Chapter 2
New Concepts for Structural Components

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Abstract This chapter is focused on analysing new concepts and trends related to the structure of machine tools. In fact, the structure of the machine has a decisive influence on the three main parameters that define the capabilities of a machine, which are: motion accuracy, the productivity of the machine and the quality of machining. In this respect, this study on structural components will add a new basic parameter, eco-efficiency, because the structure of the machine also has a decisive influence on the whole life cycle of the machine and especially on the materials and energy resources consumed: an issue of increasing concern among machine tool builders.

2.1 Introduction and Definitions

As seen in Chap. 1, the structure of a machine tool has two main functions, to hold the components and peripherals involved in the machine and to withstand the forces which are produced by the process and from the machine motions.

Within this view, the basic challenge for machine tool builders is to conceive machine tool structures that are capable of withstanding with minimum possible deflections the effects of the foreseen forces and of heating foci and at the same time consume the minimum possible in terms of materials and energy resources.

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As these two aims are opposing, the process of designing a machine tool is a trade-off between these two targets, so that the specific characteristics of a machine tool will define that balanced position between these two approaches.

In this respect, the final characteristics of a machine tool are defined by means of the following parameters:

- Productivity: The productivity of a machine is measured in terms of its *metal removal rate* (MRR), which largely depends on its kinematic and dynamic capabilities and especially on its static stiffness, which in fact is the primary reason to define the dimensions and shapes of the structural components. To this end, higher stiffness involves bigger masses, which in combination with faster motions aimed at achieving higher productivities, leads to motors of higher power that generate higher inertial forces. This in turn demands stiffer structures, which again demand a larger amount of material, so that stiff machines become productive and at the same time very energy and resource consuming.
- Accuracy: The accuracy of a machine is defined according to the deviations of the tool with respect to a desired profile while it is being moved and positioned (see Chap. 6). These deviations are largely associated to thermal effects and to the mechanical deflections that the machine components bear when inertial and process forces act on them. Therefore, the basis necessary in order to achieve accurate machines will lie in conceiving both thermally-stable and stiff structures.
- Eco-efficiency: The eco-efficiency of a machine is measured in terms of energy and material resources used and the waste and pollution created in the process. As sustainability is an issue of increasing concern in the manufacturing sector, this book will add a new aim for machine tool builders: to reduce the environmental impact associated to a machine tool throughout its entire life cycle.

The structural components of machines have a twofold impact on the global eco-efficiency of a machine: on the one hand, the largest amount of material resources in a machine is associated with its structural components. On the other hand, the energy that a machine consumes during its use phase is largely associated with the motion of movable structural components both in positioning motions and in machining motions.

Moreover, according to a study of the machine tool builder Nicolas Correa®, the use period of a machine represents more than 90% of the total impact associated with their machines. Figure 2.1 shows both graphically and numerically (by means of a *life cycle analysis,* or LCA), the total impact associated with an average medium/large size machine of Nicolas Correa® throughout its entire life cycle.

Accepting thus that the largest portion of the environmental impact of a machine tool is associated with the motions of its movable components, the reduction of each gram of material in these movable structural components will have a decisive role in the final ecological impact of the machine tool.

As a conclusion, the structure of a machine plays a key role on the final functionalities of the productivity, accuracy and eco-efficiency of that machine. The following sections will explain different strategies that can be employed to con-

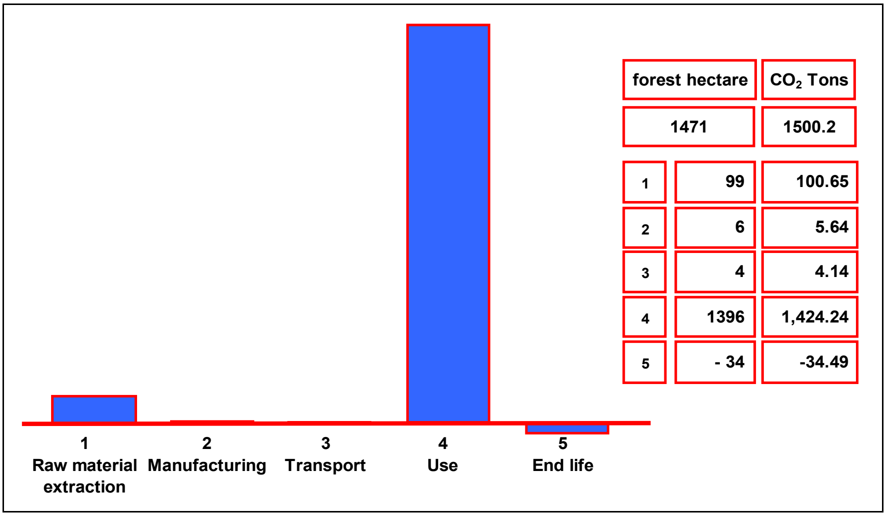


Fig. 2.1 LCA of a machine by Nicolas Correa®

ceive and produce machine structures that achieve appropriate values of productivity and accuracy by means of good thermal and vibration behaviour combined with low amounts of movable masses.

2.2 Optimised Machine Structures

Machine tools provide a relative motion between the tool and the part that is to be machined. With regard to these motions, milling machines have three Cartesian motions, with at least two of the axes mounted in serial. In some cases, the three motions are applied to the tool (really to the spindle onto which the tool is fitted); in other cases the motions are divided into the tool and the part, and only on a few occasions are the three motions applied to the part, because it is quite unusual to vertically move the table on which the part lies. Additionally, it is increasingly common for machine builders to add two additional rotational degrees of freedom to the machine, either to the headstock, or to the table or to both. They thus become machines with five degrees of freedom, i.e., five-axis milling machines.

The structure of a machine covers the components that allow the achievement of the degrees of freedom. These elements are mainly of two types:

- *The frame and bed*. They are the static part of the machine. The frame constitutes the main body of the structure, in which the bed is the solid base of the machine. The frame is usually composed of several bolted or welded components.

- *The structural components*. They are the movable parts of the machine structure, and are linked in different frame configurations. The interfaces among elements with relative motion must be as stiff as possible and highly damped along the perpendicular direction to the sliding one.

For an analysis of the advantages and drawbacks of different machine structures, it is useful to divide the structural design approaches into two groups: the *open-loop* configurations (examples in Chap. 1, Figs. 1.25 and 1.27) and the *closed-loop* configurations (Chap. 1, Figs. 1.9b and 1.22). The main conceptual difference between them is that in the open-loop case, process and inertial forces are conducted to the ground through in just one structural way. In the closed-loop concept, forces are conducted to the ground in several ways.

For the same machine strokes, the main advantage of the open-loop concept with respect to the closed-loop one is the easy access to the workzone and the lower cost. Otherwise, the closed-loop concept presents a higher stiffness at the tool tip and symmetrical behaviour with respect to thermal and mechanical loads.

Finally, the main structural components in an open-loop concept are the bed, table, column and ram, linked with sliding guideways. In the closed-loop concept, the main structural components are the table, bridge and guideways. Any of the involved components in any of the concepts can be either static or movable, i.e., the column will be movable in some machines and static in others, and the same for the rest of the structural components. Indeed, the different relative motions among these structural components will define the different machine architectures and configurations.

2.2.1 A Comparison Among Different Machine Configurations

Apart from the general characteristics associated with the closed-loop and open-loop structures mentioned above, there are few *a priori* rules that state which is the best option to select for a specific architecture and to define the relative motions between components. There are some general rules detailed here that can help the designer to select the optimal machine configuration:

- Symmetrical configurations lead to lower temperature gradients as well as to reduce bending moments.
- The overhang of cantilever-type components must be as short as possible. Indeed, cantilever components are the most critical components from a mechanical point of view, since they generate *Abbe* type errors (see Sect. 6.2.3), in which an angular compliance is amplified as a linear error by leverage effect. Several machines include a ram element, which is always a source of flexibility (machines in Chap. 1, Figs. 1.21 and 1.33). The overhang of this moveable component depends on the point to be machined, so this is a variable stiffness element.

- The path length from the tool to the workpiece through the structure should be minimal with the aim of minimising thermal and elastic structural loops [5]. The less material that separates the parts of the structural machine components that hold the tool and the part the quicker the machine will reach a stable equilibrium.

With these basic rules, and taking into account that there is not a unique optimal architecture, the design task will focus on making the components of the selected configurations as stiff and light as possible, as well as other considerations such as the cost, the ease of assembly, the workzone accessibility, the footprint and the total space occupied by the machine.

Figure 2.2 shows the different architectures that a machine builder considers when designing a hybrid heavy-duty milling and friction stir welding (FSW) machine. The company studied six architectures defining seven indicators to allow an even weighting of the drawbacks and advantages of each architecture. The seven indicators considered were the following: i) stiffness at the tool tip, ii) cost, iii) accessibility, iv) flexibility, v) homogeneous and symmetrical behaviour, vi) occupied space and vii) safety for the end user. Moreover, due to the extraordinarily high forces associated with FSW processes, which are more than the double the forces of heavy-duty milling processes, the machine builder has ranked as the "most important" the characteristics of stiffness, and after that, the characteristics of cost and risk, and has ranked as the "least important" the flexibility of the machine and the space that the machine occupies.

The main characteristics of the six considered architectures were:

1. *C Structure*, with a fixed column, and crossed slides on which a table moves in X and Y, and vertical ram in Z
2. *Fixed bridge* structure, with a movable table in X and crossed slides in Y and Z axes of the tool
3. *Fixed bridge* structure, with a movable table in X, a movable slide in Y and a vertical embedded ram in Z
4. *C Structure* with a fixed column, a movable table in X, and a movable embedded slide in Y and vertical ram in Z
5. *Travelling bridge* structure, with fixed table, travelling bridge in X, embedded movable slide in Y and vertically movable crossbeam in Z
6. *Fixed bridge* structure, with movable table in X, movable embedded slide in Y and vertical ram in Z

The main conclusion of this comparison study was that number 5 produced the stiffest architecture. The most economical solution was produced by number 1, which also provided the most workspace accessible solution. Furthermore, the most homogeneous behaviour was seen in solutions 5 and 6, both of which also provide the safest solution. Finally, there are no notable differences as regards the room that each solution occupies.

Table 2.1 summarises, using a ranking system 1 to 4 (where 1 means a "poor performance" and 4 means an "excellent performance") the main results of this study:

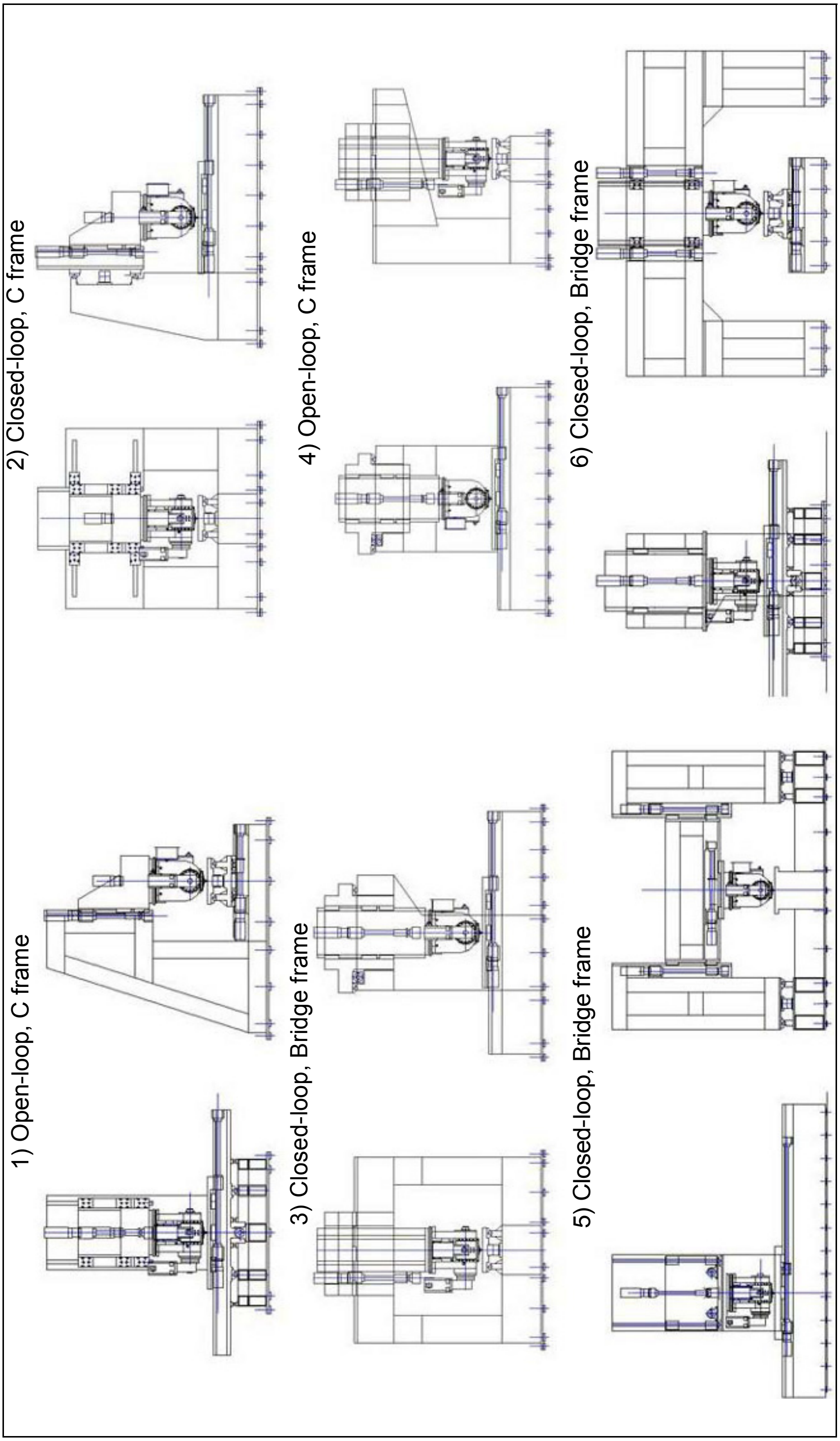


Fig. 2.2 Different machine architectures for a hybrid milling and FSW machine

Table 2.1 Comparisons among different machine architectures

	Machine architecture					
	1	2	3	4	5	6
Stiffness	1.0	2.0	2.5	2.0	4.0	1.0
Cost	4.0	2.0	1.5	3.0	2.0	2.5
Accessibility	4.0	1.0	1.0	2.0	2.0	2.5
Flexibility	3.0	1.0	1.0	1.0	1.0	3.0
Homogenous behaviour	3.0	1.0	2.0	1.0	4.0	4.0
Occupied room	2.0	2.0	2.0	2.0	2.0	2.0
Risk	3.0	1.0	2.0	1.0	4.0	4.0

In the case of selecting adequate machine architecture for a heavy-duty milling and FSW process and taking into account the high importance of stiffness for these processes, the selected architecture was the 5th.

2.2.2 Structural Components in Machine Structures

Figure 2.3 shows two machines built by the machine tool builder Nicolas Correa®. The drawing in Fig. 2.3a depicts a *C type* machine: an asymmetrical, open-loop machine, with a fixed column, a movable table in X, a movable outer slide in Z and a movable ram in Y. The drawing on the right depicts a *Bridge type*, symmetrical, a closed-loop machine, with a fixed bridge, a movable table in X, a movable outer slide in Y and a vertical ram in Z.

Despite their remarkable differences in dimensions and occupied room, their stiffness values at the three axes are somehow similar. Therefore the information of interest consists in knowing the most compliant elements of the machine, because as structural components are mostly in serial, the total compliance of the machine will be larger than the most compliant component. Moreover, when reinforcing the machine, the maximum effect is achieved when the most compliant component is acted upon.

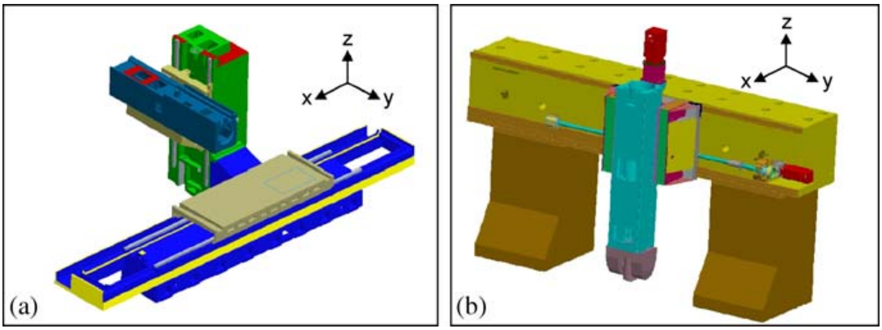


Fig. 2.3 Two machines of Nicolas Correa®: **a** C-type. **b** Bridge type

Table 2.2 Comparisons among different machine architectures

C-type machine				Bridge type machine			
Component	% Static compliance			Component	% Static compliance		
	X	Y	Z		X	Y	Z
Ram	49	27	43	Ram	53	42	26
Slide	16	12	24	Slide	10	30	18
Column	24	31	19	Bridge	35	26	46
Others	11	30	14	Others	2	2	10

Table 2.2 shows the distribution of compliance among the different structural components of the machine.

The data in this table confirms that concerning the static compliance of machines, the ram is the most critical component in almost all directions and architectures. There is also a notable influence from the column with respect to the bending directions of C-type machines. Therefore, designing optimised rams and columns for the case of C-frame machines is an issue of special relevance.

The following section will analyse the main rules for designing robust, stiff and lightweight rams and columns.

2.2.3 *Robust Rams and Columns*

Rams and columns have in most cases a square section to achieve a symmetrical and balanced behaviour concerning bending and torsion resistance. As the length of these components is defined by the strokes of the machine, there are two important aspects in designing rams and columns: 1) to define the appropriate thickness for their outer walls, and 2) to appropriately place internal ribs as a means of reaching an optimised stiffness-to-mass ratio.

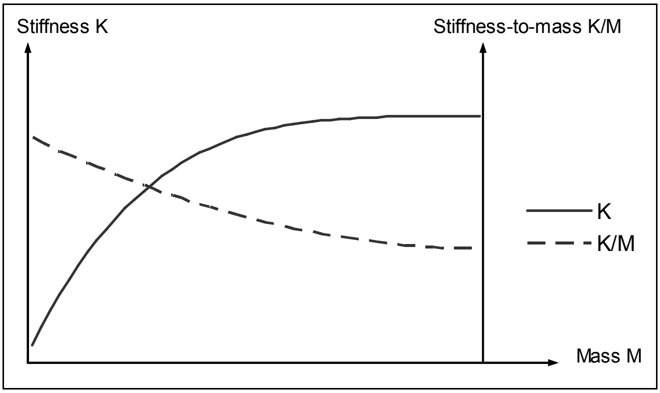


Fig. 2.4 Influence of wall thickness (and mass) on ram stiffness

With respect to the thickness of the walls, maintaining as a constant the outer dimensions of the beam, increasing the thickness of outer walls involves an increase of stiffness that is lower than the increase of mass, so that excessively thick outer walls are not an optimal solution from the eco-efficiency point of view, as Fig. 2.4 shows. Thickness and mass are directly related.

With respect to ribs, they can be either longitudinal or transversal. Longitudinal ribs are not an optimal solution for rams and columns from the mechanical point of view, because for the same amount of mass, an appropriate increase of the thickness of the outer walls allows for achieving a higher stiffness both for bending and torsion loads. Therefore, longitudinal ribs are not an optimised solution according to the stiffness-to-mass ratio.

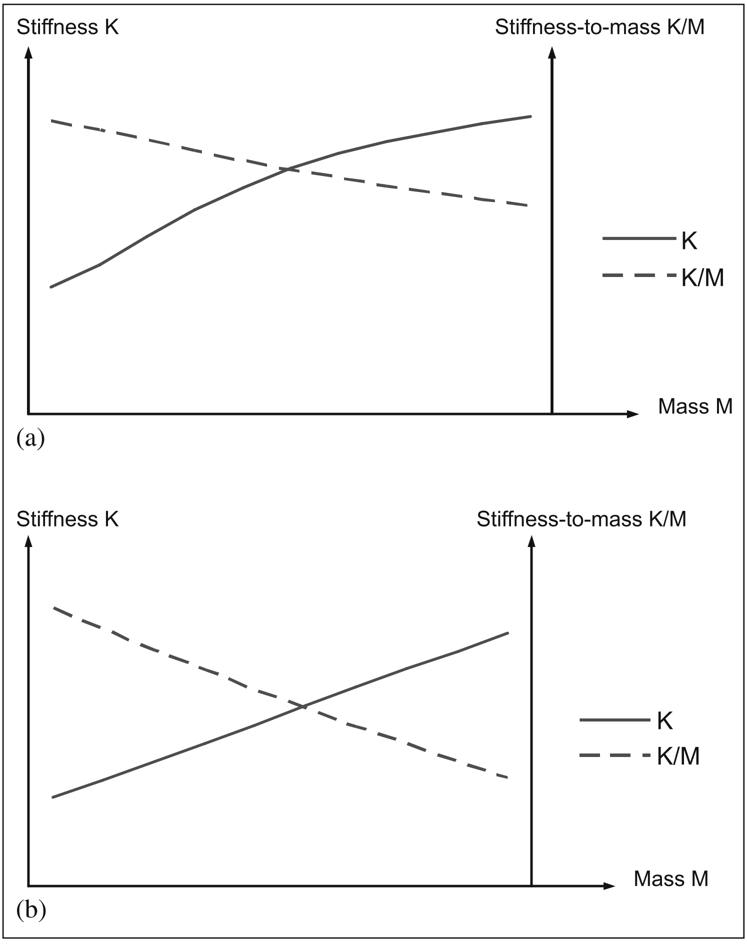


Fig. 2.5 **a** Influence of thickness of transversal ribs on stiffness of a ram. **b** Influence of number of transversal ribs on stiffness of a ram

Unlike longitudinal ribs, transversal ribs do improve optimally the mechanical behaviour of rams and columns concerning their bending and torsion resistance. Therefore, an important issue when designing columns and rams is to select the appropriate thickness of these transversal walls as well as the distance between these walls. As a reference, for an average machine ram with a square section, an optimal thickness for transversal ribs is 10 mm. There is also an optimal space between transversal ribs, which is of the order of 230–240 mm.

Similar to the case of longitudinal ribs, either an excess in the amount of transversal ribs or an excessive thickness of theirs will increase the total stiffness of the ram or column at a lower pace than the involved mass, as shown in the charts of Fig. 2.5.

2.3 Structural Optimisation in Machines

A machine tool is a spatial manipulator that is going to support high loads due to either the cutting forces or the inertial loads. The optimisation of the machine constitutive structures is an important task for designers.

2.3.1 Mechanical Requirements for Eco-efficient Machines

When designing the structural components of the machine, the target is to minimise the amount of mass of moving machine structures while static and dynamic mechanic properties maintain the desired threshold values.

As explained in the chapter introduction, the reduction of moving mass has an extraordinary impact on the environmental impact of a machine. Therefore it is worthwhile passing from a strategy based on "the stiffer the machine, the better" to a strategy based on "the lighter the machine, the better". Since lighter machines mean less stiff machines, the latter strategy requires the definition of minimum "threshold values" for the static and dynamic stiffness, so that an optimal balance between eco-efficiency, productivity and accuracy can be achieved.

With the aim of contributing to the definition of those threshold values for stiffness, Table 2.3 shows the average process forces associated with milling operations when cutting AISI 1045 steel, which have been experimentally measured on

Table 2.3 Average forces and acceptable deformations for different milling operations

Process	Average force in feed direction		Acceptable deformation
Roughing	Conventional tools:	1,500 N	Average: 100 μm
	100–125 mm. diam. tools:	3,000 N	
Semi-finishing	Conventional tools:	1,000 N	Average: 50 μm
Finishing	Conventional tools:	200 N	Average: 10 μm

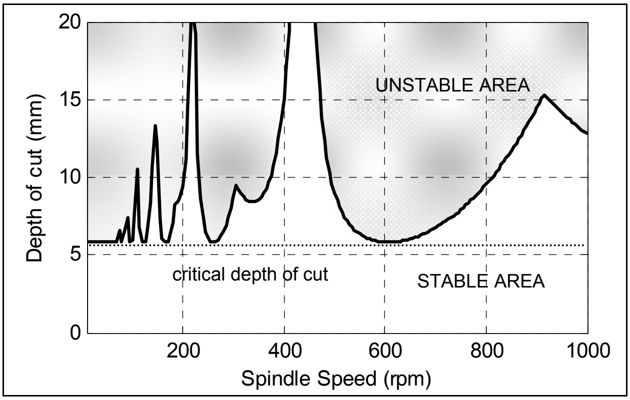


Fig. 2.6 Example of a stability lobe diagram

different machines and workshops. Table 2.3 also collects the accuracy requirements that machine end-users have provided in the survey reported in [7].

Combining the experimental forces and the average requirements coming from the end users, it was stated that a static stiffness of 20 N/μm at the tool tip can be considered as a current typical threshold value for general-purpose milling machines.

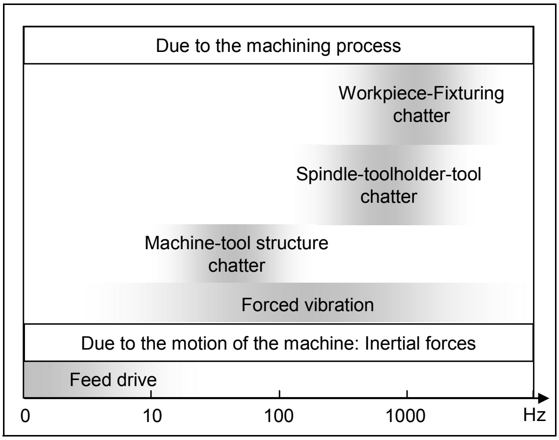
In addition to the requirement for static stiffness, dynamic stiffness is also an issue of special concern. Indeed, it is the primary reason to define the dimensions and shapes of the machine tool structural components. For an accurate definition of the threshold values for dynamic stiffness, the best utility available is the stability lobes diagram.

The stability lobes diagram is a plot that separates stable and unstable machining operations for different spindle speeds. Stable cuts occur in the region below the stability boundary, while unstable cuts (*chatter*) occur above the stability boundary [3]. An example of the stable and unstable regions is shown in Fig. 2.6. In Chap. 3 the current methods to obtain these diagrams are explained. Stability lobes are functions of the dynamic stiffness at the *tool center point* (TCP), the tool geometry, the radial immersion of tool into material, as well as of the material to be machined.

Machine manufacturers and users distinguish between two types of chatter, the so-called "structural chatter" or "machine chatter", which is a low frequency chatter, and the so-called "tool chatter", which appears at higher frequencies. In the former case, recognisable for a low-pitched sound, the chatter is associated with the structural modes of the machine, shown in Fig. 2.7. In the latter case, recognisable for a high-pitched sound, the chatter is associated with the modes of the tool or spindle. The type of chatter depends on the cutting frequencies; low cutting frequencies excite structural modes and high cutting frequencies excite spindle-toolholder-tool modes.

Therefore, the aim of an optimised machine is to ensure an acceptable critical depth of cut in every cutting direction, using the minimum movable mass. As a conclusion, the "minimum static stiffness" mentioned at the beginning of this section and the "minimum critical depth of cut" mentioned just above are the two thresh-

Fig. 2.7 View of main vibration sources in a milling machine



old values to consider in the machine design. That assures that an eco-efficient and lightweight machine is, at the same time, productive and accurate enough.

The machine mechanical modelling is a key to estimate the static and dynamic behaviour of a machine. Finite element method (FEM) based models are widely used, and will be explained over the course of the next section.

2.3.2 FEM Modelling

FEM aims at an approximation of the actual behaviour of a mechanical structure by assembling discrete and simple elements through nodes. The mechanical analyses that are conducted on a machine tool by means of FEM analyses commonly cover three stages:

1. The analysis of the static deformations and strain in a structure that is bearing static forces.
2. The analysis of natural frequencies and modes of the machine structure.
3. The analysis of the dynamic stability of cutting processes by means of analytical stability diagram lobes. The FEM can be used here as a calculation tool for the assessment of the *frequency response function* (FRF), instead of using the experimental modal analysis.

With FEM, the most complex aspect is that related to contacts between structural components along the degrees of freedom, in which stiffness, backlash and friction have a decisive influence on the damping of the machine. More than 90% of damping in a machine tool comes from bolted joints and from contacts in guideways [4]. In this respect, experimental modal analysis allows for the measuring of the natural frequencies and modes of an already-built machine, and above all allows for the measuring of their associated damping coefficients, which is the most difficult mechanical parameter to estimate. The experimental dynamic parameters allow the calibrating of the FEM models that were developed in the design phase.

The updated FEM models can be used to calculate the analytical stability lobes of the machine. Figure 2.8a shows the actual (left) and FEM modelled (right) FRFs of a milling machine at the TCP. Figure 2.8b and c show the stability lobes associated with previous FRFs for the downmilling case 45º and 225º with respect

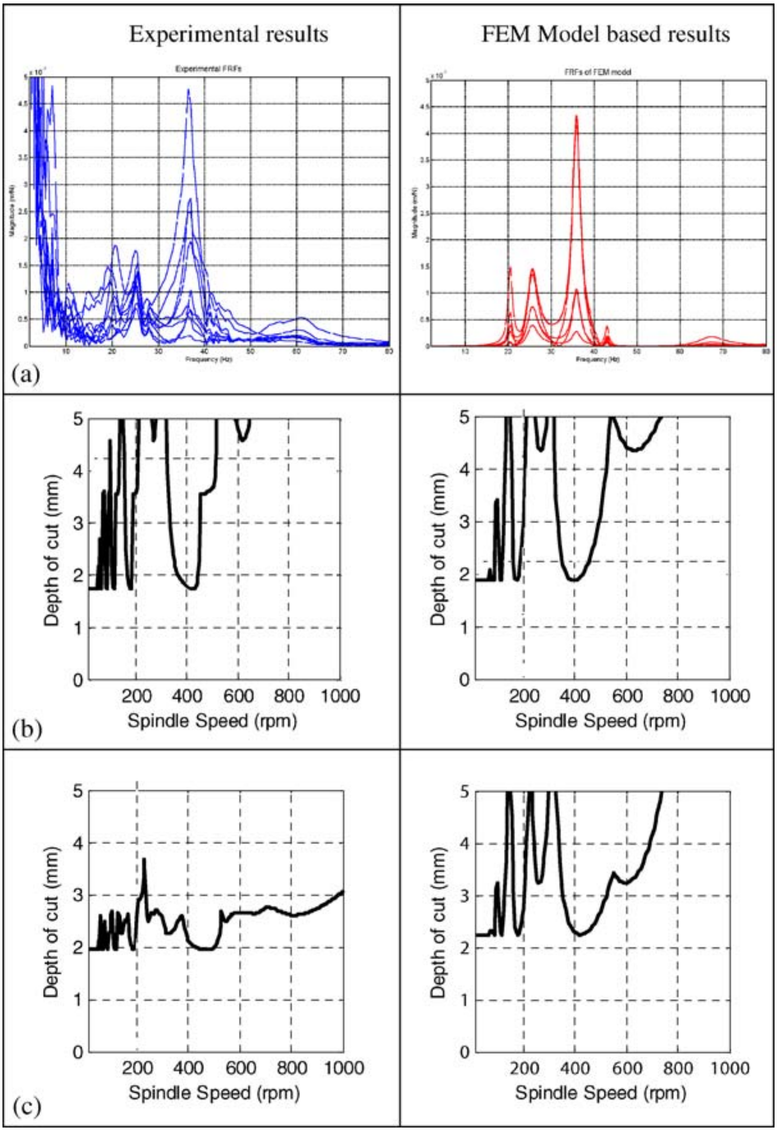


Fig. 2.8 **a** Experimental and FEM FRFs. **b** Corresponding stability lobes in the feed direction 0º, in up-milling. **c** Corresponding stability lobes in the feed direction 270º, in up-milling

to the machine axes. The experimental data shown in the left part of the chart have been achieved for a specific tool and a specific material to be machined. The right part shows the same stability lobe diagrams, with the only difference being that in this case data has been achieved from a FEM-modelled machine, in which the damping associated with each mode has been obtained from an experimental modal analysis on an already built machine.

As is shown, there is a good approximation in the 0º case and a 30% error in the 270º case. Otherwise, both the modelled-FRF and stability lobes diagrams show an acceptable level of coincidence with experimental-FRF and stability lobes. The advantage associated with modelled diagrams is that the machine models enables an evaluation of the effect of mechanical and architecture changes on the stability of cutting processes. Thus, it is possible to test several design approaches to lighten a specific machine and at the same time to validate that the aimed values of productivity are also achieved.

2.3.3 Topological Optimisation

As shown in previous sections, static stiffness and the critical depth of cut within stability lobe diagrams offer quantitative and objective parameters that allow a comparison of the performances among different machine concepts and above all, allow defining minimum thresholds to be fulfilled by eco-efficient machine tools. In fact, a reduction of masses that at the same time allows surpassing the threshold values defined for those parameters will allow an optimisation for that machine tool from the point of view of the eco-efficiency.

Focusing on reducing the movable masses, the topological optimisation of structural components is a critical issue, because this optimised mass-to-stiffness ratio will be the key to tackle effective strategies to reduce the total masses.

With the aim of supporting this objective, there are commercial programs with optimisation algorithms that starting with a given structural component remove material on that component until no further removal is possible without deteriorating the static and dynamic properties, achieving thus a topologically optimised component. What is more, an important additional objective of topological optimisation programs is to assure that the topologically and dynamically optimised structure can be manufactured in an economic way.

As an example, Fig. 2.9 shows the optimisation result for C-frame machine.

This typical structure, with a fixed support on one end and forces on the other end, has been used to analyse the performance of optimisation tools. This example shows that the topologically optimised structure (Fig. 2.9c) maintains almost the same stiffness as the original one, but with much less material [2].

With regard to the manufacturability and the economical feasibility of these optimised structures, the truss-like structures, which are the most frequent results of these automated topological optimisations, present some difficulties. As an example, cavities inside structures are difficult or impossible to manufacture. To allevi-

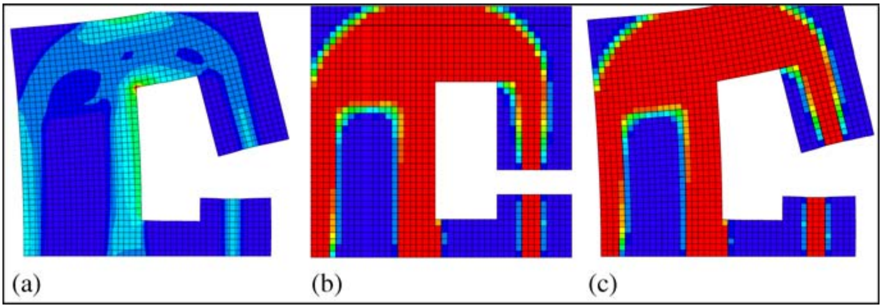


Fig. 2.9 Topological optimisation of a C-frame machine. **a** Stresses distribution map. **b** Results of the mass distribution to achieve the maximum stiffness. **c** Deformation of new distribution

ate this limitation, the automation programs include demoulding functionalities that make manufacturing possible, though the development of these parts will probably lead either to worse static and dynamic properties or to larger masses.

2.4 Structural Materials

When designing structural components to achieve eco-efficient, accurate and productive machines, the materials to be used play a key role in the final properties of components and those machines in which they are assembled. Structural materials have a decisive influence on movable masses, moments of inertia, static and dynamic stiffness and both the modal and thermal properties of the machine.

In the machine tool sector, the most commonly used materials are steel and cast iron, both of which offer an excellent stiffness-to-mass ratio as well as a good quality-to-price ratio. Nevertheless, there are materials whose properties can fit better to the specific needs of a concrete machine, as is explained over the course of the next section.

2.4.1 Involved Parameters

Regarding material properties, the most relevant features are shown, along with the influence on the behaviour of the machine:

a) Young's modulus E: High values of E have a positive influence on the static and dynamic stiffness of the machine.
b) Poisson's ratio ν and shear modulus G: High values for both are a positive influence on the machine torsional stiffness.
c) Density ρ: Low values of density within movable structures have a positive influence on the dynamic properties of the machine as well as on the bandwidth

of control loops, and at the same time high value density have a positive influence on the static elements of the structure, i.e., the base frames and beds.

d) Thermal expansion coefficient α: High values of α have a very negative influence on machine geometrical accuracy, so that the lowest possible value is desired for any case.
e) Specific heat capacity c: the low or high value of c neither positive nor negative per se. Indeed, high values of c make machines thermally stable to changing environmental temperature. At the same time, high values of c mean that machines take a long time to reach a steady state after they have been turned on, so that a trade-off is required between these two opposite effects. In this respect, the machine users usually prefer thermally robust machines when faced with changing environmental conditions, though in order to achieve stable conditions a longer period will be necessary. In such cases, a high value of c is desired.
f) Thermal conductivity k: Similar to the previous case, the low or high value of k is neither positive nor negative per se. Indeed, high values of k make machine temperatures become quickly homogeneous throughout the machine, thus avoiding partial and asymmetrical elongations in the machine. At the same time, high values of k make machines heat up in the presence of non-desired sources of heat such as motors, bearings *etc.* so that a trade-off is required between these two opposite effects. Machine users usually prefer thermally robust machines though it will lead to heat concentrations in the machine, so that in that case, a low value of k will be desired. One possibility to reach a trade-off between these two opposite effects is to have materials with low thermal conductivity k and in parallel to isolate heat sources or to evacuate heat by means of cooling systems.
g) Material and structural damping: High values of damping have a positive influence on the dynamic properties of the machine as well as on productivity, because high values of damping implies that stability lobes rise for a given cutting speed.

These properties are analysed for several materials and classified into two groups, the currently common structural materials and the innovative materials.

2.4.2 Conventional Materials for Structural Components

The most typical materials for machine tool structural components are, without any doubt, steel and above all cast iron. Steel is commonly used in welded structures; whilst for cast iron, the most common solutions are the sand casts obtained from grey cast iron and spheroidal graphite (ductile) cast iron [6]. Some parts such as headstock housings are made of cast steel.

The main advantages of these conventional materials are their low cost in comparison with other materials and their very good machinability, with possibility to

Table 2.4 Properties of materials based on Fe-C

	Steel	Grey cast iron	Ductile cast iron
Young's modulus	$2.1\cdot10^{5}$ MPa	$0.8–1.48\cdot10^{5}$ MPa	$1.6–1.8\cdot10^{5}$ MPa
Density	$7{,}850\ \mathrm{kg\cdot m^{-3}}$	$7{,}100–7{,}400\ \mathrm{kg\cdot m^{-3}}$	$7{,}100–7{,}400\ \mathrm{kg\cdot m^{-3}}$
Damping ratio	0.0001	0.001	0.0002–0.0003
Thermal exp. coeff.	$11\cdot10^{-6}\ \mathrm{K^{-1}}$	$11–12\cdot10^{-6}\ \mathrm{K^{-1}}$	$11–12\cdot10^{-6}\ \mathrm{K^{-1}}$

machine very accurate dimensions and geometric tolerances. Moreover, steel excels in terms of its high value of elasticity modulus and excellent mass-to-stiffness ratio, and the cast iron has a more than acceptable material-damping ratio, especially when compared to steel.

The main disadvantages are their relatively high thermal expansion coefficients, and in the case of steel, its very low material-damping ratio. Table 2.4 shows the main properties of these conventional materials based on Fe-C alloys.

2.4.3 Innovative Materials for Structural Components

In the sector of machine tools, materials other than steel and cast iron are not conventional for structural components, with probably some specific exceptions such as aluminium, granite and polymer concrete.

2.4.3.1 Polymer Concrete or Mineral Casting

Polymer concrete is a combination of mineral fillers graded according to their size distribution (flour, sand and different grits). The combination is bonded together using a resin system. Polymer castings are appropriate for precise machines due to their extremely low thermal diffusivity, which makes this material very stable and robust from the thermal point of view. Furthermore, its structural damping is similar to that of cast iron, although the Schneeberger® company claims its mineral casting achieves up to 10 × better values of vibration damping than steel or cast iron. Moreover, mineral-cast elements are resistant against oils, coolants and other aggressive liquids. This material includes different types of compounds and in the near future others will be developed, which will increase its application for machine tools.

2.4.3.2 Granite

Similar to the previous case, granite is appropriate for very accurate machines such as high precision milling machines and measuring machines, as a result of the excellent time stability of its properties and its good material damping (Table 2.5).

Table 2.5 Properties of polymer concrete and granite

	Polymer concrete	Granite
Young's modulus E	$0.4–0.5 \cdot 10^5$ MPa	$0.47 \cdot 10^5$ MPa
Density	$2{,}300–2{,}600$ kg$\cdot$m^{-3}	$2{,}850$ kg$\cdot$m^{-3}
Damping ratio	D = 0.002–0.03	D = 0.03
Thermal expansion	$11.5–14 \cdot 10^{-6}$ K^{-1}	$8 \cdot 10^{-6}$ K^{-1}

2.4.3.3 Fibre Reinforced Composites

Fibre reinforced composites have very high values of a specific modulus of elasticity and specific strength. Nevertheless, wider use of composites in machine tools is complicated due to some remarkable limiting factors such as their high price, their complicated joining and their complicated recycling. Indeed, the technical community is not familiar with common commercial machine tools with applied carbon fibre composites (CFCs), and in fact only some experimental research prototypes have been designed. Their mechanical properties in the fibre direction are collected in Table 2.6.

Table 2.6 Properties of CFC plates made from Prepreg[1]

	Middle modulus	High modulus	Ultra-high modulus
Young's modulus	$1–1.8 \cdot 10^5$ MPa	$1.7–2 \cdot 10^5$ MPa	$2–3.7 \cdot 10^5$ MPa
Density	$1{,}550–1{,}600$ kg$\cdot$m^{-3}	$1{,}550–1{,}600$ kg$\cdot$m^{-3}	$1{,}550–1{,}600$ kg$\cdot$m^{-3}
Damping ratio	0.001–0.05	0.001–0.05	0.001–0.05
Thermal expansion	$12 \cdot 10^{-6} \cdot$K^{-1}	$12 \cdot 10^{-6} \cdot$K^{-1}	$12 \cdot 10^{-6} \cdot$K^{-1}

2.4.3.4 Hybrid Materials and Structures

Structures using hybrid materials are usually developed and designed for specific elements. Therefore, it is important to know first the exact functionalities of the part that is to be developed, and then to find proper topological shapes as well as a macroscopic combination of involved materials [6]. A practical strategy is to use low cost materials such as steel or cast iron for the majority part, and then to use a minimal amount of high-cost materials in order to tune the properties of the part by means of computational analyses.

In the field of machine tool structures, the following hybrid structures are already known:

- Steel weld structure with polymer concrete fill: As a reference, the Spanish machine tool builder Nicolas Correa® has developed a ram made of sandwich of steel and polymer concrete. This ram displays higher damping, that has been

[1] A technique of draping a cloth over a mould with epoxi preimpregnated into the fibres

noticed in the stability lobe diagrams. Moreover, the thermal diffusivity of the machine has decreased considerably, which was one of the aims of Nicolas Correa® with respect to their customers. Furthermore, though the mass-to-stiffness ratio of polymer concrete is worse than of steel, they have achieved a 20% ram mass reduction by means of topological optimisation rules.

- Steel weld structure with foamed aluminium filling: the same company has also developed a ram made of sandwiches of steel and aluminium foam, which has shown higher damping for the whole machine. Nevertheless, this increase of damping has been anyway lower than the increase achieved when using polymer concrete.

2.4.4 Costs of Design Materials and Structures

A global view of the purchasing costs of materials and semi-finished structures, such as welded structures, is shown in Table 2.7. The table summarises the values of minimum and maximum costs found on the European market. Moreover, a value called the "specific cost" has been added, which contains information regarding the material cost and the value of the specific modulus. This is an interesting piece of information significant to the design of eco-efficient machines, since the high life cycle cost associated with the machine production time, highly recommends the use of lightweight materials.

Table 2.7 Cost of materials and structures suitable for machine tool design

	Cost [€/kg]		Specific modulus [MPa/kg·m^{-3}]	Specific cost [€/MPa·m^3]	
Design materials	Min.	Max.	Average value	Min.	Max.
Steel-welded structures	3.5	7.0	26.5	0.13	0.27
Grey cast iron	2.0	4.0	16.0	0.10	0.37
Spheroidal graphite cast iron	3.0	6.0	23.5	0.12	0.28
Polymer concrete	2.0	5.0	18.5	0.09	0.33
Granite	3.5	6.0	20.5	0.14	0.36
Technical ceramics	10.0	36.0	107.0	0.07	0.47
CFC plate, middle modulus fibre	110.0	150.0	89.5	0.95	2.40
Hybrid materials & structures	21.0	130.0	62.5	0.21	5.20

2.4.5 The Influence of Innovative Materials on Productivity

The inclusion of materials with high internal damping is always interesting to increase the productivity of the machine from the point of view of the stability

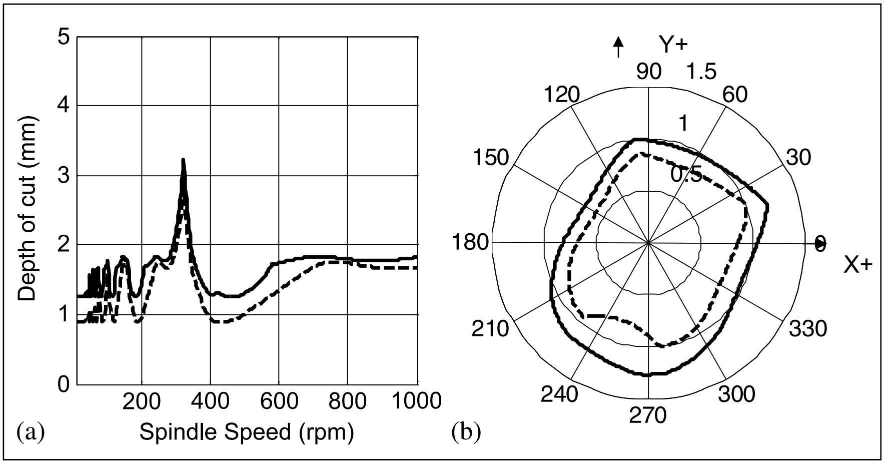


Fig. 2.10 Effect of material damping on stability lobes. **a** Feed in Y-direction. **b** Polar plot of the critical depth of cut at every direction

lobes diagram. On the other hand, the balance of internal energy dissipation is low with respect to the total energy dissipation of the machine.

As a reference, Fig. 2.10 shows the stability lobes of a machine with a structural ram bending mode of 37 Hz. The initial ram, made of welded steel, was substituted by a steel-polymer concrete sandwich. After this material substitution, the machine stiffness as well as the total mass remained almost the same, whilst the damping increased due to the effect of the polymer concrete. The stability lobe diagrams show that for a tool with a 125 mm diameter, the increase of damping associated with the polymer concrete allowed an increase in the critical depth of cut in all the speed range and for all feed directions (see Fig. 2.10b).

2.5 Active Damping Devices

In previous sections, the reduction of mass in movable components of a machine has been demonstrated to be a key point in the achievement of high eco-efficiency. Where static stiffness is concerned, the aim is to remove mass maintaining a threshold value of stiffness, and for dynamic stiffness, the aim is to maintain the productivity, limited by the stability lobe diagrams, in which the minimum values of the stability limits are dependent on the structural stiffness and damping ratio of the machine.

Within this view, an interesting machine tool design approach is to conceive it to be as light and low-stiff as possible, while at the same time increasing the damping of the machine to the equivalent proportion. Therefore, additional damping passive systems such as friction slides, viscoelastic materials and viscous fluids are interesting, as well as the use of *active damping devices* (ADDs). A typical ADD consists of a vibration sensor, an inertial actuator and a controller. ADDs are based on the principle that an acceleration of a suspended mass results in a reaction force towards the supporting structure. In order to tune the acceleration an embedded sensor monitors the supporting structure vibration; the sensor's readings are sent to an external feedback controller that drives the internal electromagnetic actuator of the ADD. As a result, these devices can damp the vibration modes that they observe in an open-loop transfer function [1].

2.5.1 The Implementation of ADDs to Machine Structures

Active devices add damping to the machine independently of its dynamic properties; therefore the correct implementation of ADDs to machine structures lies in defining how to locate the sensor and the actuator. In this respect, the best option for locating an actuator and a sensor is to know the FRFs of the machine at the *tool center point* (TCP).

From the FRFs, the maximum modal amplitudes to be reduced can be observed, which in most cases are associated with the compliance of the most flexible components such as rams and columns. The ideal place to locate the actuators is the *tool center point*, so that ADDs are placed as close as possible to it. Thus, in machines that have a movable ram, a good place to allocate ADDs is at the end of the ram close to the headstock, as illustrated in Fig. 2.11.

In Fig. 2.11, two ADD-45N of Micromega® have been placed on both sides of a horizontal ram to damp the two main ram bending modes well above 20%. More concretely, this additional active damping has allowed an average 2% of modal damping in the bending modes' rams to become an average 4% in terms of modal damping (see Fig. 2.12).

This data is very valuable when integrated in an FEM model of a machine, because if ADDs have enabled damping on modes above 20%, then the ram stiffness is able to be reduced by 20% maintaining machine productivity and therefore achieving a remarkable reduction in the total mass of the machine. In the following sections, this

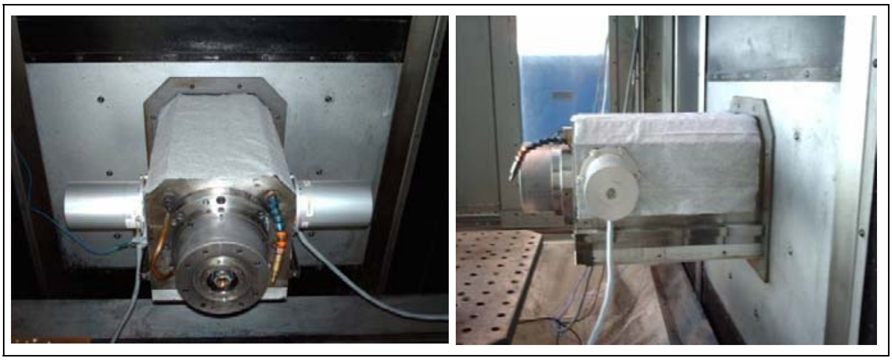


Fig. 2.11 ADDs placed on the ram of a milling machine, by Fatronik®

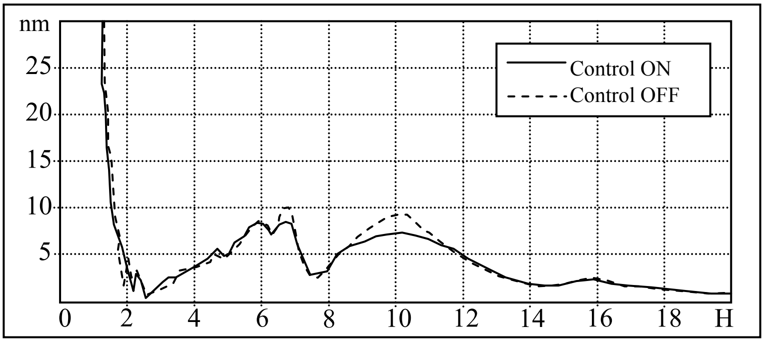


Fig. 2.12 FRF of a horizontal milling machine with and without active control

modelling of machines that incorporate passive and active damping devices are analysed thoroughly.

2.6 The Influence of New Structural Concepts on Productivity

Previous sections have analysed how the dynamic behaviour of the machine structure affects the dynamic stability of the cutting processes, especially in the 0–100 Hz frequency range, at which low-frequency modes of the machine structure can be detected. These structural machine modes can be modelled by means of either FEM or lumped-parameter models, allowing both models the calculation of the compliance and the FRFs at the TCP.

Though FEM models are more accurate, lumped-parameter models are more flexible, in the sense that they can provide qualitative information that can be very useful for designers in the machine conception phase.

Thus, taking as reference the machine whose FRFs were shown in Fig. 2.8, they showed a main mode at 37 Hz that a modal analysis confirmed that was associated to the bending of its horizontal ram. For that machine and that mode, a mechanical system of one degree of freedom has been used, on which modifications of mass, stiffness and damping can be applied. On the other hand, in order to obtain the stability lobe diagrams, a 125 mm diameter cutting tool with 9 edges that machines AISI 1045 steel has been considered.

2.6.1 The Influence of New Design Concepts for Structural Components

Taking as our reference the machine mentioned above, and focusing on the 37 Hz mode, which has been modelled as a system of one degree of freedom, the following design approaches may be conducted:

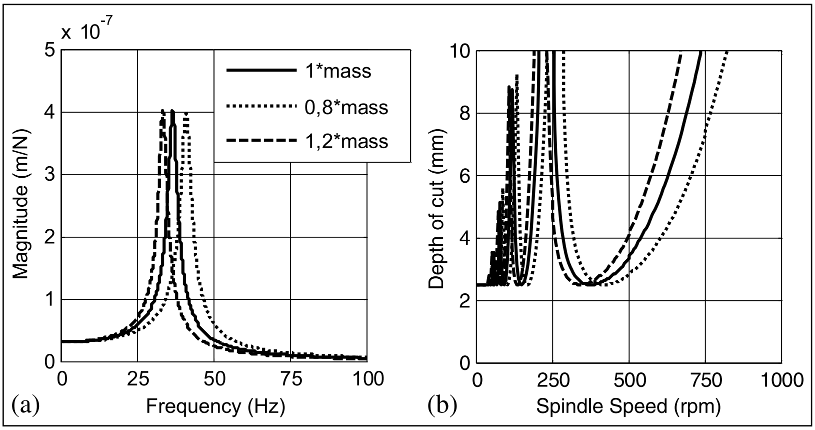


Fig. 2.13 Effect of variable mass and same stiffness on the following. **a** Direct FRF in X. **b** Stability lobes

If this design criterion is applied, the stability areas among lobes increases and the critical depth of the cut remains steady, so that the influence of this design concept is relatively low.

1. *To keep the stiffness associated to the mode, modifying the modal mass.* This makes the frequency response move horizontally, i.e., towards lower frequencies for higher masses and towards higher frequencies for lower masses (see Fig. 2.13). Its effect on the stability lobes is that they also move horizontally along the graph, and in the same direction as in the frequency domain.
2. *To maintain the mass associated with the mode and increase the stiffness associated with the mode.* This design concept increases both the natural frequency

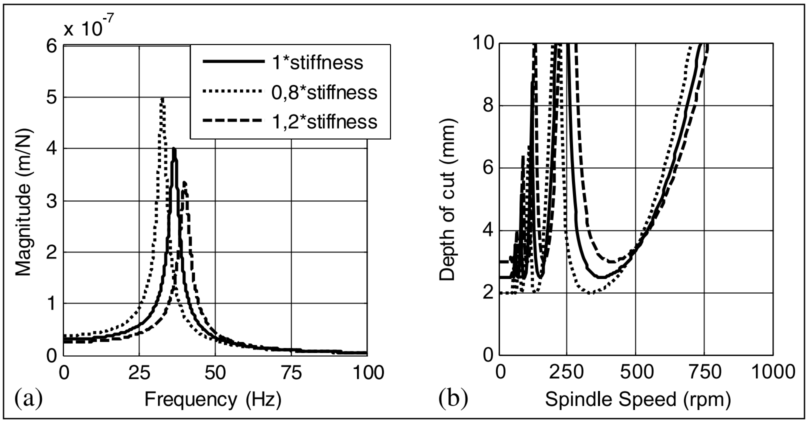


Fig. 2.14 Effect of variable stiffness and same mass on the following. **a** Direct FRF in X. **b** Stability lobes

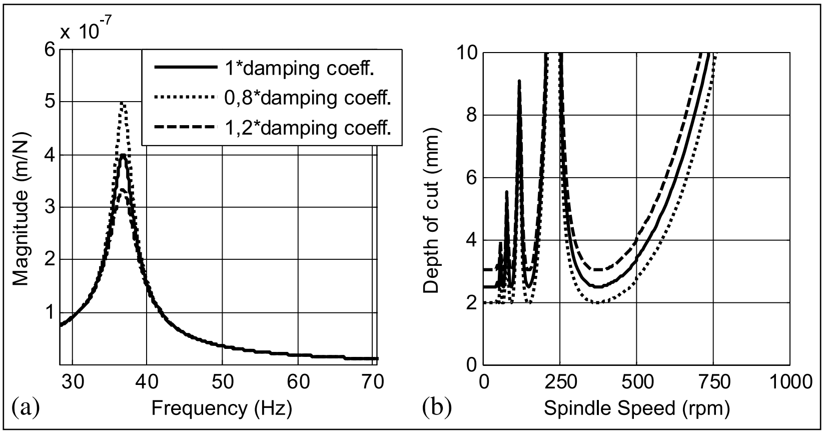


Fig. 2.15 Effect of variable damping on the following. **a** Direct FRF in X. **b** Stability lobes

and dynamic stiffness of the ram, and makes the stability lobes move horizontally towards higher spindle speeds and, above all, makes the lobes move upwards, so that the critical depth of cut increases (see Fig. 2.14).

When this design criterion is applied, the stability areas between lobes increases and simultaneously the critical depth of cut increases, so that this design concept allows for an increase in the productivity of the machine. In fact, the percentage increase in terms of stiffness is directly translated into an increase in the critical depth of cut. As an example, if the stiffness increases by 20% with the same mass, the critical depth of cut also increases by 20%.

3. *To increase damping associated to the modes.* This design concept reduces modal deformation at natural frequencies and causes the stability lobes to move vertically, increasing thus the critical depth of cut (see Fig. 2.15). Static stiffness does not change.

Table 2.8 Overview of the effect of the three design approaches on the dynamics of a 1 degree of freedom modelled machine

Design approach	Frequency, ω	Static deflection, δ	Max. dynamic amplification, D
Mass variation: $m = x \cdot m_0$	$= \left(1/\sqrt{x}\right) \cdot \omega_0$	$= \delta_0$	$\approx D_0$
Stiffness variation: $k = x \cdot k_0$	$= \left(\sqrt{x}\right) \cdot \omega_0$	$= (1/x) \cdot \delta_0$	$\approx (1/x) \cdot D_0$
Damping variation: $\xi = x \cdot \xi_0$	$= \omega_0$	$= \delta_0$	$\approx (1/x) \cdot D_0$
Nomenclature:			Basic formulation:
ω: Natural frequency δ: Static deflection D: Max. dynamic amplification	k: Stiffness m: Mass ξ : Damping ratio x: Variation ratio (per unit)		$\omega = \sqrt{(k/m)}$ $D \approx (1/2\xi) \cdot \delta$

Similar to the previous case, the percentage increase in damping is directly translated to an increase of the same percentage in the critical depth of cut. Therefore, it is possible to reduce the machine stiffness by a specific percentage, with its subsequent associated reduction of mass, maintaining the productivity of the machine.

The three approaches are summarised in Table 2.8, which provides an overview of the influence of the mass, stiffness and damping variation on the natural frequency, the static deflection and the maximum dynamic amplification.

Given the fact that the damping variation approach increases the productivity of the machines without a penalisation of mass, the method of active damping will be analysed thoroughly here.

2.6.2 The Influence of ADDs on Productivity

The influence of material damping is low on the total damping of a machine. Thus, in the case that a higher amount of damping is required to further increase the productivity of the machine, ADDs are an interesting option.

Figure 2.16 shows the influence of having placed the two ADD-45 of Micromega® shown in Fig. 2.11 in the direction X of an actual horizontal milling machine. As can be seen, the additional damping that these two actuators have added to structural modes has allowed a move in the critical depth of cut in all cutting directions, (the effect being especially high in the direction in which the actuators were placed). As a result, it can be seen in the diagram in Fig. 2.16a, that the critical depth of cut in direction X (0° in the polar diagram) has passed from the initial 1.7 mm (dashed line) to almost 8 mm (continuous line). The introduction of damping can be extended to the rest of the directions by placing additional ADDs on the ram of the machine.

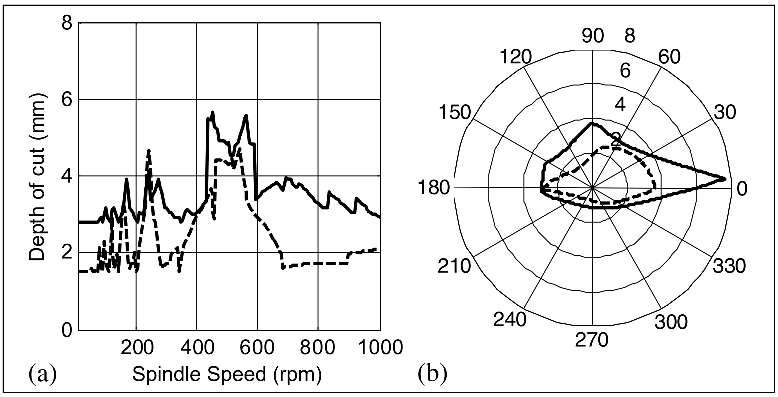


Fig. 2.16 Effect of active damping on stability lobes. **a** Feed in Y+ direction. **b** Polar plot of the critical depth of cut at every direction

2.7 Future Trends in Structural Components for Machines

The main trend in the field of structural components is the *de-materialisation* of their structural components, passing from stiffness-aiming machines to lightweight and robust machines, as seen in Fig. 2.17. This can be tackled mainly by integrating in the structural components active elements such as active piezo-layers, active damping devices and magneto-rheological fluids. In fact, these ubiquitous sensors and actuators will allow the passing from current machine conceptions based on mechanical stiffness to innovative machine conceptions based on mechatronic robustness, similar to axes levitating on magnetic bearings, which show a precise and robust behaviour despite not having any mechanical support.

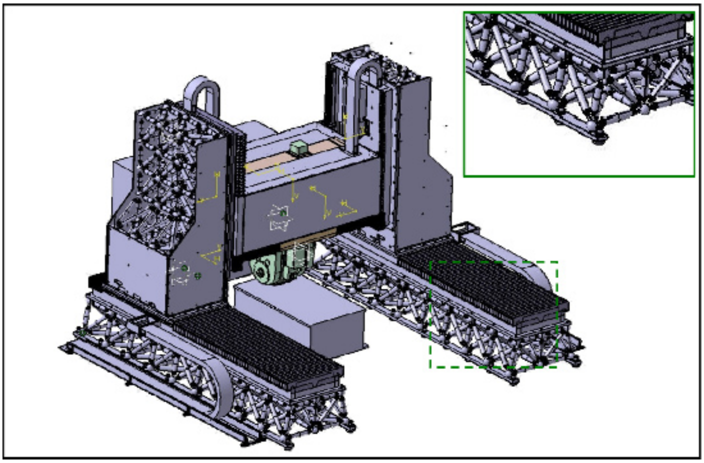


Fig. 2.17 Prototype with structural parts made with ball-bars frame, by Fatronik®

Finally, current machine specifications are defined as a trade-off between productivity, accuracy and surface quality. Within a view of sustainable machine tools and processes, this chapter has introduced a new triangle of specifications based on productivity, accuracy and above all, eco-efficiency.

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