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structural parts of machine tools
machine tools lightweight design
non-conventional materials in machine tool design
feed drive complex model

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APPLICATION OF UNCONVENTIONAL MATERIALS ON PRIMARY STRUCTURAL PARTS OF MACHINE TOOLS

The paper is mainly focused on possible domains of application of composite sandwich materials in the field of machine tools. A theoretical case study analyzing the effect of application of composite sandwich materials on the dynamics of the X-feed-drive axis of the horizontal milling machine is presented. The benefits of composite sandwich materials are discussed and summarized in the context of modern machine tools and their desired static and dynamic properties. Experimental case study is also presented.

1. INTRODUCTION

The whole machine tool branch is nowadays looking for proper ways to improve machine tool parameters and the utility value of MT for manufacturers. We can recognize these perspective domains to improve parameters of future machine tools:

1. Optimal design of machine tools primary frame and drives supported with advanced and modern virtual prototyping methods and simulation technologies including mechatronic simulations, topological optimization method, advanced FEM simulations, coupled field simulations etc.

2. Implementation of new sensors, actuators and methods for a better drives control, geometrical compensations determination and machine tool geometry corrections. There can be recognized an increased focus to research and implement new self-learning methods and self-adapting strategies to raise “intelligence” of machine tools.

3. Usage of advanced components and mainly advanced and unconventional materials and material structures in the field of primary structural parts of machine tools. Many current research projects are focused on finding a proper field to use advanced materials and material structures in the machine tool branch.

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The above mentioned list is not complete but it summarizes important orientations in the research and development activities in the machine tool field.

There are briefly presented perspective unconventional materials and a simulation case study of a milling machine with a sandwich structure in this paper. At first, an importance of design materials for the fundamental machine tool properties will be illustrated. Afterwards, there will be described simulation tests made on a virtual prototype of the X-axis with a sandwich structure column.

2. UNCONVENTIONAL MATERIALS

The most common and typical materials for machine tools body and main parts design are steel and cast iron. Main parts made as steel welded structures are used less commonly. Relatively old but not widely used materials are polymer concrete and granite.

When thinking about new machines with high reduction of movable masses and excellent modal parameters it is necessary to think about new and unconventional materials. The following table contains basic overview and comparison of common materials used in the field of machine tools with Al alloys, carbon fibre composites, ceramics and hybrid materials.

We can find remarkable values in the table 1 (Fig. 1) (marked in orange). It seems that structural parts made from carbon fibre composites or technical ceramics can have very good stiffness and modal parameters. However, hybrid structures are closer to real applications from the cost point of view.

		Density [kg/m^3]	Young's modulus E [GPa]	Specific modulus (E/density) [10^6.m^2/s^2]	Modal damping	Costs and design difficulty
Common materials	Grey cast iron	7100-7400	80-148	11-21	***	*
	Spheroidal graphite cast iron	7100-7400	160-180	22-26	**	**
	Steel (welded steel structures)	7810-7860	205-210	26-27	*	**
Unconventional materials	AL alloys and composites	2600-3460	70-81	20-31	*	***
	Granite	2600-3150	47-66	15-25	**	***
	Polymer concrete	2300-2600	40-50	15-22	***	***
	Carbon fibre composites	1550-1600	100-630	63-406	***	******
	Ceramics based on Al and Si	3150-3500	270-430	77-137	*	*****
	Hybrid materials and structures	2500-4000	100-250	25-100	***	****

Fig.1. Properties of common and unconventional materials in the field of machine tools

Importance of the material choice for machine tool properties is more in detail described in [9]. In this paper there are shown relationships between material changes and the machine fundamental properties.

3. CASE STUDY – MACHINE PRIMA S

3.1 MACHINE DESCRIPTION

Not all the parts of a machine tool are proper for material changes. It seems clearly from many measurement performed in RCMT on three or four axes milling machines that the worst dynamic behaviour has the X-axis. This is very often caused by the first parasitic eigenmode of the vertical column. That is why it was decided to concentrate on this type of machine and on the X-axis.

The machine tool called Prima S is one of the possible configurations of the milling machine series Prima from production of the Czech machine tool manufacturer TOS Varnsdorf, a.s. The following simulation study and a case study are made on the basis of a virtual prototype of this machine. The machine Prima S is a four axis milling machine with a horizontal spindle and a rotary table. The maximal strokes at axes are: X_{max} = 1400 mm, Y_{max} = 1400 mm, Z_{max} = 700 mm. The basic weights are: ram and cross slider m_{ram} = 1080 kg; spindle m_{spi}= 200 kg; column (steel welded structure) m_{col} = 4370kg; the total mass of all movable parts of the X-axis m_{totX} = 5650 kg. Basic outside dimensions of a steel welded column: hight L_{colY} = 2680 mm; width L_{colX} = 900 mm; depth L_{colZ} = 910 mm. The drive of the X-axis is based on a rotating ballscrew with a belt transmission and a servomotor from the serie Siemens 1FT6.

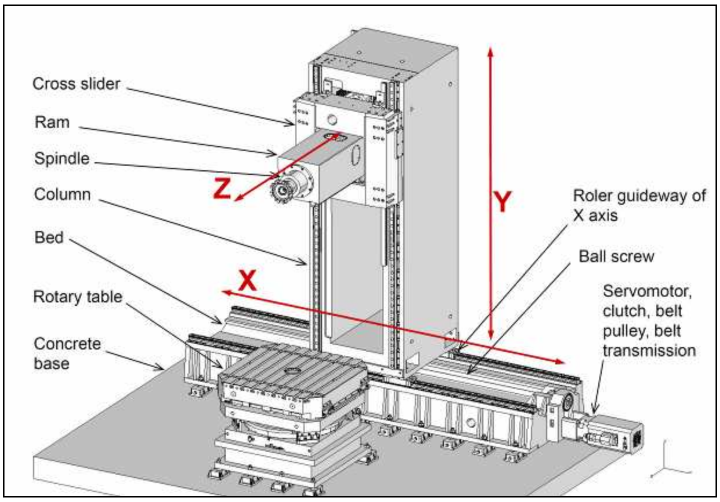

Fig. 2. Machine Prima S

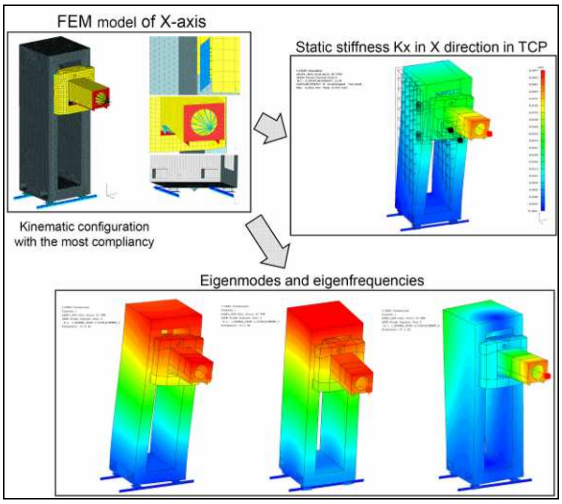

Fig. 3. FE model of the machine

The most important parameters determinated by the mechanical parameters of the machine tool frame are static stiffness, modal parameters and total mass. These resulting properties are observed in relation with changes of material, dimensions and structure of the machine tool column. The first antiresonance frequency of the X-axis drive was also observed on the tested machine. Figure 3 demonstrates basic results of static stiffness and eigenmodes from a FEM model.

3.2. AN ALTERNATIVE DESIGN AND THE DESCRIPTION OF VARIANTS AND MATERIALS

There have been prepared 24 alternative variants of X-axis design for the purpose of the study of an influence of materials and structure changes on the resulting qualities of the whole X-axis. The respective variants differ in these parameters:

a) Four different widths of the column in X direction: 900mm (100%), 1020mm (113%), 1100mm (122%) and 1200mm (133%).

b) Three different materials of the outside skin of the sandwich: i) Prepreg based carbon fibre laminate (LAM-I.) with high strength carbon fibres (lamina properties: E_X = 74653MPa, E_Y = 27449MPa, G_{XY} = 16987MPa); ii) Prepreg based carbon fibre laminate (LAM-V.) with high modulus carbon fibres (lamina properties: E_X = 370000MPa, E_Y = 5500MPa, G_{XY} = 4000MPa); iii) Steel plate (E=206000MPa, G=80155MPa).

c) Two different thicknesses of the outside skin of the sandwich: T_{20}=20mm and T_{30}=30mm.

An alternative column is designed as a hybrid structure which combines a basic steel welded structure and closed sandwiches on the side of the column. The sandwiches are made from core and skins. The most stiff aluminium foam ALPORAS from Gleich GmbH Company is used as a core material. The basic material parameters of aluminium foam are: density=268 kg.m^{-3}, static share modulus G_{CS}=225 MPa and dynamic share modulus G_{CD}=466 MPa. The mechanical parameters of ALPORAS foam were derived from series of our own static and dynamic laboratory experiments.

All FEM models are built up in system I-DEAS and the used modelling strategies for composites are verified by experiments on sandwich samples.

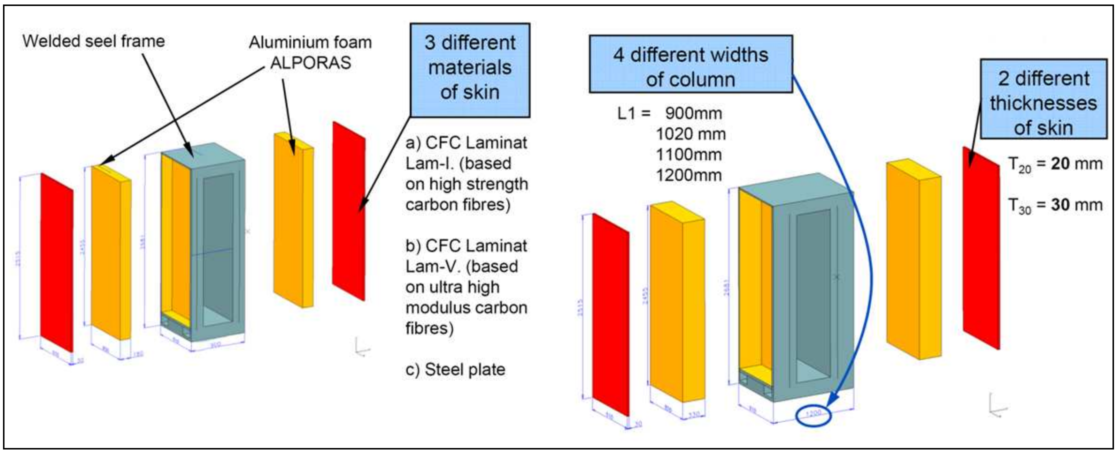

Fig. 4. Alternative variants of the column.

3.3. RESULTS FROM FEM MODEL

There has been made a FEM model for each individual alternative variant and values of static stiffness Kx. The first eigenfrequency and the total mass of the X-axis were obtained. Static stiffness results were derived from a model with static material properties of core aluminium foam and results for modal properties from a model with dynamic material properties of AL-foam. The FEM models have been designed on the basis of the classical laminate theory and with respect to [1]-[3].

Results of all 24 variants in comparison with the value valid for the original design of the X-axis and the column (red marked value) are shown in the following figures.

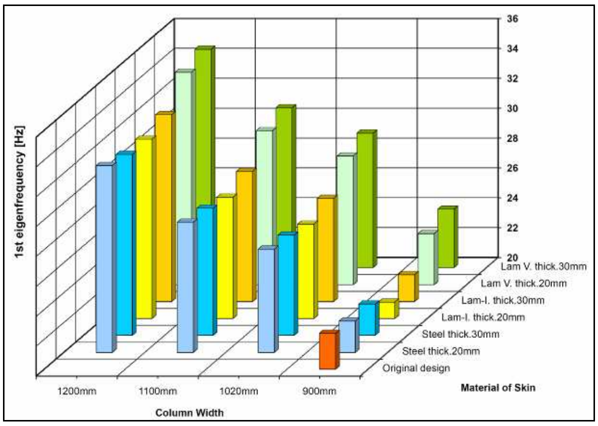

Fig. 5. 1st eigenfrequency of a parasite eigenmode corresponding to the X-direction.

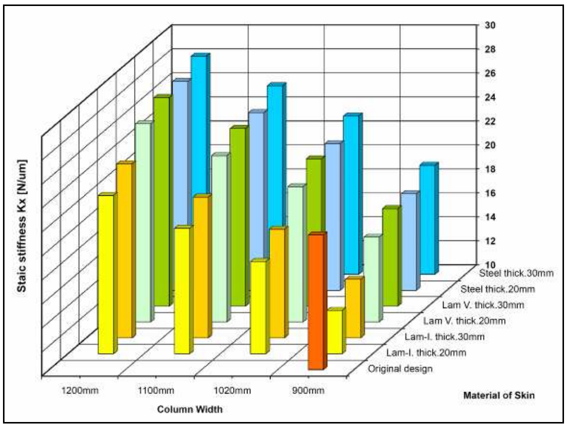

Fig. 6. Static stiffness Kx in X direction read in the tool centre point (TCP)

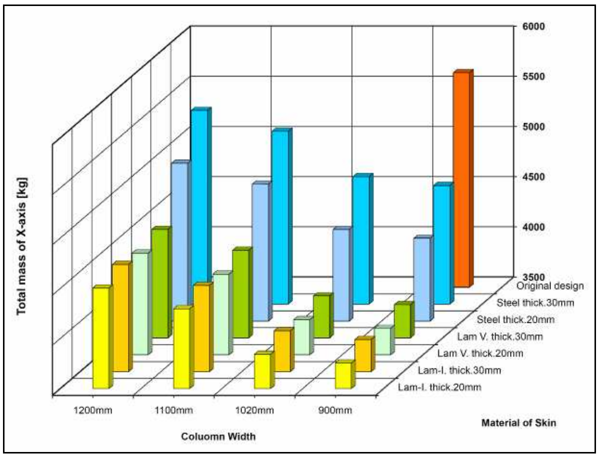

Fig. 7. Total mass ox the X-axis including all movable parts

All the alternative variants have lower total mass than the original design. It is evident from Fig. 5 that the first eigenfrequency is very strongly dependent on the column width and that variants using laminate skins based on ultra-high modulus carbon fibres bring very good results. The monitored value of static stiffness is very closely dependent on the column width as well and variants with steel skins and skins made from ultra-high modulus carbon fibres composite give good results in this case.

From the static stiffness point of view we can claim that results are not satisfying for all the alternative variants with column width 900 mm (with the exception of the variant 900-30-LamV) and for the variants with Lam-I used as a skin and with the column width 1020mm. All the other alternative variants have comparable or even better values of static stiffness. We will not consider any variants with static stiffness lower than the value for the original design in the following observation.

3.4. DESIGN OF OPTIMAL DRIVES AND A COMPLEX MODEL

The dynamical properties of the virtual X-axis including first antiresonance frequency were investigated. Obtained results were important for design of sufficient drive configuration. Variants with the best parameters were chosen among all the alternative variants on the FEM results basis and these variants were sorted into groups with similar total mass. There were created three mass groups in this way: 5600kg, 4500kg and 3900kg.

Group with 5600kg: 1200-30-LamV-4578 kg; 1200-20-Steel-5070 kg; 1200-30-Steel-5428 kg

Group with 4500kg: 1020-20-Steel-4409 kg; 1200-20-LamI-4501 kg; 1200-30-LamV-4578 kg

Group with 3900kg: 900-30-LamVl-3830 kg; 1020-20-LamI-3840 kg; 1020-30-LamV-3917 kg

Design of the feed drive components and parameters has been solved by means of the RCMT specialized expert software system called DDR [10]. The particular components and parameters (the motor, the gear ratio, the ball screw lead, the diameter of the ball screw, the size of the belt pulley, etc.) have been designed optimally for the specific mass group.

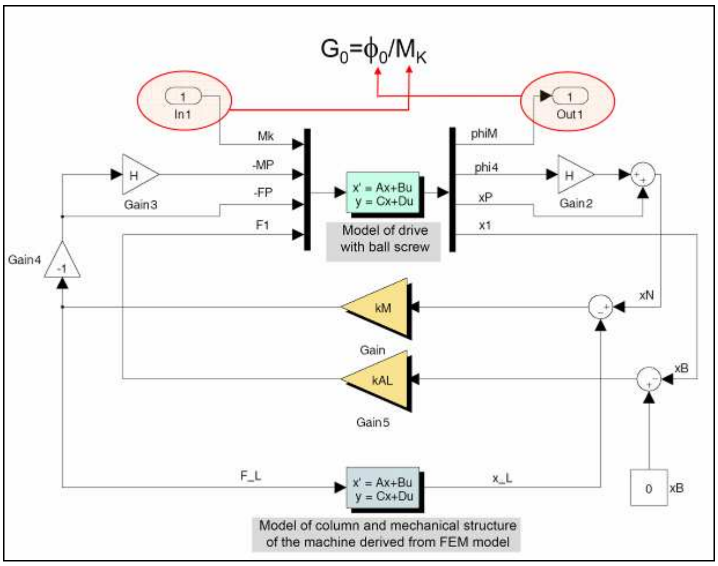

Fig. 8. Scheme of a virtual model of the X-axis.

Then a virtual model of the whole X-axis based on a FEM model of the mechanical structure and a separate mathematical model of the drive has been derived, see Fig.8 for the details.

The description of the X-axis dynamic properties is based on the modal decomposition technique in modal coordinates and on transformation into the state-space expressed by means of the A, B, C and D matrices.

Figures 9, 10 and 11 show the resulting computed transfer function $G_0=\phi_0/M_K$ with the first antiresonance frequency. As high value of the first antiresonance frequency as possible is the usual need for a design process of a machine drive and frame because it is known that the value of the first antiresonance frequency of the drive has direct and strong influence on the general axes and drive parameters and behaviour. Each individual alternative design variant of the X-axis gets a different resulting value of the first antiresonance frequency and this simple and discrete value can be used to judge each alternative design.

3.5. RESULT OF SIMULATION STUDY DISCUSSION

A) The alternative variant with the lowest mass and with dramatically reduced parameters and sizing of drive's components.

The alternative variant 1020-30-LamV-3917 kg has static stiffness slightly higher than the original design but this design solution has the total mass lower by 1.7 tons. The motor used for this variant is from lower size series (it means the lowest price of the motor as well as lower size and price of the drive unit). The applied ball screw has diameter 63 mm instead of the original value of 80mm and it has smaller size of the clutch. Furthermore, the resulting antiresonance frequency (24.6Hz) is about 20% higher comparing to the original design (20.4Hz).

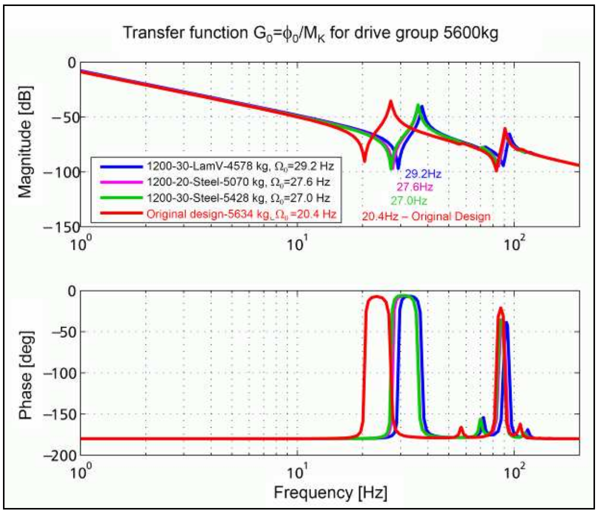

Fig. 9. Transfer fn.$G_0=\phi_0/M_K$, drive group 5600kg.

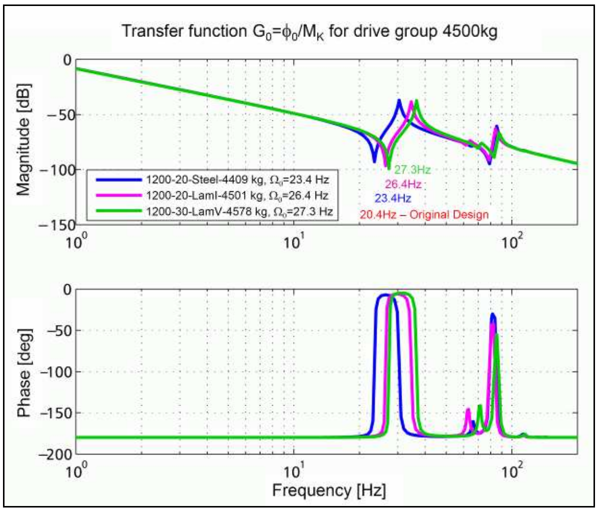

Fig. 10. Transfer fn. $G_0=\phi_0/M_K$,drive group 4500kg.

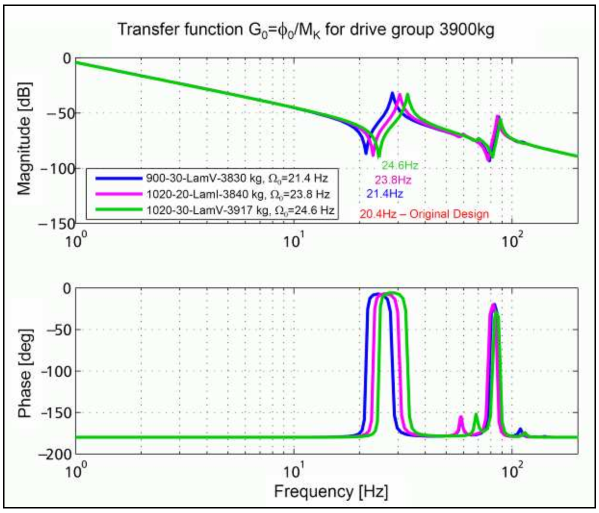

Fig. 11. Transfer fn. $G_0=\phi_0/M_K$, drive group 3900kg

B) The alternative variant with the highest value of the first antiresonance frequency.

The alternative variant 1200-30-LamV-4578 kg has static stiffness higher than the original design by 33%, however this design solution has the total mass lower by 1.1tons. The used motor and the other servodrive components are the same as for the original design however the resulting first antiresonance frequency 29.2Hz is about 43% higher than in the original design (20.4Hz). From the cost point of view then the saved 1.1tons of the steel column respond to approx. 3200EUR. Contrariwise, additional costs of the laminate skins are approx. 25000EUR and costs of aluminium foam ALPORAS are approx. 14000EUR.

Other interesting alternative variants with relatively cheap outside skins of a sandwich made from steel or high strength laminate are mainly: 1200-20-LamI-4501 kg, 1020-20-Steel-4409 kg, 1200-20-Steel-5070 kg. Unfortunately, these alternative variants have poor resulting properties comparing to variants with skins made from ultra-high modulus carbon fibre composite.

3.6. EXPERIMENTAL DATA OBTAINED ON REAL STRUCTURE

Based on the mentioned facts and presented analysis a project of an alternative column structure development has been launched. This research project, which is focused on the experimental evaluation of the simulated properties, represents one of the projects solved under the RCMT main research program financially supported by the Ministry of Education of the Czech Republic. Alternative design of column part was derived from the real machine tool column design (see Fig. 12). Basic structure of the column is steel welded frame with diagonal internal ribs. Alternative design is based on the steel welded structure, however, the lateral walls are thicker and made as sandwich-structure plates. Sandwich structure is composed of steel plate skins and aluminium foam core (See Fig. 13), for which ALPORAS foam from the Gleich GmbH Company is used. All the design was optimised with respect to the weight, static stiffness and modal parameters using the simulation procedure introduced in previous chapters.

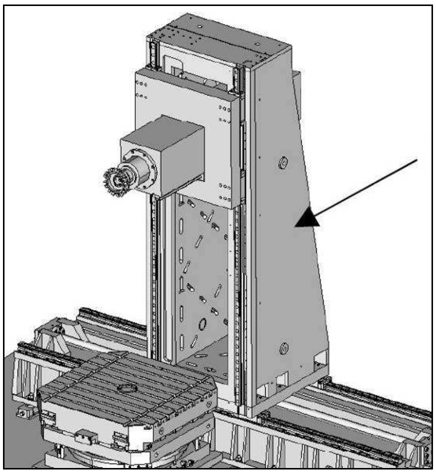

Fig. 12. Actual structure of Machine Prima S with modified column made as a steel welded structure.

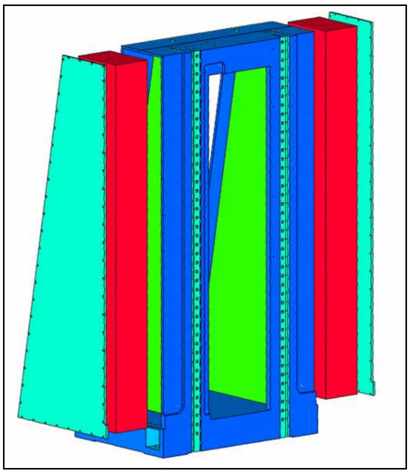

Fig. 13. Alternative design of column with the side plates made from sandwich panels.

Alternative column part was made using relatively complicated technological procedure. The procedure is in more detail presented in [7] and [8]. Most difficult technological problem was the joining of foam core and the steel structure. The core has to be made as precise as possible with respect to real dimensions of the side packets in steel welded base frame. Aluminium cores are glued into the side pockets and as a final step steel plate skins have been glued and fixed by screws. Picture illustrating the manufacturing of the alternative column is given in Fig. 14. and Fig. 15.

Fig. 14. Alternative column manufacturing. Picture shows glue application on the aluminium foam core (made from Alporas foam)

Fig. 15. Alternative column with glued-on cores before montage of side covering plates.

At the same time, measurements of the common column and alternative column properties have been performed. Attention has been focused on static stiffness measurement and modal analysis. Static stiffness measurement was made on the columns fixed on the bottom side at the position proposed for linear guideway fixing. Column was always loaded by the dynamometer at the top of the column, whereby the displacements have been measured from the external, independent frame structure. Modal analysis measurement was performed in the configuration of vertically laying and unanchored columns. The excitation of vibrations was made by the modal hammer. Using the accelerometers and B&K software, eigenmodes and modal parameters were evaluated.

Global results derived from the first experimental work made on the both columns provide interesting data. The original design weight is 3420 kg, alternative design features the weight of 2690 kg, which means the 730 kg reduction of the machine tool movable mass. Original design is characterized by the stiffness value of 34,2 N/μm in the *X* direction, while the alternative design features the value of 73,5 N/μm. This higher value is result of the application of the sandwich structure and also increased width of the column. The static stiffness in the *Z* direction is compared in the next step. Original design provides 127 N/μm while the alternative design 196 N/μm. Concerning the modal parameters, all of the structural bending modes are characterized by the frequency values elevated by about of 20 %.

Fig. 16. One of the experimental arrangements of both columns (common and alternative) for static stiffness measurement

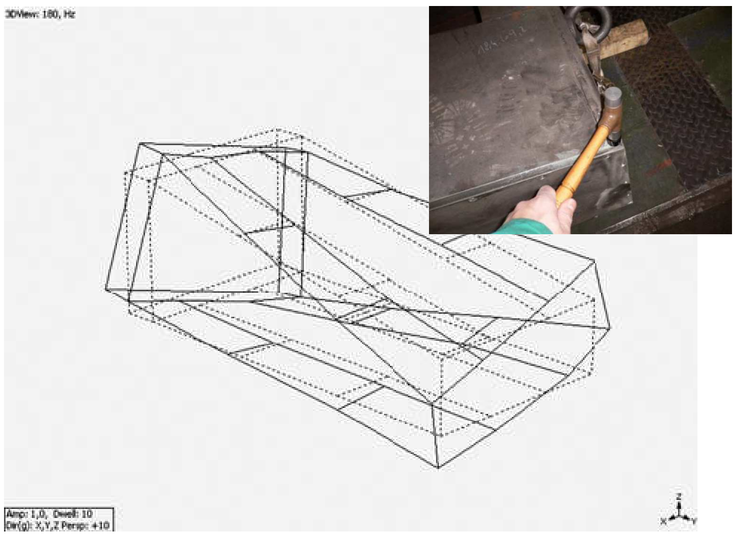

Fig. 17. Example of measured eigenmode and experimental arrangement during modal analysis.

Better damping of the alternative structure was expected in comparison with common structures but it is not much improved. Increase of damping values on the main structural eigenmodes is approximately 35 %. Finally, the cost should be also mentioned. The price of the alternative column was about 42 % higher than that of the common one if the whole cost related to manufacturing of the real column including all the material cost, welding cost, heat treatment cost, cutting operation cost, assembly cost, etc. are compared. This represents relatively high increase of the production costs. Certain reduction of the cost in the case larger scale production could be expected. All of the mentioned results are clearly shown in the Fig.18. Research work of this project in the RCMT continues and final results may be expected at the end of 2010.

From the technical point of view, presented results obtained from real measurement are very promising. This experimental work proves that the sandwich materials can bring new added value in the machine tool design characterized by higher static stiffness and lower weight, at the same time without too drastic manufacturing costs increase.

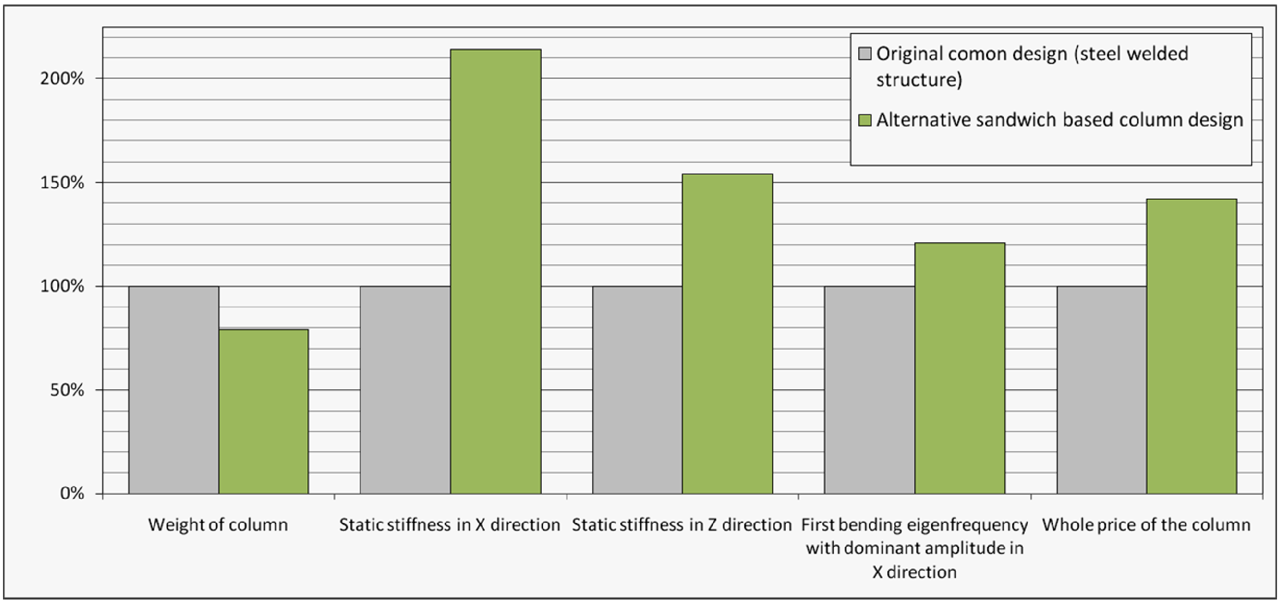

Fig. 18. Comparison of the selected properties of the common and alternative column design. All of the data is derived from real measurement and real manufacturing process. [8]

4. CONCLUSION

Using advanced materials and material structures in the field of primary structural parts of machine tools is a very perspective and hopeful way to improve the behaviour of the future machine tool generations. These conclusions could be presented on the basis of the mentioned simple case study and the previous analyses:

a) There are components, parts, axes and design units in the field of machine tools whose properties can be significantly improved by using advanced materials or material structures. The first antiresonance frequency of one of the alternative variants from the presented case study has achieved an increase by 43% and it induced a reduction of the total mass by 19%. These values are unreachable without using new advanced materials.

b) Basic purposes of unconventional materials usage in the machine tools are: i) to decrease mass of parts and structures, ii) to increase eigenfrequencies on eigenmodes which are parasitic for drives and stability behaviour, iii) to increase vibration damping of all critical eigenmodes. Increasing values of static stiffness are not a primary motivation and it is usually sufficient if an alternative design has static stiffness similar to the original design.

c) General problems obstructing to wide and prompt applications of unconventional materials in the field of machine tools are: i) relatively high costs comparing with common materials, ii) unusual manufacturing processes for MT manufacturers, iii) unusual and complicated joining and fixing with other parts of a machine, iv) very complicated design and simulation methods for parts design, v) scepticism from the side of manufacturers and customers. A wider use of advanced composites in the field of machine tools may not be expected in the near future, but many research projects solve these topics in close cooperation with MT manufacturers and they find proper ways to use advanced materials in the context of MT nowadays.

d) A very promising strategy to apply advanced materials sooner is to combine the maximal possible amount of cheap conventional materials (steel and cast iron) and the minimal necessary amount of expensive advanced structures in one part design. Such structures or materials are called hybrid structures or hybrid materials. (An excellent research in this field is presented in [4] and [5]). Such a strategy is a big challenge for the up-to-date research.

e) Usage and application of unconventional materials are purposeful only together with the use of advanced methods and strategies to optimize MT properties. For example, it is obvious that an application of advanced materials in structural parts is senseless and noneffective if the drive is not designed optimally and advanced optimization techniques are not used for parts design. It is necessary to remember that application of unconventional materials is not the single way to improve MT properties and behaviour.

More details related to this paper can be found in [6].

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