AN IMPACT OF THE STEEL-CONCRETE COMPOSITE SUPPORTING STRUCTURE ON THE DYNAMIC PARAMETERS OF THE MACHINING CENTER

DOMINIK HERMANSKY, JIRI MAREK

Brno University of Technology, Faculty of Mechanical Engineering,
Institute of Production Machines, Systems and Robotics, Brno, Czech Republic

DOI: 10.17973/MMSJ.2022_03_2020017

Dominik.Hermansky@vutbr.cz

A self-excited vibration, called "chatter", is a main limiting factor in chip-forming metal machining. The reduction of machining productivity, worsened machined surface quality and the reduction of lifetime of the machine tool parts, particularly the cutting tool itself, occur as a result of the chatter. There are more ways to suppress this undesired effect of machining. The most common and simplest variant is the structural modification of the supporting parts of the machine in order to increase the dynamic stiffness and damping.
In most cases, manufacturers of the machining centers use traditional metallic materials (steel, cast iron) for construction of the machine supporting system. However, these materials have some limitations. In order to improve the dynamic parameters of the machine during machining process it is appropriate to combine these materials with others to create hybrid, composite structures.
Authors of this article have performed the real experiment in order to test the real dynamic properties of the vertical multitasking machining center with the turning operation prevailing. The individual segments of the supporting structure are made of the composite material – a combination of a steel welded structure filled with high-strength cement concrete.

KEYWORDS

machine tool, chatter, steel-concrete composite

1 INTRODUCTION

Each machine tool in the production process must have certain required parameters. Accuracy and productivity are the most important criteria to determine the machine value. The accuracy is related to the dimensional deviation of the machine part from the theoretical dimension in the drawing of the machined surface. Just as important is to achieve high productivity of the machine while maintaining the reliability and efficiency of machining.
Thanks to the modern tools and special types of tool geometry, several times more material can be removed from the workpiece comparing to the recent past. The machine tool must have good mechanical properties to ensure high productivity and accuracy. The publication [Marek 2020] describes the effects of influencing CNC machine tool operation. They are included here vibration, impurities and heat. One of the main limitations, directly related to the productivity and accuracy of the machine is the chatter, which arises as a result of machining and the cutting process itself. This undesirable effect during machining causes a productivity and quality reduction of the machined surfaces, significantly shortens the lifetime of the cutting tools and other components on the machine. The self-excited vibration effect can occur during several technological operations, for example during turning, milling, drilling etc. Identification of errors on a vertical lathe caused by machining and prediction of machining accuracy is describe in the publication [Holub 2013]. Overview of the problems caused by the self-excited vibration – Fig.1

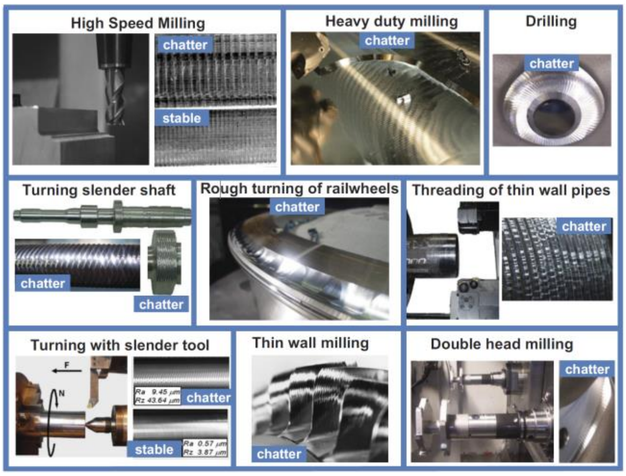


Figure 1. The problem of chatter in machining [Munoa 2016]

Requirements for prediction and suppression of undesirable impacts of the chatter is one of the major problems of the present and the near future. It is necessary to deal with this issue in the process of development, design, production, and operation of the machinery. One of the main reasons is to increase machining performance. Modern cutting materials are able to cut faster than conventional carbon steel tools. The higher productivity of cutting process brings the risk of more frequent chatters. The impact of the change in machine tools structure on the above phenomenon is also significant. Due to the linear and rotary axes speed increase it is necessary to optimize the parts of the supporting structure to obtain a low weight, often at the expense of the stiffness and damping. At higher feed speed traditional sliding guides with high damping effect are also replaced by rolling guides with lower damping and higher flexibility. [Munoa 2016]
The structure material used for the machining center supporting system may have significant impact on the dynamic characteristics of the machine. [Mohring 2015] provides an overview of the current research in the field of various materials and design solutions for machine tools supporting systems. The most commonly used are traditional metallic materials – various types of steel and cast iron. Their main advantage is the affordable price and well-mastered production technology. However, there has been an increased interest in alternative materials on the basis of composite, concrete, natural granite, etc. recently.

2 MATERIAL REQUIREMENTS FOR THE SUPPORTING STRUCTURE

The selection of material to be used for construction of the machine supporting system has to be always done based on the physical characteristics of the material. These properties have a direct impact on the technical and operational properties of the machine [Marek 2014]:

- the high stiffness and strength (static stiffness)
- the low weight (dynamic properties of the drives)
- the high vibration damping (dynamic stiffness)
- the low internal tension (long-term accuracy)
- the low thermal expansion and conductivity (thermal stability)
- the low energy costs for material procurement
- the low material costs

As mentioned in above list, the material properties requirements are often opposing. As far as the vibrations suppression during machining is concerned, the physical character of vibrations and damping is still hard to describe. This is one of the main strands of research in the manufacturing engineering field. It can be stated that high damping values are shown in materials, composed of several macroscopic phases or materials with a higher number of internal interfaces between their individual components. The concrete-based materials with the gravel and the binder (cement, polymer) as two major macro components, are the typical representatives of the first group referred. Materials with significant transitions and interfaces are for example fibrous composites, eventually materials with foam fillers. The combination of the above materials with the conventional metallic materials is also common – the hybrid structures. Hybrid supporting structures are used as a replacement for most often used materials – steel and cast iron. The advantage of their use is the increase of physical parameters while maintaining a good economic aspect. The materials used for machine tools supporting structures and the values of some of their physical parameters are in [Marek 2014]

3 STEEL-CONCRETE COMPOSITE MATERIAL IN MACHINE TOOLS CONSTRUCTION

As already mentioned, the traditional metallic materials have certain limitations, that is why the authors of this report have carried out an experiment aiming to test the dynamic properties of the real vertical machining center. It is a multitasking center with turning as a prevailing operation (60%). The designation of the machine is VTL-250 and all individual segments of the supporting structure are made of the composite material – a combination of a steel welded structure filled with high-strength cement concrete. It is a comprehensive and systematic development of a completely new and unique prototype of a machine for medium-heavy workpieces using a virtual model in the pre-production phase.
The authors follow up on the previous research in the application of steel-concrete composites application for a different type of machine. [Hermansky 2016] provides a brief description of the process of the steel-concrete composite design for the bed and the column of the horizontal drilling machine.
Recently, several attempts have been made to apply the combined, i.e. hybrid materials to construct the machine tools. The combination of metallic materials (steel) and the concrete filling is the most common variant. The polymer concrete or standard cement concrete is used. The steel parts are connected to the concrete using ribbings and special connecting elements. Framag company, for example, deals with such parts production issues. The advantages and benefits of such material are described for example in [Denkena 2004]
Most of the implemented studies were focused primarily on the smaller size CNC machining centers. This report focuses on the field of machine tools for heavy and medium-heavy workpieces. Similar application can be found for example in [Vasilevich 2016]

4 VERTICAL TURNING CENTER VTL-250 WITH THE STEEL-CONCRETE COMPOSITE SUPPORTING STRUCTURE

Figure 2. Vertical turning center VTL-250

The supporting structure of the machining center consists of the following main parts:

- bed + table
- columns
- columns connecting part (crossbar)
- crossrail
- railhead
- headstock

The bed components, two columns, the crossbar and the crossrail are made of the steel-concrete composite. It is an optimized ribbed steel welded structure filled with high-strength special concrete.
Concrete suitable for steel-concrete parts construction for accurate machine tools belongs to category of so-called high-strength concrete (HSC). Compound steel profiles or welds filled with concrete were introduced to be used in construction for various supporting structures approximately 15 years ago and became known as steel-concrete composites. They always consist of the steel profile (a tube, a profile I, U, or T or the welded structure of various shapes) filled with high-strength concrete which adds stiffness to the whole steel structure.
The combination of the steel and concrete has been used for decades in the form of so-called reinforced concrete. This combination works quite well thanks to practically the same thermal expansion ratio of concrete and steel, thanks to which this composite does not cause any problems in case of temperature changes. In terms of durability, another excellent property of concrete is a low pH value (12.0 through 12.5), which allows so-called steel passivation and thus avoids its corrosion even in the moist conditions.
The general requirements on mechanical properties of high-strength concrete suitable for steel welded structures filling are following:

- minimum compression strength: 80 MPa
- minimum tensile strength in bending: 6 MPa
- minimum static elastic modulus: 37 GPa
- minimalization of volume negative changes, that means the shrinkage of concrete must not exceed 0.5 mm / m

These requirements are common to steel-concrete parts used in a civil engineering. In general, all technological processes are very similar.

Figure 3. Steel-concrete components – the bed (up) and the column (down) after being filled with high-strength concrete

5 DESIGN AND ANALYSIS OF INDIVIDUAL PARTS OF THE SUPPORTING STRUCTURE

When designing a composite part, it is necessary to pay close attention to the perfect steel frame connection with the concrete filling. The connections take place by means of massive ribbing of the steel welded structure and also by means of connecting elements that are commonly used in construction. FEM calculations, especially ANSYS software, were used for topological optimization in order to achieve high stiffness while maintaining a reasonable weight.

The ideal state of perfect concrete-to-weld walls adherence is obviously not achievable. For that reason, it is necessary to determine the imperfection rate of the connection. A procedure that can determine this parameter very accurately has been established. Comparing of the experimental modal analysis of the individual parts to a FEM calculation analysis is the most appropriate tool for this purpose. The Figure 4 shows the measured and calculation values of the first three natural frequencies of the column together with the relevant deformation shapes. It is clear from the results that for the real components the natural frequency value is shifted to lower values. It is caused by the imperfect steel-to-concrete connection and therefore the loss of the overall stiffness of the composite part occurs. The calculation model can then be easily modified, for example by the concrete stiffness modulus change, so that the overall stiffness of the part corresponds to the experimentally obtained data.

Based on experience and long-term research, it has been found that deviations between the model and the measurement will only become apparent after a longer time. Usually when the part is handled improperly or after machining the parts. The concrete is separated from the steel structure and thus the composite loses stiffness. For smaller and stiffer composite parts, the agreement between calculation and measurement is almost perfect. Therefore, the authors assume that the construction of the model is at a good level without significant errors.

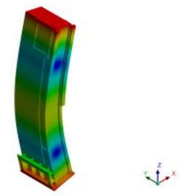
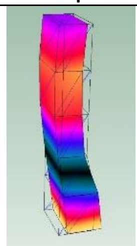
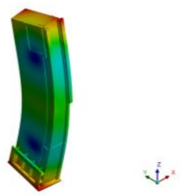
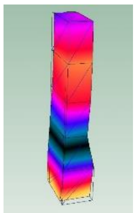
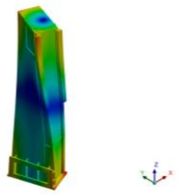
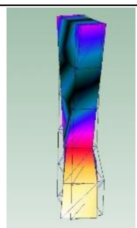
FEM Calculation		Experiment	
Deformation shape	**Frequency**	**Deformation shape**	**Frequency**
	101 Hz		90 Hz
	165 Hz		148 Hz
	176 Hz		171 Hz

Figure 4. Comparing the calculation and experimental modal analysis of the steel-concrete composite column

Experimental modal analysis was performed in the so-called free condition. The modal impact hard-tip hammer 8208 was used as a frequency actuator and the reactions of the structure were detected by the type 4225 B accelerometer, the equipment together with the evaluation software were provided by Brüel & Kjaer company.

6 ANALYSIS OF THE OVERALL DYNAMIC PROPERTIES OF THE MACHINE

Properly adjusted calculation models of individual components allow to determine the dynamic parameters of the entire machine. After completion and implementing the machine these parameters were obviously verified by an experiment.

An amplitude-frequency characteristic was chosen to assess the quality of the dynamic behavior of the machine in order to assess the impact of filling the welded structure with concrete. The graph in Figure 5 shows the effect of the concrete filling on the dynamic parameters of the machine. The concrete filling increases the stiffness, weight and damping of individual parts of the machine supporting structure. The graph shows that in the area of lower frequencies (natural frequencies 16 Hz + 27 Hz) the dynamic stiffness is higher, because these are natural frequencies that are related to the machine frame. However, the critical natural frequency of 40Hz is not significantly affected by the concrete filling, because this natural frequency is related to the deformation of the ram. Measurements and FEM analysis were performed for the direction in the X axis. In this direction, the rail head moves along the cross rail.

Using the steel-concrete composite for the supporting structure also results into a significant increase in the static stiffness of the machine tool. However, measurements and FEM analysis of this characteristic are not the subject of this article.

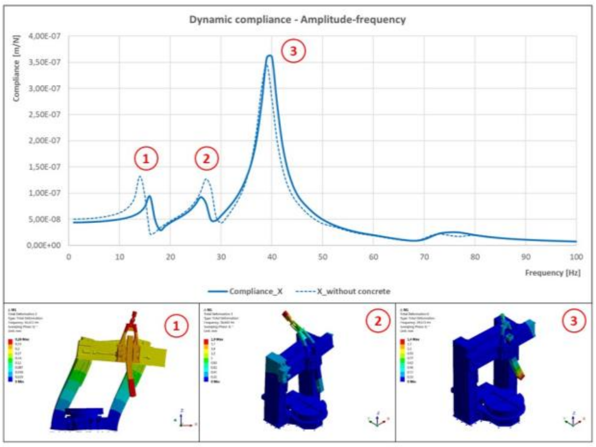


Figure 5. Dynamic characteristics of the machining center

Figure 6. Experimental verification of the dynamic properties of the machine

7 CONCLUSION

The development of steel-concrete components for the bigger machines both in size and power is a relatively difficult process that requires a lot of experimenting and testing. The authors of this article have been focusing on this issue since 2014. Several machines of various configurations have been implemented and then introduced to the real production process. Practical knowledge, the authors' experience and findings presented in this article indicate that the steel-concrete components can be applied in the construction of larger and more robust machining centers. A positive effect in terms of increased static and dynamic stiffness is expected. Especially in the field of high-speed machining of the workpieces using the materials that are difficult to process, such as the parts for aerospace industry. The usage of stiff supporting structures with higher damping level is a possible solution to eliminate negative effects related to the power machining.

ACKNOWLEDGMENTS

These results were obtained with the financial support of the Faculty of Mechanical Engineering, Brno University of Technology (Grant No. FSI-S-20-6335).

Machine VTL-250 was built by companies Fermat and AM Finance.

REFERENCES

[Denkena 2004] DENKENA, B., F. KALLAGE, M. RUSKOWSKI, K. POPP and H.K. TÖNSHOFF, 2004. Machine Tool with Active Magnetic Guides. CIRP Annals [online]. 53(1), 333-336 [cit. 2017-11-29]. DOI: 10.1016/S0007-8506(07)60710-0. ISSN 00078506.

[Holub 2013] HOLUB, M.; MICHALICEK, M.; VETISKA, J.; MAREK, J. Prediction of Machining Accuracy for Vertical Lathes. In Mechatronics 2013 Recent Technological and Scientificdvances. 1. Springer International Publishing Switzerland: Spinger, 2013. p. 41-48. ISBN: 978-3-319-02294-9.

[Hermansky 2016] Hermansky, D., Marek, J., “Steel-concrete Composite Material in CNC Machine Tool Structures”, Acta Mechanica Slovaca, vol. 20, no. 2, pp. 55-61, 2016.

[Marek 2014] MAREK, J., 2014. Construction of CNC machining tools III. Prague: MM publishing. MM special (special edition). ISBN 978-80-260-6780-1.

[Marek 2020] MAREK, J.; HOLUB, M.; MAREK, T.; BLECHA, P. Geometric Accuracy, Volumetric Accuracy and Compensation of CNC Machine Tools. In Machine Tools. IntechOpen, 2020. p. 1-19. ISBN: 978-1-83962-351-6. DOI: 10.5772/intechopen.92085.

[MOEHRING 2015] MOEHRING, H-Ch., BRECHER, Ch., ABELE, E.,FLEISCHER, J. and BLEICHER, F. 2015. Materials in machine tool structures. CIRP Annals [online]. 64(2), 725-748.

[Munoa 2016] MUNOA, J., BEUDAERT, X., DOMBOVARI, Z., ALTINTAS, Y., BUDAK, E., BRECHER, C. and STEPAN, G.. Chatter suppression techniques in metal cutting. CIRP Annals [online]. 2016, 65(2), 785-808 [cit. 2020-04-22]. DOI: 10.1016/j.cirp.2016.06.004. ISSN 00078506.

[VASILEVICH 2016] VASILEVICH, Yu. V., DOUNAR, S. S. and KARABANIUK, I. A., 2016. FINITE ELEMENT ANALYSIS OF CONCRETE FILLER INFLUENCE ON DYNAMIC RIGIDITY OF HEAVY MACHINE TOOL PORTAL. Science & Technique [online]. 15(3), 233-241 [cit. 2017-11-29]. DOI: 10.21122/2227-1031-2016-15-3-233-241. ISSN 2414-0392.

CONTACTS:

Ing. Dominik Hermansky
Brno University of Technology
Faculty of Mechanical Engineering
Institute of Production Machines, Systems and Robotics
Technicka 2896/2, 616 69 Brno, Czech Republic
e-mail: Dominik.Hermansky@vutbr.cz

prof. Dr. Ing. Jiri Marek Ph.D., DBA
Brno University of Technology
Faculty of Mechanical Engineering
Institute of Production Machines, Systems and Robotics
Technicka 2896/2, 616 69 Brno, Czech Republic
e-mail: marek@fme.vutbr.cz