerospace)
Automotive subcontractor (Fordonskomponentgruppen, FKG): Leax

Other companies: ETP Transmission, Mircona, Saab and Spirex Tools

Project leader: Thomas Lundholm, KTH Royal Institute of Technology,
thomas.lundholm@iip.kth.se, +4687906381