“Advanced Hybrid Mechatronic Materials for ultra precise and high performance machining systems design”

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FINAL TECHNICAL REPORT

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1. TECHNICAL OVERVIEW

The HyMM research is focused on new materials for macroscale applications in machine tools area to reach a full and deep integration between structural and mechatronic parts of the machines in order to get an “unicum” solution able to achieve all the required performances.

Therefore, the primary goal is to achieve cost-effective structural solutions consisting of a new class of ***“hybrid mechatronic material***” based on ***smart and multifunctional composite materials*** and capable of performing a wide set of multiple functions ranging from high and adaptable damping and stiffness characteristics to more demanded new requirements (such as structural and measuring/active-control function), in order to achieve **extremely** high dynamic/thermal stability required in **extremely** fast and high precision machining.

The main expected benefits coming from the follow-ups of the above mentioned results will be:

- reduction of part weight of more than 50÷70%;
- increase damping capacity of 10 times;
- reduction of electric power consumption (due to ultra-light structures) of 50÷60%;
- reduction of machine noise emission of 3÷5 dB;
- improved quality of the machined workpiece;
- reduction of environmental impact of ultra-light machine life cycle.

The scientific and technical workplan, the main project output and milestones

The proposed programme is divided into 8 interrelated **workpackages**:

- WP1: *Investigation and research on Basic Materials*
- WP2: *Development of Smart Composite Materials with multifunctional and adaptive features*
- WP3: *Development of technologies for multi-function integration and control*
- WP4: *New simulation and modelling techniques including Life Cycle Analysis (LCA)*
- WP5: *Development and integration of Hybrid Mechatronic Systems (HyMM demonstrator)*
- WP6: *Testing, qualification and validation of HyMM demonstrator*
- WP7: *Innovation-related activities*
- WP8: *Project management*

The main expected **results** and related **milestones** are reported below:

- M1: *Outcomes of basic materials RTD*: advanced basic materials to develop smart composite structures or machine tools applications will be identified and characterised.

- M2: *Innovative adaptive structure prototype*: a critical machine part designed, built and validated (test bench) using new smart composite structures and adaptronics concepts.
- M3: *Prototype of Hw&Sw modules* enable to integrate multifunctional features and perform efficient electronic control of smart structures.
- M4: *Modelling and Simulation techniques* for virtual evaluation of performances of smart mechatronic structures. The simulation methodology has been preliminarily validated through numerical-experimental results comparison related to smart-part prototype developed in WP2.
- M5 *HyMM demonstrator*: consisting of a mobile machine axis morphology (of a ultra high speed milling machine, for dies&mould machining) which includes smart mechatronic structure and related control Hw&Sw modules, enable to reach ultra-high precision and dynamic performances.
- M6 *Final Validation of HyMM*: through qualification test aimed at verifying that expected results are achieved both in terms of weight reduction, increased accuracy/performances, and cost-effectiveness.
- M7: *Innovation-related activities reports* which address the aspects related to the exploitation and dissemination activities and a full socio-economic evaluation of the project results.

2. SUMMARY OF THE SPECIFIC OBJECTIVES

In the M0÷M42 timeframe, HyMM project concluded the RTD works related to all the WPs.

A summary of the work carried in each workpackage during the reference period and the related results is included below:

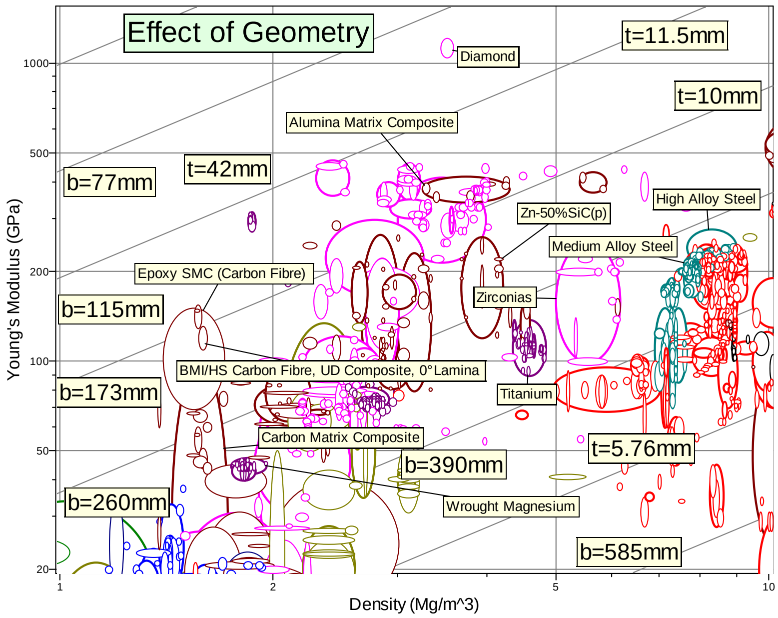
➨ WP1

Investigation of advanced solutions for structural materials to increase damping capacity and stiffness/weight efficiency.

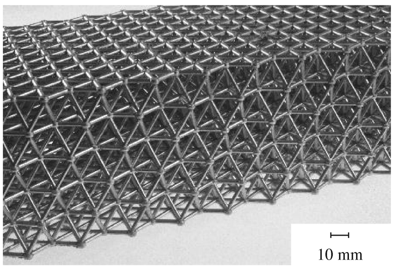
The importance to have light-damped structural design is related to get improvements in the dynamic behaviour in the range 0÷50Hz. Here the purpose was to achieve high Kv factor (gain of position loop of CNC machine) which in turn means to reduce “contouring errors” during machining while increasing acceleration (and Jerk) of the machining cycle (increase productivity!). The basic requirements of light weight/structural passive solutions are reported here below:

- reduction of weight of RAM structure of 50÷70% compared to the conventional cast iron solution;
- keep or increase the static stiffness of Ram;
- respect the geometric constrains;

- maximise the damping (5÷10 times more than the structural damping of Ram in cast iron);
- minimise the cost.



After all the investigations, the conclusions led to the adoption for HyMM project of structural solutions based on CFRP with UHM (Ultra-High Module carbon fibers having Young Module E>700 Gpa) and sandwich panels with metallic lattice cores (both materials have been used to design and develop smart active morphing samples within WP2).

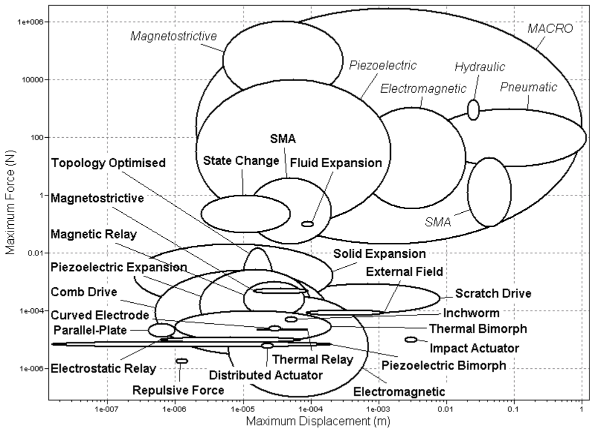


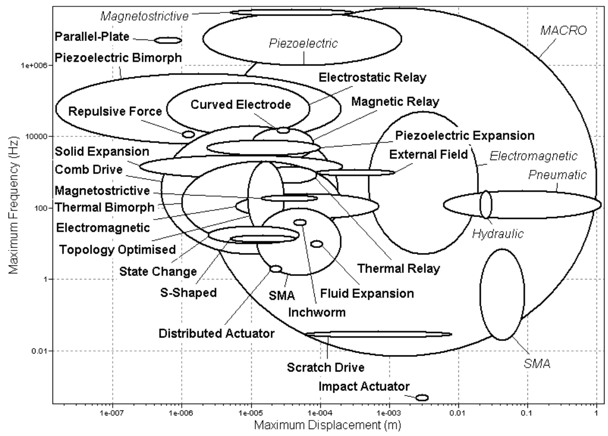
Lattice core

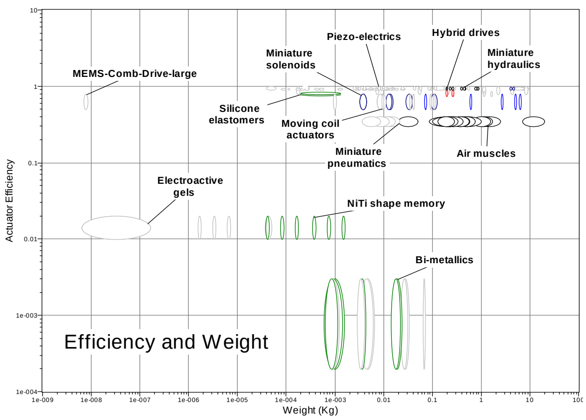
Within this WP a wide investigation on smart materials for actuators and smart sensors and their classification on the basis of features and performances expected (for potential applications for adaptive structure in machine tools sector) have been done as well.

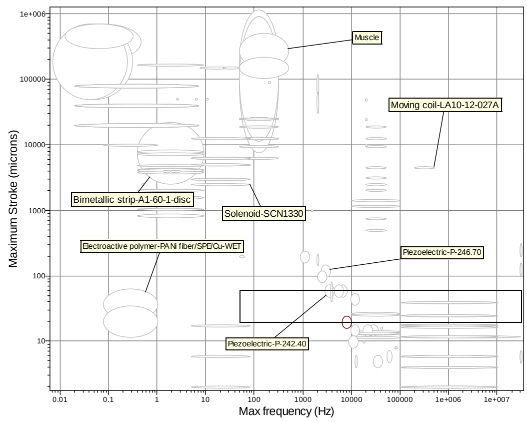
This investigation regarded a wide range of materials typology: Piezoelectric, Piezostrictive, Piezo-fibers composite, Piezo-films, Shape Memory Alloys (SMAs), Magnetostrictive materials, Magnetorheological Fluids (MRFs) and Fiber Optic sensors.

The use of such smart actuators/sensors is foreseen for improving machine dynamic behaviour at medium-high frequency domain, 50÷500 Hz range (e.g. active vibration suppression/active damping) and also for applications in machine thermal control (to reduce thermal error effects during machining operations).









A deep iteration process and analysis have been run by imposing proper criteria to satisfy the strict requirements to be applied in high performance machine tools, in particular max. forces, operative frequency, max. displacement, stiffness, dimension, weight/efficiency, resolution,…

➡ WP2

Within this WP several concepts have been developed, the most interesting ones regarded the following:

- PZT actuators located spindle flange elements for AVC (Active Vibration Control) => Smart Platform;
- A robust and low-cost displacement sensor to measure actuators stroke with sub-micron resolution and high frequency bandwidth => (Smart Disc Sensors based on PZT thin film);
- Active PZT Fibers Composite (AFC) based on piezo-active fibers embedded in Polymeric Matrix composite (e.g. CFRP);
- Hybrid smart composites based on PZT ceramic foils and Shape Memory Alloys (SMAs) wires embedded in Fiber Reinforce Polymer (FRP);
- Active morphing structure based on lattice materials;
- Morphing structure based on Shape Memory Polymer (SMPs) sandwiches;
- Multifunctional low-density syntactic foams (3-phase polymeric foams with hollow glass microsphere, to be used as damping filler in smart structures);
- Novel Magnetic Rheological Fluids (MRFs) and Magnetic Rheological Elastomers (MREs) with tuneable properties (damping vs. stiffness) for innovative adaptive vibration control concept;
- Smart composite plate embedding fiber optic sensors (FBGs Fiber Bragg Gratings) for thermal monitoring and compensation of structure;

A short description of each of the new smart concept and sample are reported here below.

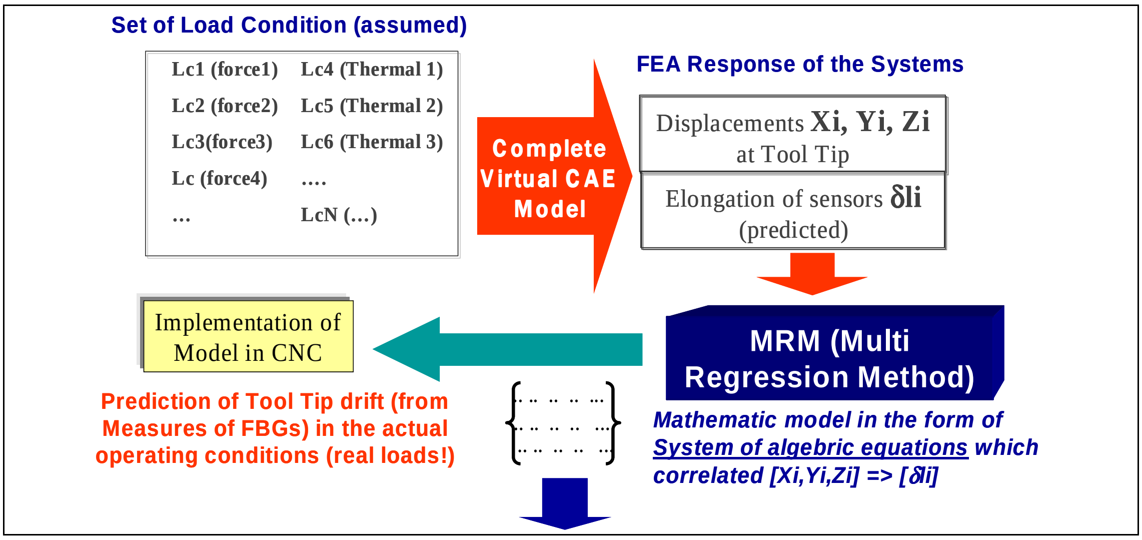
➡ WP3

Prototypes of novel low cost and compacted high voltage PZT driver/amplifier has been developed and tested. Data logger and control SW have been completed too.

This device provides the necessary power with a range of voltage of: 0÷1000 Volt. Its dimensions have to be as small as possible to permit its integrations into the smart devices. The sinusoidal 8 kHz PWM implemented is able to give a 0.01 mm range to the platform dynamics up to 200 Hz. Some problem related to the noise emission in the initial version have been definitely solved.

Finally the algorithms for real-time compensation of thermal errors based on FBGs optical sensors and MRM (Multi-Regression Model) have been developed. This model is an advanced mathematical statistical model which consists of a system that correlates the sensor measurements with the tool tip drift. The coefficients of the prediction models are calculated (through regression techniques) starting from the FEA static and thermal model of Ram (see WP4 result description), imposing different load conditions that represent as much as possible the actual working loads, and reading the virtual displacements of FBGs sensors.

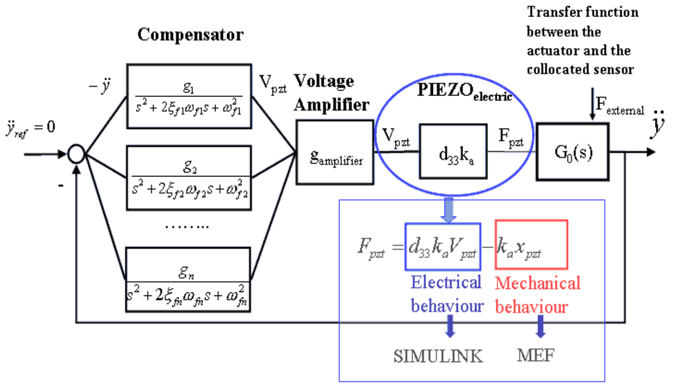
Here below the overall approach is schematically reported



➨ WP4

Within this WP methodology for modelling the behaviour of a complete adaptronic structure has been developed. An adaptronic system is composed by the mechanical structure, the smart sensors, the smart actuators, the controller board and the electronic components (such as the amplifiers) that assure the working of the whole system. The modelling of the whole adaptronic system has been done in the software tool called SIMULINK^{TM}, a toolbox of MATLAB^{TM} , importing the "reduced order model" matrix of the mechanical structure from FEA tools.

The model was focused on simulation of piezoelectric materials, sensors and controllers integrated in the loop.



The electrical behaviour of the PZT fibers and foils has been modelled in FE environment. Electrical field has been modelled as an external temperature and the piezoelectric coefficient has been modelled as a thermal expansion coefficient. In this way, it has been possible to simulate in FEM the coupled (electrical + mechanical) behaviour of the PTZ fibers and SMA as well.

These refined models have been used to predict and optimise the behaviour of smart composite samples defined and developed in WP2.

➡ WP5

The design of a new adaptive Ram which integrates smart optical fibers FBG for thermal error compensation (HyMM Demonstrator) of HSC milling machines has been provided.

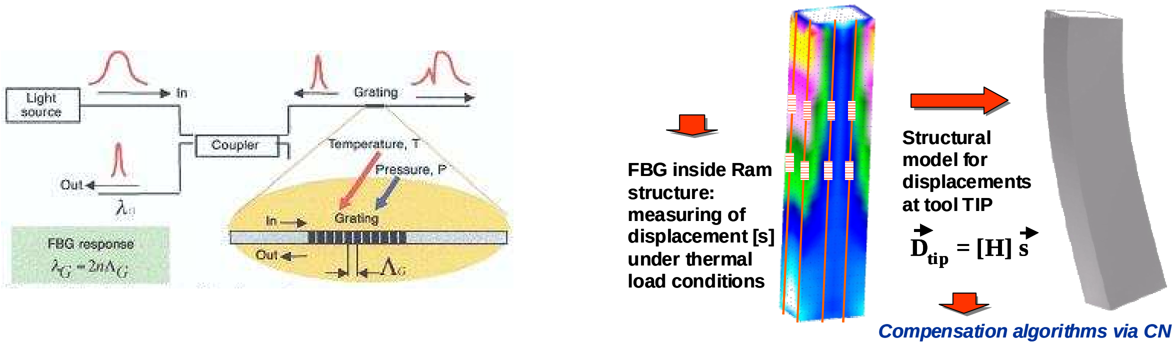
Concept of HyMM demonstrator: CFRP solution

The sample is composed of two parts: the passive and the active solutions.

- Passive structure: CFRP (Carbon Fibers UHM), circular section.
- Active: **Smart thermal measuring device based on optical fibers sensors** (FBG) plus (eventually) Active Vibration Control (Smart Platform).

The FBG fiber-optics have been integrated in the Ram structure in order to measure the total axial elongation of each side of the structure (due to combined static and thermal loads). These on-line measures will be used as input in a structural mathematical model of the part that will predict the drift (in the three space direction) of the tool tip. The outcome will be an algorithm (matrix of thermal drift errors, developed in WP3) that is read by the CNC to compensate in real-time the position of tool tip under working conditions.

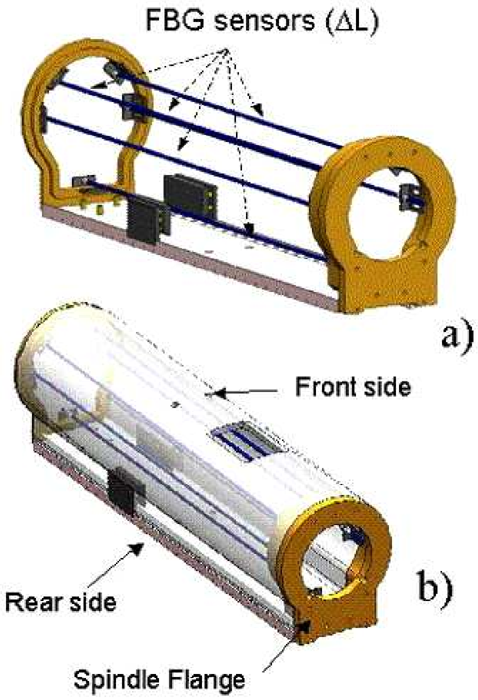
The picture here below shows the basic principle of this concept.



Concept of FBG application

The smart Ram solution has been studied and the preliminary design has been concluded.

The material configuration is reported here below.



The ram is a very critical part regarding thermo-structural behaviour, especially in precise HSC milling machine for dies and moulds machining.

These *on-line* measures will be used as input in a structural mathematical model of the part that will predict the drift (in the three space directions) of the tool tip.

The outcome will be an algorithm (in a form of linear equations) that is put into the CNC to compensate in real-time the position of tool tip under working conditions.

The Fidia machine on which, in the future, the Ram will be integrated is a 3-axis milling machine for high speed machining of 3D complex shape products (e.g. dies and mould) where high accuracy and finishing standard of parts are strictly required.

A static and modal analysis has been carried out to evaluate global structural performance of the smarty structure.

The static behaviour of the Ram using basic CFRP solution is quite good (Kx: +21%, Ky: +50%) and the mass decreasing meets the goals (-52%).

This results can be considered acceptable as, according to past experiences, the actual stiffness of the structure is approximately 10÷20% (average estimation) less than the FE calculated one. The thermal behaviour, as expected, is quite critical due to the effects of aluminium plate (guide support) placed on the back of the RAM (thermal drift DY = 0.09 mm is quite high).

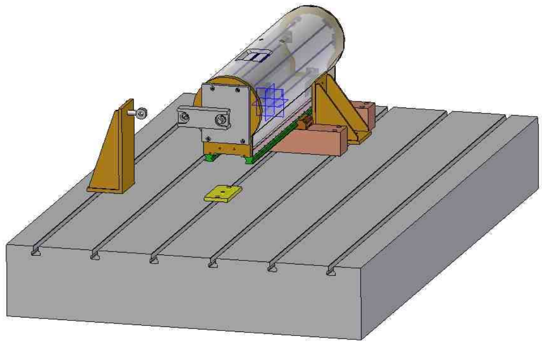
To mitigate these errors the FBG fiber-optics sensor have been integrated (as previously described) to predict and compensate the tool tip drift.

The algorithms for real-time compensation of thermal errors (starting from FBGs optical sensors measures) are based on a novel sophisticated MRM (Multiple-Regression Model) that have been developed in WP3.

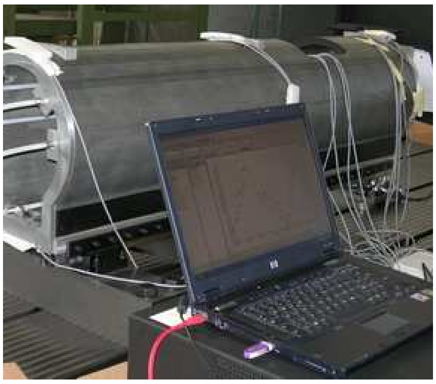
The HyMM prototype have been finally manufactured and assembled.

The test-bench have been designed and setup.

The characterization/validation test of HyMM prototype have been done in WP6.

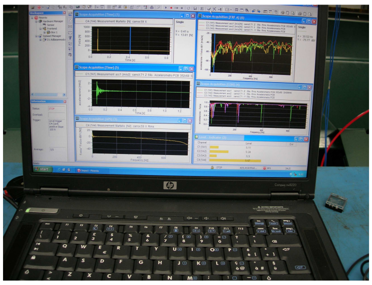


Test-bench model



Test-bench setup

Reading Unit for optic fiber sensors



Acquisition systems for experimental Modal Analysis

❑ WP6: Characterisation test on HyMM demonstrator

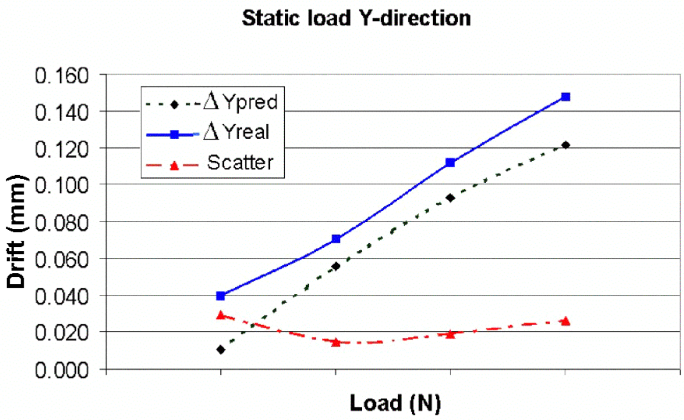
Within this WP the following experimental activity have been performed in order to verify structural performances of the HyMM demonstrator (smart Ram):

- **Static tests,** in order to evaluate the static stiffness in the X, Y RAM axis direction.
- **Free-free modal analysis,** in order to evaluate the natural frequencies, damping and the corresponding modal shapes.
- **Modal analysis on the constrained Ram,** through the carriages and the kinematics chain support. By these tests the natural frequencies, damping and the corresponding modal shapes have been evaluated.
- **Thermo-structural test**: to evaluate the effectiveness of prediction of the deformation state of the HyMM demonstrator through the FBG sensors arrangement and related smart algorithms.

The last one has showed the real effectiveness of the proposed smart materials applications structure for thermal error compensation.

The first validation trail has been conducted applying a static force at tool tip and comparing the actual measure of tip displacement (by the laser interferometer) and the predicted one through the model prediction models developed in WP3 (Multiple Regression Methods).

The comparison is reported in the graph here below:

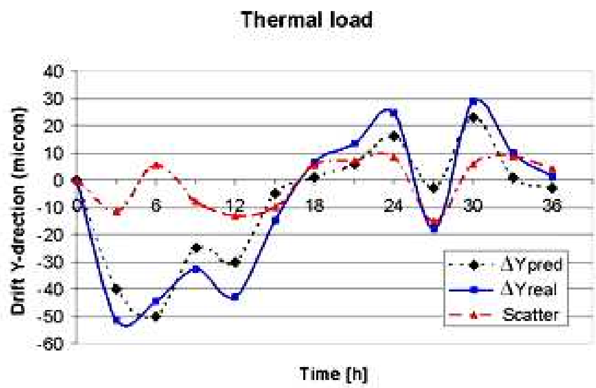


Static force effects: actual tool tip displacement vs. predicted one

The difference between actual and predicted values is also due to the fact that the statistical prediction model takes into account the influences of thermal loads (that, in this initial test, were not applied).

Another experimental test has considered the analysis of thermo-structural effects due to thermal loads application (e.g. combination of influence of environmental temperature cycling and wall overheating of the ram sample) within a defined period of time (2 days).

The results are reported in the following figure, where the measured actual drifts and the respective predicted values are plotted on a time scale.



Combined thermal load: actual tool tip displacement vs. predicted one

It can be seen that the prediction algorithms have performed well in predicting the actual displacement of tool tip. If no compensation were provided, the total error due to thermo-static effect would be the one represented by the “continue” curve (max. ~ 51 micron), while the effect of compensation reduces this “error” to the value represented by the “difference” between “dotted” curve and the “continuous” one (see dashed curve on the graph). It can be seen that in the compensated case the maximum drift error window is approx. ± 10 micron.

3. COMMUNICATION STRATEGY

Short text format data are preferably sent by e-mail, allowing to often interchange technical data, test results and analysis.

To exchange larger data files (for example tasks reports, pictures, presentations, deliverables) partners used an FTP server connection (through username and password), set up and managed by ISC. Every important project document and deliverables will be available to all partners and EC on the FTP server, making partners aware of it by e-mail "availability" message.

4. INTELLECTUAL PROPERTY RIGHTS (IPR)

The partners have signed the consortium agreement to handle IPR issues and ensure good work practice within six months from the start of the project.

All the Project Partners have active patenting and licensing policies. All industry partners of the consortium have contacts with patent lawyers. Use of existing patents by the other partners in the project have been secured within the consortium agreement. It is intended by each partner to protect any commercially significant innovations by patents.

The consortium is constantly monitoring publications for new patent applications in the area of smart materials applied to machining systems and equipment which exploit HSC strategies, power saving and noise reduction concept. Other details about machining process will be kept secret for a period of up to three years after the end of the project, as far as they will not be patented.

5. DISSEMINATION

The official project WEB-SITE has been setup:
http://www-mech.eng.cam.ac.uk/hymm/

Other important dissemination activities have been addressed during the project period, in particular partners has presented the HyMM project results in several national conferences and has contributed in the preparation of relevant scientific papers. Here below the main dissemination issues are summarised:

- Publication of a technical papers related to HyMM activities (for "public" purposes) that has been presented at the "IPROMS 2005, 2006 and 2007 Virtual Conference" (Website: http://conference.iproms.org), under the topic "Intelligent and competitive manufacturing engineering".

- Presentation done by CeSI at an Italian Workshop targeted to SMEs, in which HyMM activities have been mentioned

- Hybrid adaptronic structure for ultra precise milling machine", presented by Angelo Merlo in the "Adaptronic Congress" that took place in Göttingen-Germany in May 3-4, 2006.
- "Advanced hybrid mechatronic materials for ultra precise and high performance machining systems design", presented in CIRP ICME conference, Ischia, July 2006.
- "Materiales mecatrónicos híbridos avanzados para el diseño de sistemas de mecanizado ultra-precisos y de alto rendimiento", published in the spanish scientific journal IMHE 2006 – January/February Volumen II, pages 185-188.
- Mai, S. P., Fleck, N. A., Lu, T. J., 2006. "Optimal design of box-section sandwich beams in three-point bending". To appear in International Journal of Solids and Structures.
- Srikantha Phani, A., Mai, S.P., Fleck, N.A., Woodhouse, J., 2006. A prismatic-core design for a milling machine component. *International Journal Machine tools and Manufacture* (submitted).
- Weng Ting 2007. Ph.D thesis. "Thermofluid characteristics of metallic 2D cellular materials" (in preparation).
- Mai, S. P., Fleck, N. A., 2007. "Lattice tubes: mechanics and actuation". International Journal of Solids and Structures (in preparation).
- "Hybrid adaptronic structure for ultra precise milling machine", presented by Angelo Merlo in the "Adaptronic Workshop" that took place in Wuerzburg-Germany on March 1st, 2007.
- Scientific paper "Compensation of thermal drift of machine tools structures through a novel sensing concept based on Fibre-Optic technology" presented at the CIRP International conference, Liverpool, May 2007.

Dissemination activities will of course continue in the coming future.

6. CONCLUSION

❑ Main claimed achievements

- Wide investigation on smart materials technologies for actuators/sensors, and classification of them on the basis of the features/performances expected. Analysis and study of smart material properties towards potential applications for adaptive structure in machine tools sector.

- Investigation of advanced solutions for structural hosting materials to increase damping capacity and stiffness/weight efficiency.

- Characterization trials (static, dynamic and thermal) on identified hosting structural materials, including:
  - CFRP with new UHM carbon fibers,
  - 3d Cellular Lattice materials,
  - Multifunctional low density syntactic foam (3-phase polymeric foams with hollow glass micro-spheres, to be used as damping filler in smart structures).

- Concept studies, design, fabrication and experimental characterization of novel smart material samples:
  - Novel compact, robust and low-cost displacement sensor based based on PZT thin film [Patented solution].
  - Smart plate with embedded fiber optic sensors (FBGs Fiber Bragg Gratings and Fabry-Perrot interferometer) for structural monitoring.
  - Active morphing structure (tube) based on lattice materials.
  - Active PZT Fibers Composite (AFC) based on piezo-active fibers embedded in Polymeric Matrix composite (e.g. CFRP).
  - Smart composites (Garland) based on radial PZT ceramic foils embedded in a CFRP (HS fabric) circular plate.
  - Hybrid smart composite based on PZT foil and Shape Memory Alloys (SMAs) wires embedded in Fiber Reinforce Polymer (FRP).
  - Morphing structure based on Shape Memory Polymer (SMPs) sandwiches.
  - Novel Magnetic Rheological Fluids (MRFs) and MR Elastomer with tunable properties (damping vs. stiffness) for innovative adaptive vibration control concept [Patent pending].
  - PZT actuators located spindle flange elements for Active Vibration Control: Smart Platform.

- Development of methods and embedding techniques for cost-effective fabrication of smarts structures (for machine tools applications).

- Development of integrated mechatronic simulation techniques to evaluate performances of above mentioned smart concept solutions (to be used as selection and driving criteria of proposed solutions).

- Development of new Hw&Sw architecture (low-cost) for smart control of mechatronic structures (Smart Platform) and algorithms for real-time compensation of thermal errors based on FBGs.

- Concept study, analysis and fabrication of cellular periodic materials (corrugated core) and CFRP to design the selected structure (Ram) of Fidia machine: weight reduction of 50% and damping increasing have been achieved.

- **Design, mnfg and validation of final HyMM demonstrator**: The HyMM demonstrator consists of an innovative smart/adaptive part prototype (of a milling machine) based on integration of FBG optical fibers in a CFRP composite matrix, for real-time thermo-structural deformation measuring and compensation.

❑ Final results

- A novel smart structure (HyMM DEMONSTARTOR) of a machine tool which integrates optical FBG displacement sensors has been designed and manufactured for testing. The selected part is a ram (Z-axis of a HSC milling machines), made of CFRP material.

- The model for tool tip drift prediction based on Multiple Regression Techniques has been implemented. This prediction model correlates the real-time FBG sensor measurements with the actual displacement at tool tip due to random load conditions (static and thermal).

- A test bench has been set up to experimentally validate the proposed prediction model on the above mentioned smart structure.

- Experimental results showed and confirmed the expected effectiveness of the proposed demonstrator: very good prediction of real position of the tip under thermo-structural), with reduction of residual error downwards to 10 micron.

- Further researches and tests are planned in order to consolidate and optimize the proposed solution.

During this 4 year of intensive RTD activities within HyMM project the Partners state that:

- A huge number of very promising results (including methodologies, samples, prototypes, test-benches, demonstrator) have been provided.
- Very novel ideas and original "smart materials" concepts have been developed and tested.
- A patent have been registered, and other are pending.
- Good links and cooperation between partners have been established, and collaborations will continue in the future.