Application of composite materials for lightweight and smart structures design of high performance milling machines

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ABSTRACT

The most recent R&D activities, approaches and applications of advanced materials for design and fabrication of light and damped structures for high performance machine tools (MT), are presented. New solutions include: CFRP (Carbon Fibres Reinforced Polymer) with UHM (Ultra High Module) carbon fibres and hybrid sandwich (multi-materials layered) structures. Through simple considerations it is demonstrated how advanced materials ensure that MT components have a better static, dynamic and mechatronic behaviour than other conventional materials. Two case studies of the application of advanced materials to realise MT structural elements having a sandwich structure are reported.
The CFRP-based solutions allow to get a consistent mass reduction (-40%) without reducing the overall stiffness, while the sandwich solution show a less consistent reduction in term of mass (-20%) but a great benefit in term of modal damping increasing (up to 8 times higher than conventional steel structures). The effectiveness of the described solutions has been confirmed by experimental tests which have validated the design methodology as well.
This work will finally describe an innovative multifunctional machine tool structure based on a novel principle of real-time compensation of unpredictable structural deformations (due to thermal and static loads cycling) through the integration of smart fibre-optic FBG (Fibre Bragg Gratings) sensors into the structure itself. These smart sensors are suitable to measure both strains and temperature with very high accuracy and resolution. The measurements (linear elongation) from these sensors will be post-processed to predict the actual distortion/deformation of the structure (at tool tip location) in the 3D space domain through special algorithms based on MRA (Multiple-Regression Analysis). Experimental test has proven as well the potential of the proposed smart structure for thermal deformation monitoring and compensation in MT operation environments.

1. INTRODUCTION

The ever growing competition on the international markets pushes manufacturers towards shorter design cycles and decreasing manufacturing times and costs for their products. This trend generates a demand for smart, flexible and faster machining systems, easy to set up and configure, which are able to drastically reduce machining time, while improving the final accuracy. Machine Tools (MT) axis acceleration 2 to 3 times higher than conventional ones together with machining accuracy in the sub-micron range (considering a workpiece size in the macro-domain, e.g.1000 mm!) will be the most probable targets of the new generation of machining systems inside manufacturing shops. Strong mass reduction of mobile machine parts together with the increasing of their stiffness and damping to get excellent static, dynamic and thermal stability of the structures are then becoming a "must", to ensure a technological and cost-effective achievement of such an ambitious goal. Typical examples of machine structures are the mobile parts of milling machines, grinding machines, laser cutting machines, coordinates measuring machines, etc.
The introduction of composite materials in this new industrial market will surely bring a great advances in term of dynamic performances and will represent a new challenge for design engineers and huge opportunities for the composite manufacturers.

Conventional materials for building MT are cast iron, welded steel and, in some cases, aluminium-alloys. Although these materials represent a very consolidated technology for MT engineers, the need to ensure such high performances requires the investigation of a new class of materials with improved inherent properties in terms of specific stiffness and structural damping [1] and dimensional stability.

This work presents the most recent R&D activities, approaches and applications of composite materials to design and manufacture lightweight and damped structures of high performance milling machines (for precision dies and moulds machining). These new solutions include: CFRP (Carbon Fibres Reinforced Polymer) and hybrid Sandwich (multi-materials layered) structures. The aim of these applications is the increasing of the dynamic stiffness and chatter stability of the machines, while reducing their moving masses. Chatter vibrations result from a self-excitation mechanism in the generation of chip thickness during machining operations [2,3]. This phenomenon is not induced by external periodic forces but by forces generated in the vibratory process itself.

To select the most effective structural parts to be redesigned using new technologies, a FE (Finite Element) multipurpose analysis in combination with a static and dynamic sensibility has been carried out. The static sensibility analysis is based on the evaluation of the contribution of each single structure/component of the machine to the global compliance at the tool tip, while the particularity of the dynamic sensibility analysis is related to the evaluation of the percentage contribution of each machine part to the dominant vibration modes in terms of strain energy percentage and kinetic energy percentage of the total.

The strain energy is directly proportional to the stiffness while the kinetic energy to the mass. From this analysis it is possible to evaluate some critical design indexes which helps engineers to identify the critical elements, and then to concentrate the design efforts only on the elements where the modifications are more effective.

In the following chapter, some design considerations regarding the achievement of the best static, dynamic and mechatronic behaviour for a MT are reported. The third chapter shows how the design aspects are better fulfilled by advanced materials in comparison with conventional materials employed in MT fabrication. Then two case-studies (milling machining centre prototypes) for application of CFRP and sandwich materials are presented and the achieved results are commented upon as well

In both cases a thermo-symmetric design of structures has been adapted in order to minimise thermal distortion effects.

Finally a third case-study has been reported to show a new potential approach to face thermal problems when the thermo-symmetric design of structures is not feasible.

In fact a well-known problem is the thermally induced stress concentrations and distortions at the interface between a CFRP elements and other machine parts (e.g. flanges, guideways, inserts, etc) made of steel or aluminium, due to differential thermal coefficients of expansion (CTE) of the two materials. Then, in this case, the benefits of mass reduction are definitely penalised by structural geometrical errors arising from the mentioned thermal stability issues. In this contest a novel smart structure based on integration of Fibre Bragg Grating (FBG) optical fibres with the CFRP element have been proposed [4]. FBG sensors are capable of measuring with extremely high accuracy (in real time) the “deformed” states of the structure itself, and then, through proper thermo-structural model, predicting the displacement at tool tip.

2. MACHINE TOOLS DESIGN CONSIDERATIONS

There are many aspects that affect the machining accuracy and the cutting conditions of an high performance MT. The most important ones regard the static, dynamic, mechatronic and thermal behaviour of the machines. Static, dynamic and mechatronic design issues are briefly summarised here below, while thermal aspect are discussed in chapter 6.

2.1 Static and dynamic behaviour

In order to analyse the machine performances, the static and dynamic problems should be considered separately. While the static behaviour of a MT is clearly characterised by the static stiffness (defined as the ratio between the static load due to the cutting force and the related displacement at the tool tip), the dynamic behaviour and its physical causes are still not fully understood. What is certain is that vibrations in MT are induced by periodic forces and can be divided into two categories: forced (and free) vibrations and self excited vibrations (chatter).

2.1.1 Forced (and free) vibrations

The forced vibrations are induced by unbalance effects, gear and bearing irregularities, multi-tooth cutter impact as well as the motion of the foundation. Free vibrations produced by shocks under practical conditions frequently occur too. Since both forced and free vibrations are often encountered and difficult to avoid, the evaluation of the critical frequencies of the machine is fundamental in order to know whether the excitation forces can cause resonance problems and produce an unacceptable accuracy of the workpiece.

As far as these vibrations are concerned, one of the most important parameters able to characterise the dynamic behaviour of the structures is the dynamic stiffness K_d (defined as the ratio between the static stiffness K_{st} and the dynamic amplification factor Q). K_d is mainly a function of Young's modules of the materials constituting the structures and it depends also both on the mass involved in the vibration and on damping present in different forms (viscous, hysteretic and Coulomb). In practical situations (where viscous dissipation forces act), Q is directly proportional to the mass M and inversely proportional to the modal damping D. Therefore, reducing the mass and/or increasing the damping, the dynamic stiffness (and then, the dynamic performances) increases.

2.1.2 Self-excited vibrations

Self-excited vibrations (chatter) are a basic instability of the cutting mechanism itself. This phenomenon is not induced by external periodic forces but by forces generated in the vibratory process itself (the dynamic cutting process). Chatter vibrations result from a self-excitation mechanism in the generation of chip thickness during machining operations.

Chatter vibrations depend both on the spindle speed and on the axial depth of cut. In particular, as shown in Figure 1, at a given spindle speed, a top limit for the axial depth of cut exists under which the chatter vibrations phenomenon does not occur (Tlusty [1], Tobias [2] and Merrit [3]). This top limit (indicated by DOC) is inversely proportional to the cutting constant K_f of the workpiece material and to the flexibility of the structure expressed by the real part $G(\omega_c)$ (where ω_c is the chatter frequency).

$$DOC = \frac{-1}{2K_f \cdot G(\omega_C)} \qquad (1)$$

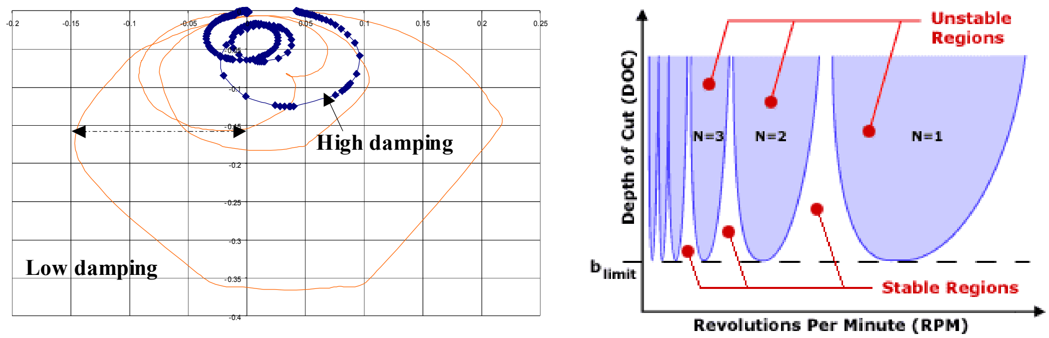


Figure 1: Stability of a cutting process

A down limit b_{limit} (depth of cut) exists below which stability is guaranteed.
This means that, if DOC is selected using the minimum value of $G(\omega_c)$, named G_{min}, the avoidance of chatter is guaranteed at any spindle speed.
As it can be seen from Figure 1 flexible or low damped machines will reduce the axial depth of cut (and so the productivity) as they have high value of G_{min}.
b_{limit} can be enhanced increasing the stiffness and the damping of the involved structures.

2.2 Mechatronic behaviour

The mechatronic behaviour of CNC machines refers to the dynamic behaviour within a closed control loop, and typically is related to the evaluation of five basic types of contouring errors E_i:

- E_s = Steady-state error at constant acceleration along a straight line
- Et = Transient error (peak value) at beginning/end of acceleration/ deceleration phase
- Em = Overshoot error at stop
- Er = Mean radial error on a circle (in steady-state condition)
- Erc = Circularity error on a circle (in steady state condition)

The contouring error E_i depends on the straight line acceleration A, on the position loop gain K_V and on a coefficient λ_i which is a function of the feed forward transfer function and the axis transfer function:

$$E_i = \lambda_i \cdot \frac{A}{{K_V}^2} \qquad (2)$$

K_v is directly proportional to the first critical mechanical frequency ω_d (within the loop) and to the global damping coefficient D of the machine as shown by the following

$$\frac{K_V}{\omega_d} \propto D \qquad (3)$$

ω_d depends on the stiffness k and on the mass m of the structure in the following way:

$$\omega_d \propto \left(\frac{k}{m}\right)^{1/2} \qquad (4)$$

So, even in this case from (2), (3) and (4) it results that the contouring error E_i basically can be reduced by the increasing of the stiffness k and the damping D of the structure, and/or reducing its mass m:

$$E_i \propto \frac{m}{k \cdot D} \qquad (5)$$

3. MATERIALS TECHNOLOGY IN MT DESIGN

From the considerations made in Chapter 2, it results that, in order to improve the static, dynamic and mechatronic behaviour of a MT, it is necessary to reduce its mass and enhance its damping and stiffness. The mass reduction involves another advantage: less mass to move means less inertia and so less energy “absorbed” by the machine.

Let’s now compare several materials employable to realise structural components of a MT. The aim is to individuate which material ensures the best static, dynamic and mechatronic behaviour of the machine. The selection strategy is based on the evaluation of two parameters which can be considered merit indexes: the structural index (Ashby [4]) and the damping coefficient. The structural index is given by $E^{1/3}/\rho$, where E is the Young’s module and ρ is the density of the material. This index regards the material mass and stiffness. In particular, for a prescribed stiffness, materials with the same structural index have the same weight. The weight is minimised (and the stiffness is increased) by selecting materials with large values of structural indexes.

Figure 3 shows a chart (Ashby [4]) through which it is possible to select a material on the basis of its structural index. Materials with the same structural index lie on the same line whose slope is 1/3 (the chart is in logarithmic scale).

Conditions on the static, dynamic and mechatronic behaviour of a structure can be translated into conditions on the structural index and the damping coefficient (in particular, referring to the chart below, materials with the best structural index lie in the top-right zone).

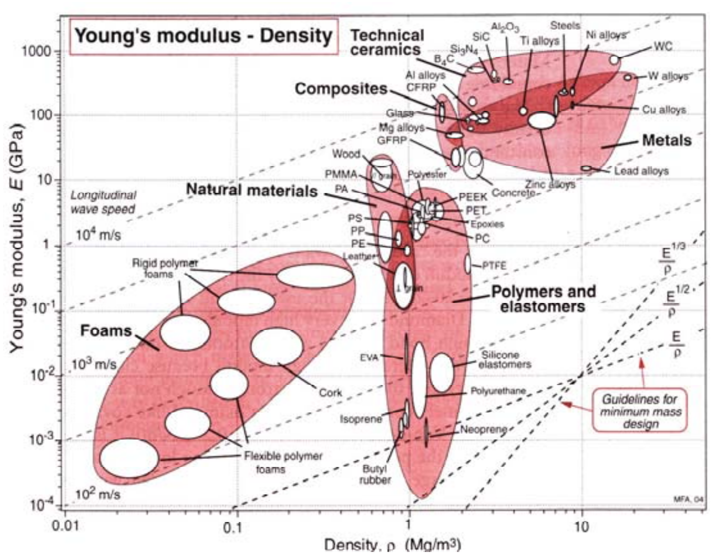


Figure 3: Ashby’s charts (E- ρ) for materials selection

Let’s compare the following materials: Cast iron, Steel, Aluminium alloys, Mg alloys and CFRP (Carbon Fibre Reinforced Polymer, considering three types of carbon fibres: HS (High Strength), HM (High Module), and UHM (Ultra High Module, that is with a Young’s module higher than 700 Gpa). The values assumed by the structural index $E^{1/3}/\rho$ and by the damping coefficient η for these materials are reported in the Table 1.

As far as the damping coefficient is concerned, because of its variability, to consider a range of values is better than assuming a single value for each material.

	$E^{1/3}/\rho$ $[Gpa^{1/3}/(Mg/m^3)]$	η
Cast iron	0.63	$1.2 \cdot 10^{-3} \div 1.7 \cdot 10^{-3}$
Steel	0.77	$6 \cdot 10^{-4} \div 10^{-3}$
Aluminium alloys	1.5	$2 \cdot 10^{-4} \div 4 \cdot 10^{-4}$
Mg alloys	1.9	$10^{-3} \div 10^{-2}$
HS CFRP	3.3	$1.5 \cdot 10^{-3} \div 3 \cdot 10^{-3}$
HM CFRP	4.0	$1.5 \cdot 10^{-3} \div 3 \cdot 10^{-3}$
UHM CFRP	4.4	$1.5 \cdot 10^{-3} \div 3 \cdot 10^{-3}$

Table 1: Materials structural index and damping coefficient

As can be seen from the above table, the material characterised by the highest values of the structural index and the damping coefficient (that is, having the best static, dynamic and mechatronic behaviour) is the UHM CFRP. Another advantage associated with the employment of UHM CFRP is its low thermal expansion coefficient. Actually, also Mg alloys have a high value of damping but this material is extremely expensive, especially due to the high manufacturing costs.
In the two case studies described in Chapters 4 and 5, CFRP-based solutions are used to design and produce MT structural components. In the first case-study, a HM CFRP unidirectional layer is used as an external skin of a sandwich multi-material structure. Basically, in comparison with the monolithic CFRP solution, the proposed sandwich structures are cheaper because the nobler material is employed just to realise the sandwich skins.
The chart in Figure 4 shows how, selecting the materials for the core and the skins of the sandwich structure appropriately, an hybrid solution can be obtained whose structural index is higher than that of its two constituents. Moreover, there are further advantages in terms of damping thanks to the presence of bonded junctions.

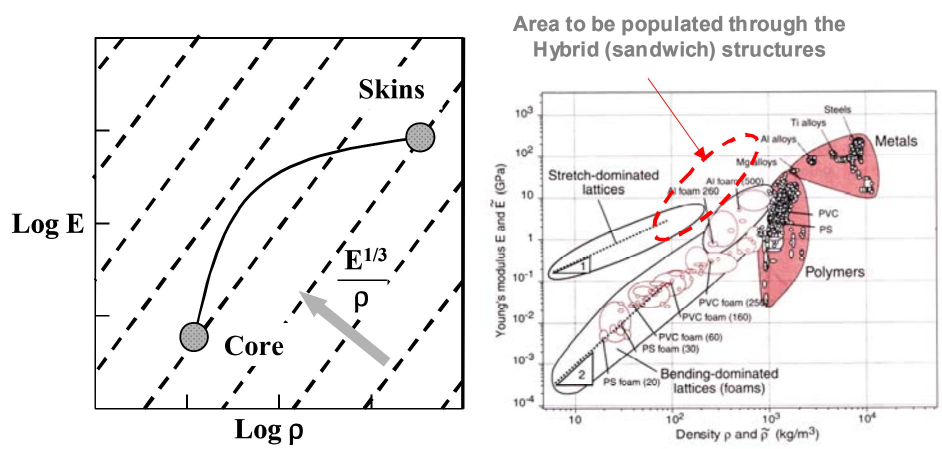


Figure 4: Structural index of sandwich panels

On the other hand the UHM CFRP as monolithic solution in some case results is extremely advantageous in terms of weight reduction (the second case-study) while the cost-effectiveness strongly depends on the fabrication process selected for the composite part.

4. CASE STUDY 1: HIGH SPEED MACHINING CENTRE

The here presented case study is related to the applications of a hybrid multi-materials sandwich to design novel MT parts of a linear motors horizontal (3-axis) machining centre for prismatic component machining.

To select the most effective structural part to be redesigned using new technologies, a FE multipurpose analysis has been carried out. The aim of this application is the increasing of the dynamic stiffness in order to get the advantages described in the previous chapters. Figure 5 shows the FE design flowchart.

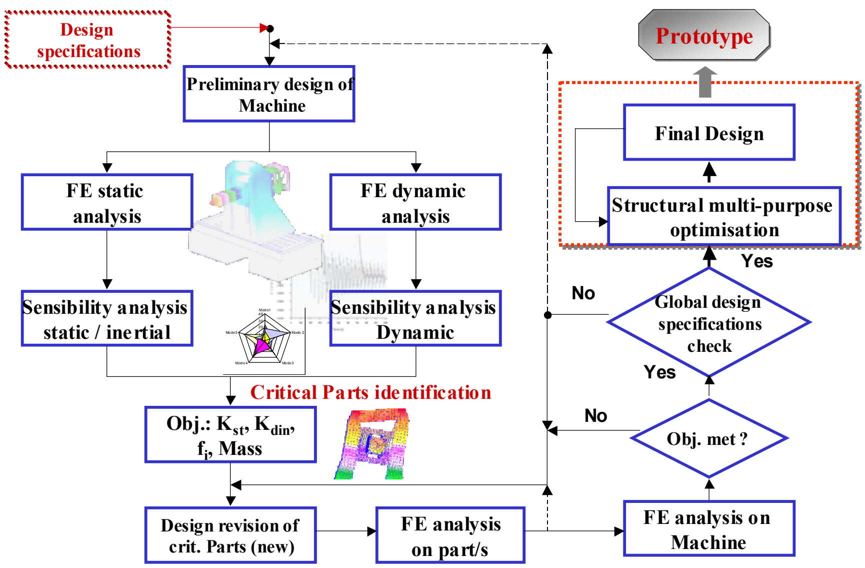


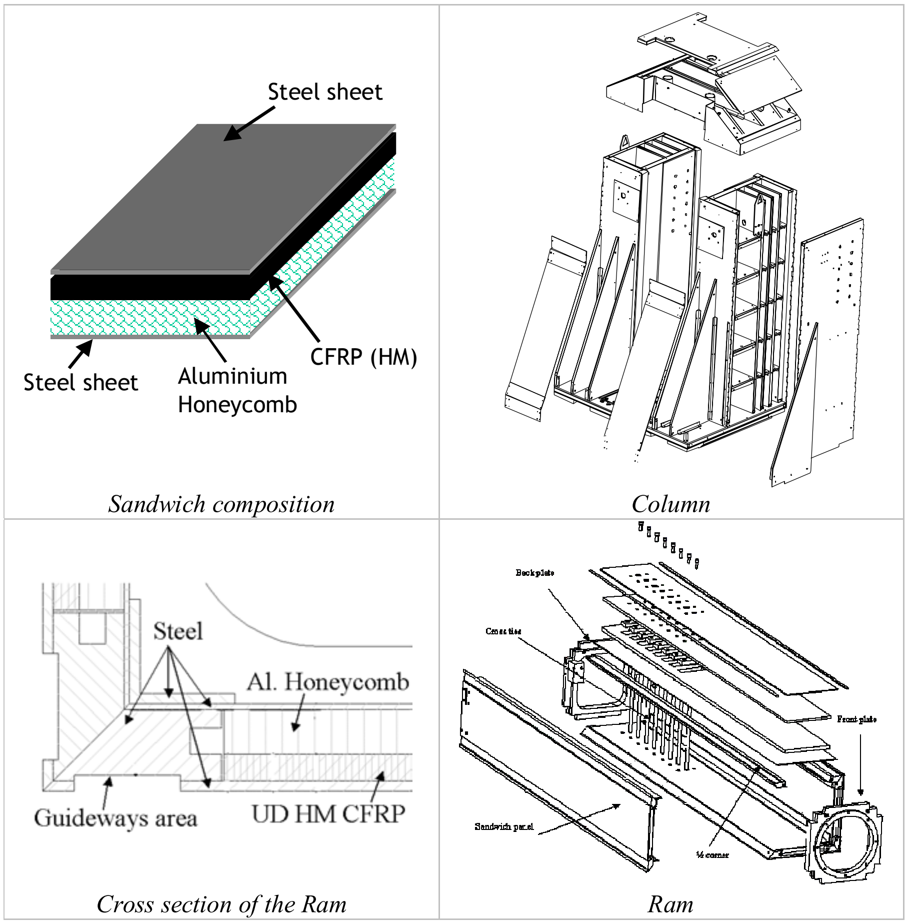
Figure 5: The FE design flowchart

The static sensibility analysis is based on the evaluation of the contribution of each single structure/component of the machine to the global compliance at the tool tip, while the particularity of the dynamic sensibility analysis is related to the evaluation of the percentage contribution of each machine part to the dominant modes in terms of strain energy percentage and kinetic energy percentage of the total.

$$E_s = \frac{1}{2}[u]^T[K][u] \qquad (6)$$

$$E_C = \frac{1}{2}[\dot{u}]^T[M][\dot{u}] \qquad (7)$$

As seen, the strain energy E_s is directly proportional to the stiffness while the kinetic energy E_c to the mass. From this analysis it is possible to evaluate some critical design indexes on which to individuate the critical elements and so to concentrate the effort design only on the elements where the modification is more effective. According to this analysis the Ram (Z-axis) and the Column (X-Axis) resulted as the most critical components. Therefore, starting from an existing conventional High Speed Machining Centre, the Ram and the Column have been substituted with novel ones. The electro-welded steel structures have been substituted with a hybrid sandwich structure (steel/CFRP/Al-honeycomb/steel) as shown in the following figure.



Sandwich composition — *Column* — *Cross section of the Ram* — *Ram*

Figure 6: Sandwich hybrid material and applications

Panels have been joined through gluing technology.
The actual damping has been increased up to 3 times for the Ram and 8 times for the Column. The saving in mass for both the components has been the 20 %.

5. CASE STUDY 2: ULTRA HIGH SPEED MODULE

This second case study regards an Ultra High Speed Module (the morphology is the similar to the previous one but with smaller size), where the steel RAM has been substituted with another one made in a hybrid material structure. The external skin is in thin steel plates glued on an internal tube fabricated through filament winding technology (the material is UHM carbon fibres for the square tube and HM fibres for the inner corners, used as local stiffeners).

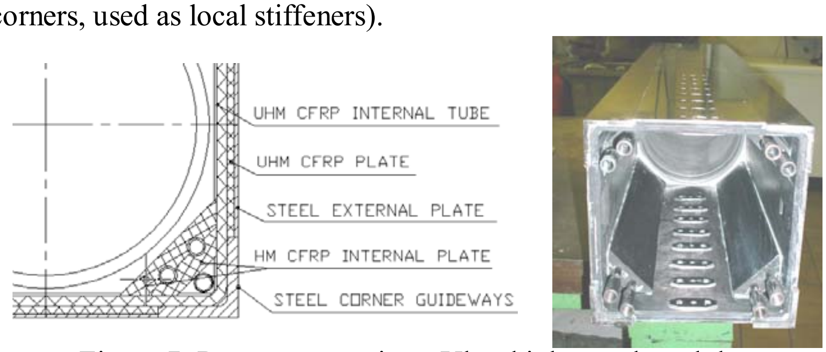


Figure 7: Ram cross section - Ultra high speed module

The inner corners include also aluminium pipes used for cooling and thermo-conditioning of the part.
The fibre orientations of CFRP tube has been optimised in order to minimise the mass and maximise the stiffness and the first modal bending frequency. The achieved results are very good with a mass reduction of 40 % and the damping increased by 2.5 times. The advantages in terms of weight saving are greater than the solution described in the first case-study while the damping increasing, as expected, is a little bit lower than the previous one (due to less number of glued layers).

6. CASE STUDY 3: SMART STRUCTURES

A strict requirement that the machine tool design engineers have to fulfil in order to drastically reduce machining time while improving the final accuracy is the thermal stability. In particular, a well-known problem is the thermally-induced errors arising from thermal deformations of the machine elements caused by internal/external heat sources and differential coefficients of thermal expansion (CTE) between CFRP material and metallic end-fitting, inserts, etc. (Fig. 8).

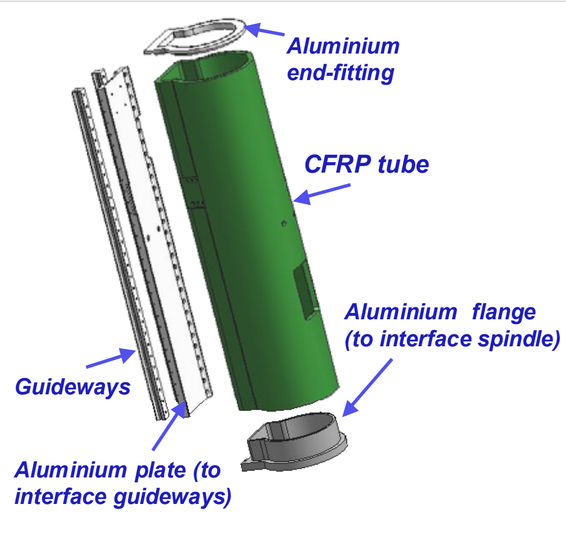
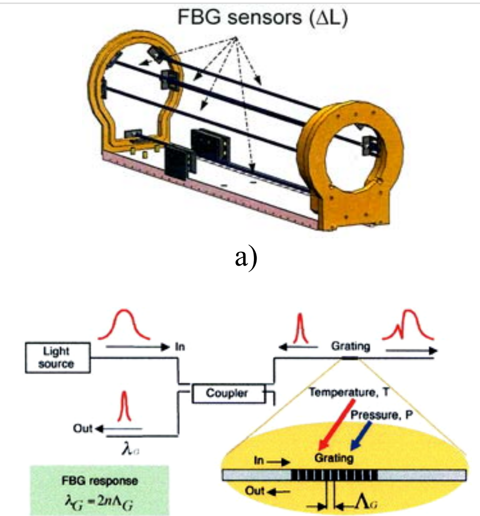


Fig. 8: Machine tools part (ram) made in CFRP with metallic end-fittings



b)

Fig. 9: a) Ram with FBGs sensors
b) Principle of FBG sensor

The SMART structure here proposed consists of an innovative machine tool part, the ram (Z-axis) of a milling machine made of CFRP material, which integrates a set of the FBG displacement sensors (Fig. 9 a) to measure the overall elongation (integral effect) of some critical point-to-point dimension of the part geometry.
A uniform FBG includes a segment in which a periodic modulation of the core refractive index is implemented (Fig. 9 b). When an external mechanical or thermal deformation is imposed onto the grating area, the grating periodic spacing and consequently the effective reflective index will be altered [5]. So, the Bragg wavelength will shift because of changes in either the refractive index or the periodicity of the grating. An optical spectrometer can thus provide a measure of the total strain affecting the grating.
Five FBG sensors have been placed in the ram structure in order to measure the total axial elongation of each side of the structure. These on-line measures will be used as input in a structural mathematical model of the part — based on MRA (Multiple-

Regression Analysis [6]) — that will predict the drift of the tool tip in the three spatial directions.

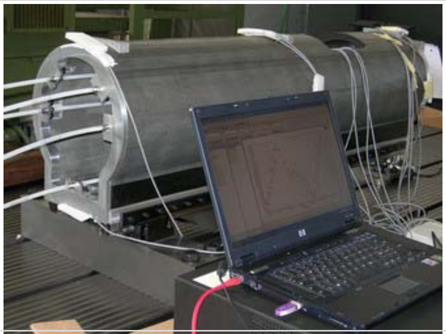


Figure 10: Test-bench setup of Ram with FBG sensors

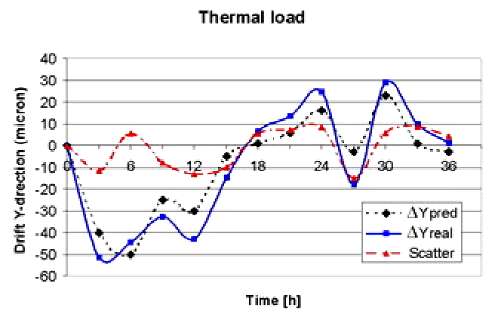


Figure 11: Test results - actual tool tip displacement vs. predicted one.

To validate the model, a test-bench has been set-up (Fig. 10). During the experimental tests, the thermo-structural effects due to thermal loads application (changing the ambient temperature) over a prescribed time period have been monitored. The results (Fig. 11) showed that in the compensated case the maximum residual drift error at tool tip can be potentially reduced within a window of approx. ± 10 µm by the proposed model and algorithms, while without compensation the drift due to thermo-structural distortions would be approx. ± 50 µm.

6. CONCLUSION

The two reported case studies of novel light-damped machine tools structures show the big potentiality offered by the application of advanced materials in high performances machine tools. Firstly the combination of hybrid materials (steel, CFRP, Al honeycomb) and an intensive use of gluing technology allow to increase damping and, at the same time, to get a consistent mass reduction (up to 40%) without reducing the overall stiffness.

Moreover the integration of FBG sensors into a CFRP structure allows a compensation of geometrical distortions (due to differential CTE between CFRP material and metallic end-fitting, inserts) through a thermo-structural prediction model based on real-time sensors measurements.

The effectiveness of the described solutions has been confirmed by experimental tests which have validated the design methodology as well.

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