N. KĘPCZAK*,♯, W. PAWŁOWSKI**, Ł. KACZMAREK***

CAST IRON AND MINERAL CAST APPLIED FOR MACHINE TOOL BED - DYNAMIC BEHAVIOR ANALYSIS

ODLEWY ŻELIWNE I MINERALNE STOSOWANE NA ŁOŻA OBRABIAREK - ANALIZA WŁAŚCIWOŚCI DYNAMICZNYCH

Cast iron and mineral cast are the materials most often used in the machine structural elements design (bodies, housings, machine tools beds etc.). The materials significantly differ in physical and mechanical properties. The ability to suppress vibration is one of the most important factors determining the dynamic properties of the machine and has a significant impact on the machining capabilities of a machine tool. Recent research and development trends show that there is a clear tendency to move away from the traditional iron casting to the mineral casting, due to better dynamic properties of the latter. However mineral cast as a structural material for the whole machine tools bed turns out to be insufficient due to its poor mechanical strength properties. The best solution should benefit from the advantages of the cast iron and mineral cast materials while minimizing their drawbacks. The paper presents numerical modal analysis of two lathe beds: the first one made of gray cast iron and the second one made of hybrid connection of cast iron and mineral cast. The analysis was conducted in order to determine the dynamic properties of two bodies of similar shapes made in the traditional (cast iron) and innovative hybrid (cast iron and mineral cast) technology. In addition, an analysis of the static structure rigidity of the two beds was performed. During the simulation studies it was found a significant increase in dynamic stiffness and static rigidity of the machine tool body made of hybrid connection of cast iron and mineral cast. The results of numerical simulations have confirmed the desirability of using hybrid construction because the dynamic properties of such a body are more advantageous in comparison with the conventional body made of cast iron.

Keywords: cast iron, mineral cast, dynamic properties, modal analysis, machine tool bed

Żeliwo oraz odlewy mineralne są materiałami konstrukcyjnymi najczęściej wykorzystywanymi w dziedzinie projektowania elementów strukturalnych maszyn (korpusy, obudowy, łoża obrabiarek). Te materiały znacząco różnią się pod względem zarówno właściwości fizycznych, jak i mechanicznych. Zdolność do tłumienia drgań jest jednym z najważniejszych czynników determinujących właściwości dynamiczne urządzenia i ma znaczący wpływ na możliwości obróbkowe maszyny technologicznej. Najnowsze badania oraz trendy rozwojowe pokazują, że istnieje wyraźna tendencja do odchodzenia od tradycyjnych odlewów żeliwnych w kierunku odlewów mineralnych, ze względu na lepsze właściwości dynamicznych tych ostatnich. Jednakże odlewy mineralne jako materiał konstrukcyjny na całe łoże obrabiarki okazuje się być niewystarczający ze względu na słabe właściwości mechaniczne. Najlepsze rozwiązanie powinno korzystać z zalet żeliwa i odlewów mineralnych, jednocześnie minimalizując wady obu materiałów. W artykule przedstawiono teoretyczną analizę modalną dwóch korpusów obrabiarki: jednego wykonanego z żeliwa szarego oraz drugiego wykonanego z hybrydowego połączenia żeliwa i odlewu mineralnego. Analiza została przeprowadzona w celu określenia właściwości dynamicznych dwóch korpusów o podobnych kształtach wykonanych w tradycyjnej oraz nowatorskiej technologii odlewniczej. Dodatkowo przeprowadzono analizę sztywności statycznej konstrukcji obu korpusów. Podczas badań symulacyjnych stwierdzono, wzrost sztywności dynamicznej oraz wzrost sztywności statycznej korpusu obrabiarki wykonanego z hybrydowego połączenia żeliwa szarego i odlewu mineralnego. Otrzymane wyniki badań teoretycznych potwierdziły celowość stosowania budowy hybrydowej, ponieważ właściwości dynamiczne tak wytworzonego korpusu są korzystniejsze w porównaniu z korpusem wykonanym z tradycyjnego odlewu żeliwnego.

1. Introduction

In the past three decades, modal analysis has become a major technology in the quest for determining, improving and optimizing dynamic characteristics of engineering structures [1]. It has been successfully applied to solve structural dynamic problems in mechanical [2-6] and aeronautical [7] engineering. Recently modal analysis has also found its broad applications for civil and building [8] structures, biomechanical and harvest [9] problems, space structures, electrics and electron-

---

*   INSTITUTE OF MACHINE TOOLS AND PRODUCTION ENGINEERING, FACULTY OF MECHANICAL ENGINEERING, LODZ UNIVERSITY OF TECHNOLOGY, 1/15 STEFANOWSKIEGO STR., 90-924 LÓDŹ, POLAND

** INSTITUTE OF MACHINE TOOLS AND PRODUCTION ENGINEERING, FACULTY OF MECHANICAL ENGINEERING, LODZ UNIVERSITY OF TECHNOLOGY, 1/15 STEFANOWSKIEGO STR., 90-924 LÓDŹ, POLAND

*** INSTITUTE OF MATERIALS SCIENCE AND ENGINEERING FACULTY OF MECHANICAL ENGINEERING, LODZ UNIVERSITY OF TECHNOLOGY, 1/15 STEFANOWSKIEGO STR., 90-924 LÓDŹ, POLAND

♯   Corresponding author: norbert.kepczak@dokt.p.lodz.pl

ics [10] acoustical instruments [11], transportation [12] and nuclear plants.

Modal analysis is the process of determining the inherent dynamic characteristics of a system in forms of natural frequencies, damping factors and mode shapes, and using them to formulate a mathematical model for its dynamic behavior. The formulated mathematical model is referred to as the modal model of the system and the information for the characteristics are known as its modal data [1]. The system must meet several requirements in order to apply the modal analysis method for its examination i.e. it has to be linear, time-invariant and observable and it must obey the Maxwell's reciprocity theorem. These basic prerequisites must be checked and fulfilled prior performing modal analysis test of the system. The modal analysis (MA) can be performed as theoretical, experimental or operational modal analysis. Theoretical MA usually applies Finite Element Method (FEM) to solve dynamic problems of the analyzed structure.

Also in the field of construction of the machine tool bodies several researches were conducted. Modeling and structural analysis of main spindle housing structure made of different materials [13] as well as comparative studies which led to dynamic test results achieved with some alternative materials applied to manufacture machine tool structures [14] were performed.

Bodies are elements of machine tools which connect basic assemblies and mechanisms into a whole structure. Their role is to keep the other parts and assemblies in a specific mutual position. Generally, the machine tool consists of the main body (the bed), being the primary support structure and a few or a dozen smaller bodies, which are joined (bolted, welded or joined slideably) to main body and constitute a whole machine tool. Most of the machine tool beds are made of gray cast iron or modified cast iron [15].

Cast iron is a high carbon alloy of iron with carbon, usually also with silicon, manganese, phosphorus, sulfur and other ingredients. Contains from 2.11 to 4.3% carbon in the form of cementite or graphite. The occurrence of a particular phase of carbon depends on the cooling rate and chemical composition of the alloy. One of the types of cast iron is gray cast iron wherein the carbon is present as graphite. Its name comes from the fact that his breakthrough is gray. Regarded as the cast iron of higher quality and is more ductile, easily treatable, has a good fluidity and has a smaller shrinkage casting – (around 1.0%) than the white cast iron. It is used to make bodies, housings, blocks of pumps, compressors and motors although it is more brittle and susceptible to cracking than steel [16].

The global industry is constantly looking for new design solutions and new materials which properties may improve the quality of manufacturing products, reduce the costs associated with the manufacturing process, increase the flexibility of this process, etc. [17].

Recent research and development trends show that there is a clear tendency to move away from the traditional iron casting in the direction of mineral casting, due to better dynamic properties [18]. Mineral cast (PC – polymer concrete) is a complex material composed of particles of inorganic aggregates, such as basalt, spodumene, fly ash, river gravel, sand, chalk etc. connected by resin (usually epoxy resin) [19]. The volume ratio of the filler (aggregates) to the binder (resin) is about 9÷1 [17]. Figure 1 shows an example of the structure of mineral cast with aggregates of different grain size. Depending on a kind of aggregates used in mineral cast material the grains may be of a size from tenths of a micron to about ten millimeters [19].
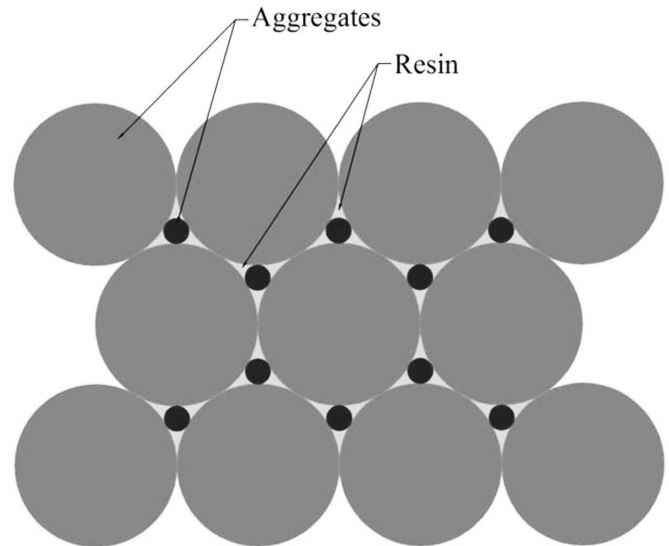

Fig. 1. An example of the structure of mineral cast with aggregates of different grain size [18]

Depending on the type and size of used aggregates and quantity of the resin, curing time may take from several minutes to several hours. Depending on the requirements for the achieved precision, tolerances and surface roughness, mineral cast can be made in wood, plastic, metal, cast iron mould or a combination of the above [20].

The ability to suppress the vibration is one of the most important factors determining the dynamic properties of the machine and has a significant impact on the machining capabilities of machine tool. Typically, machine parts are made of cast iron, which has high damping ratio. However, casting processes require an open structure and small thickness, due to the possibility of contraction cavities. These requirements can result in low resonance frequency of the whole construction. Mineral casting allows using closed structures with thicker walls, which leads to higher resonance frequencies of the structure [21].

2. Methodology

Theoretical modal analysis is defined as a self-problem which depends on mass matrix, rigidity and damping ratios [22]. The theoretical modal analysis requires to solve the self-issue for the assumed structural model of the construction. So designated sets of free vibration frequencies, damping coefficients and modes of vibrations allow to simulate the structural behavior at any extortion, selection of controls, design modifications and other. Theoretical modal analysis is used in the design process, when there is no possibility to conduct the experimental research on the real object [22].

Before the exact dynamic analysis, the experimental study of the mechanical properties of mineral cast samples was per-

formed in order to determine the parameters necessary to create the model of the mineral cast material in CAD software – Autodesk Inventor. The most important parameters were tensile strength, compressive strength, Young's modulus and Poisson's ratio. The material which was used for tests was mineral cast material offered by EPUCRET and commercially available under the name EPUCRET 140/5. This material is usually used for casting small parts of machines such as the guides, tables or beds, which mass is not exceeding 500 kg. Results of experimental strength tests of the samples made of mineral cast EPUCRET 140/5 material are presented in Table 1 [23]. Those values were applied to create the model of mineral cast material and implemented into the Autodesk Inventor material library.

TABLE 1

Mechanical properties of mineral cast [22]

Properties	Value
Tensile strength [MPa]	18,42
Compressive strength [MPa]	106,60
Young's modulus [MPa]	29738
Poisson ratio [—]	0,222

Figure 2 shows an isometric view of a body which has been analyzed. It is the bed of the lathe which is produced by Koluszki Foundry and Machinery. Its dimensions are 300 mm×300 mm×2000 mm (height×width×length). The body is made of gray cast iron. Casting technology imposes design constraints including achieving as uniform thickness of the walls and ribs of casting element as possible. Application of different thicknesses and variable cross-sections of elements may result in negative phenomena during casting or cooling such as contraction cavity. This is a significant technology limit resulting in a necessity to adjust the shape of the structural element to the requirements of the casting process.

Fig. 2. Isometric view of the body

For this reason, the body in cross-section has some hollow spaces (Figure 3), which in the following analyzes have been filled with mineral cast material to create a hybrid body (Figure 4). Filling the cast iron body spaces by cement polymer is intended to improve the dynamic properties of the hybrid body,

because some positive changes can be expected as a result of the use of material with much higher coefficient of damping than that of cast iron. These properties are also changed by increasing the weight of the body and include improvement of static stiffness of such a hybrid body. All these changes are intended to increase the natural frequency of the basic modes, which is highly desirable for enhancing the functional properties of the machine tool body. The dynamic properties of the body significantly influence the results of the machining process.
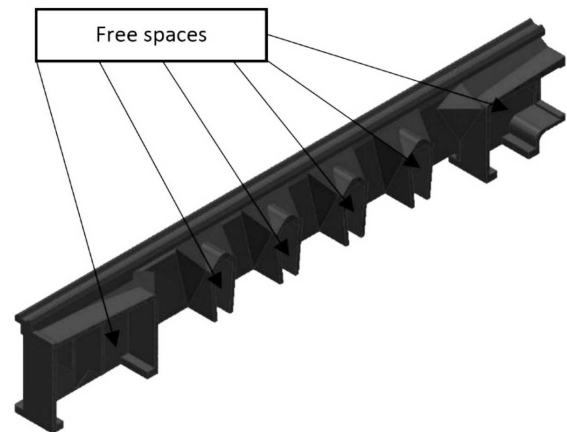
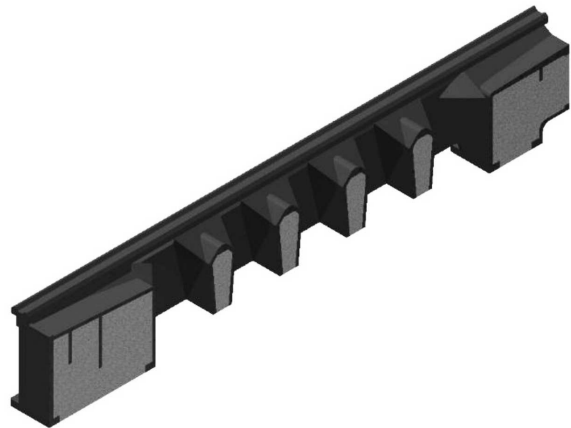

Fig. 3. Cross-section of the body with free spaces

Fig. 4. Cross-section of the body with spaces filled with mineral cast material

Theoretical modal analysis was conducted in order to answer the question of whether and to what extent the iron cast body filling by mineral cast will change the dynamic properties of the hybrid body. The analysis was performed based on 3D models of the machine tool body.

During investigation the theoretical modal analyses have been conducted for the first twenty vibration modes and their frequencies of the body. The mechanical properties of both materials used in the analyses are presented in Table 2.

Boundary conditions definition was a very important aspect during the analyses. On the left and right side of the body there are 8 (4 on both sides of the body) mounting holes, through which the bed is mounted to the basement. The model has been fixed on these mounting holes cylinders (Figure 5) which has blocked movement in all directions in both cases of the iron cast and hybrid body.

Mechanical properties of materials used in analyses

	Cast iron[*]	Mineral cast
Tensile strength [MPa]	997	18
Compressive strength [MPa]	—	106
Young's modulus [GPa]	168	30
Poisson ratio [—]	0,29	0,22
Kirchhoff's modulus [MPa]	64900	12000
Density [g/cm^3]	7,15	2,30

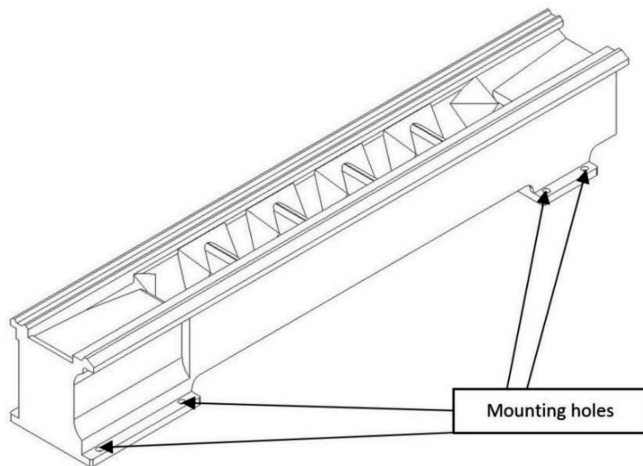[*] mechanical properties of cast iron are taken from the materials library of Autodesk Inventor 2015

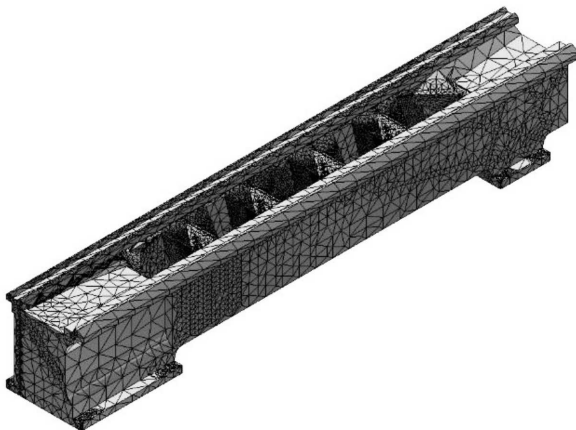

Fig. 5. Places of fixing the body

Fig. 6. View of meshing of the iron cast body

The finite elements mesh setting was another very important problem during the analysis. The smaller size of the mesh element the more elements, nodes and number of equations to be solved. In the case of smaller elements the time of meshing was longer but the results were more accurate. Figures 6 and 7 show the view of meshing of the iron cast body and hybrid body. The iron cast body mesh had 407740 nodes and 231853 elements and the hybrid body mesh had 475499 nodes and 277603 elements. The increase in number of elements and nodes is a result of meshing the spaces of the body filled with the mineral cast material. Having defined all necessary settings the theoretical modal analysis was carried out.
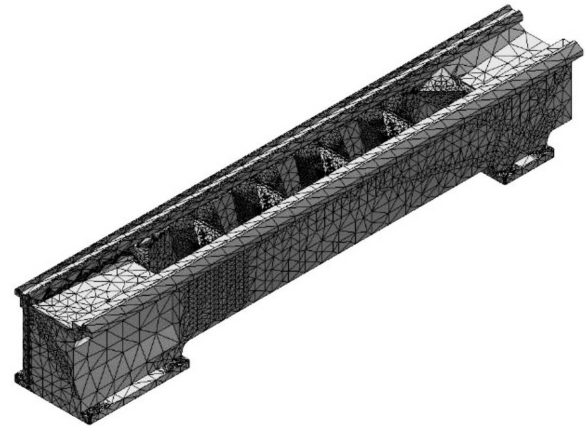

Fig. 7. View of meshing of the hybrid body

Additionally, the static analysis was conducted in order to determine whether or not the static rigidity increases after filling the spaces of the bed with mineral cast material. Both bodies were loaded with force of 500N in all 3 axes as it is shown in Figure 8. Identical way of mounting and the same parameters of meshing were used like in previous analyses. The state of stress and strain of the bodies (traditional and hybrid) with static load was analyzed.
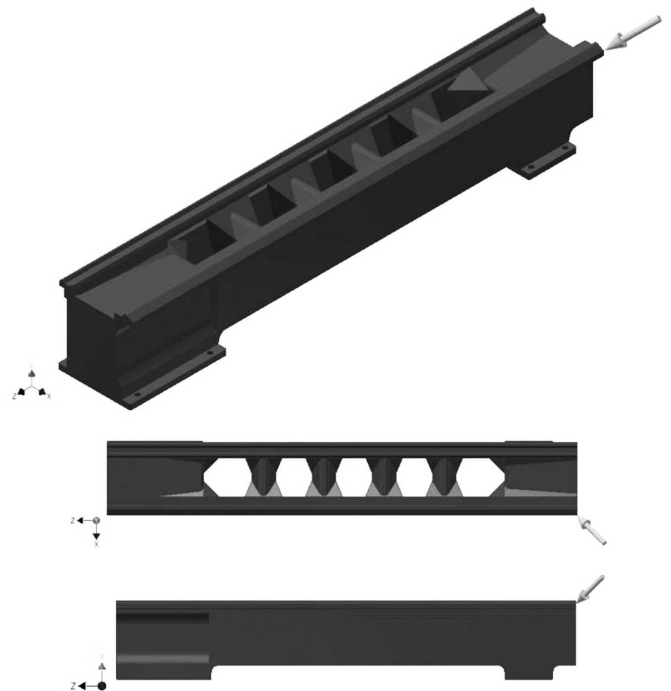

Fig. 8. Static load of the body

3. Results and discussion

Results of simulations are presented in Table 3. Modes of vibrations were marked from F1 to F20.

As it is shown in Table 3 for analyzed modes the increase of value of natural frequency as a result of filling the hollow spaces by mineral cast material was observed. For comparison in the Figures 9 and 10, 11 and 12 and also 13 and 14 the appropriate modes of both bodies are presented. It can be alleged that in the case of hybrid body the increase of dynamic stiffness appeared because the increase of natural vibrations frequency was observed.

Results of theoretical modal analysis

Mode	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Cast iron body	189 Hz	333 Hz	364 Hz	393 Hz	477 Hz	510 Hz	593 Hz	765 Hz	861 Hz	902 Hz
Hybrid body	195 Hz	356 Hz	409 Hz	425 Hz	473 Hz	632 Hz	6 Hz	783 Hz	861 Hz	977 Hz
Mode	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20
Cast iron body	1016 Hz	1079 Hz	1107 Hz	1136 Hz	1198 Hz	1258 Hz	1267 Hz	1357 Hz	1383 Hz	1438 Hz
Hybrid body	987 Hz	1049 Hz	1085 Hz	1257 Hz	1266 Hz	1336 Hz	1503 Hz	1556 Hz	1600 Hz	1649 Hz

Fig. 9. F1 mode of the iron cast body – frequency 189 Hz

Fig. 12. F4 mode of the hybrid body – frequency 425 Hz

Fig. 10. F1 mode of the hybrid body – frequency195 Hz

Fig. 13. F8 mode of the iron cast body – frequency 765 Hz

Fig. 11. F4 mode of the iron cast body – frequency 393 Hz

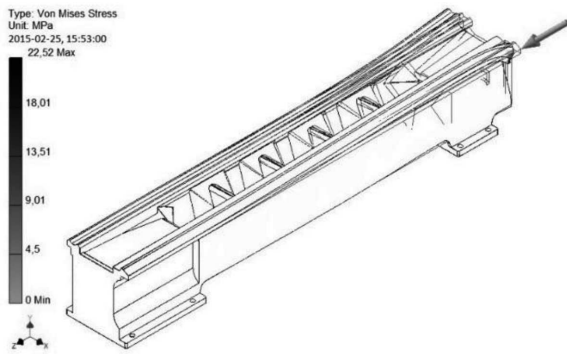Fig. 14. F8 mode of the iron cast body – frequency 783 Hz
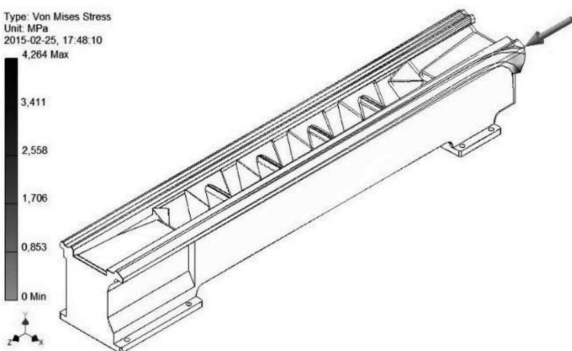
Fig. 15. Stresses of the iron cast body

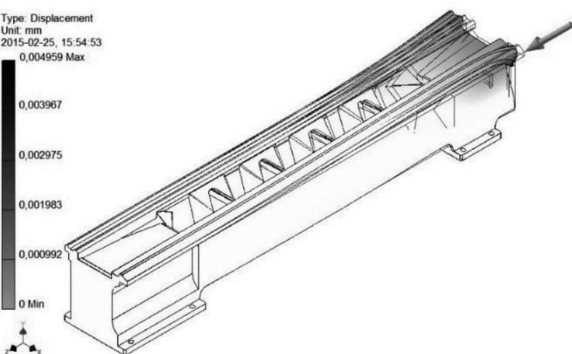Fig. 16. Stresses of the hybrid body

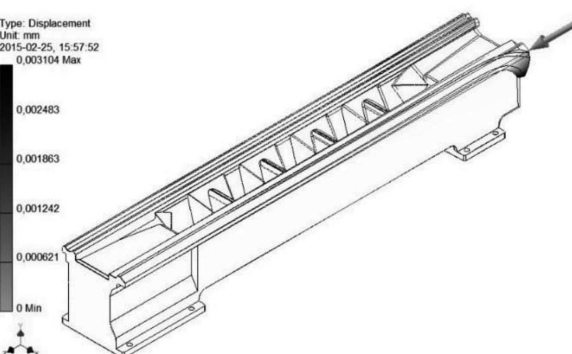

Fig. 17. Displacements of the iron cast body

Fig. 18. Displacements of the hybrid body

As it is shown in the Figure 15, 16, 17 and 18 in the case of hybrid body made of connection of cast iron and mineral cast stresses and resultant displacements under static load were lower than in the case of construction made of traditional cast iron. For the cast iron body maximal stress was 22,52 MPa and maximal displacement was 5 μm, whereas in the case of the hybrid body maximal stress was 4,26 MPa and maximal displacement was 3 μm for the same load conditions. It can be stated that increase of static rigidity has appeared as a result of hybrid construction of the body.

4. Conclusions

Two machine tool bodies have been analyzed. The first one was made of cast iron, and the second one was made of connection of cast iron and mineral cast. The first twenty free vibration modes and their frequencies have been numerically investigated. In the case of the hybrid body the increase of free vibrations frequencies from 3,2% (for low frequencies) to 12,8% (for high frequencies) was observed. These results, especially considering high efficiency of damping in the case of vibrations of high frequencies, are very promising from the manufacturing point of view. The vibrations of high frequencies are the typical excitation source arising in the cutting process. Therefore, damping capabilities of the machine tool system are very important as far as the manufacturing accuracy of the machined surface is concerned. Consequently, the machine tool beds are traditionally made of gray cast iron which is considered as a material which has very good ability to suppress the vibration. However application of new structural material which is mineral cast with the traditional cast iron enhances damping properties of the body construction even more.

Additionally, static analysis showed that the stiffening of the hybrid body made of cast iron and mineral cast appeared. Dynamic and static research confirmed the thesis that application of mineral cast has an influence on improvement of both static and dynamic properties of machine tool bodies construction.

During the numerical modal analysis the finite element method was used to examine both the traditional and the hybrid body made of two structural materials. On the boundary of these two materials there was a contact modeled as the bonded joint. It was a certain simplification because the model of contact between cast iron and mineral cast needs to be examined and identified experimentally. Additional simplification is the model of the mineral cast material which was assumed to be isotropic. This assumption can be justified by a high-volume of the material of mineral cast in the comparatively large previously hollow spaces of the machine tool bed and the experimental identification of the required strength parameters applied in the material model.

In spite of these simplifications which were applied in the model it should be noted that a very clear trend of improvement of dynamic properties of the hybrid body in relation to the purely cast iron body was observed. This conclusion needs to be verified experimentally in order to create the body of machine tool of much better static and dynamic properties. However, having evaluated the results obtained in numerical simulations, application of cast iron along with mineral cast material in construction of machine tools bodies seems to be highly advisable and promising. That approach benefits from

advantages of both structural materials properties while min-
imizing their drawbacks.

REFERENCES

[1] J. He, Z. Fu, Modal Analysis, Butterworth-Heinemann (2001).

[2] M. Matsuo, T. Yasui, T. Inamura, M. Matsumura, High-speed Test of Thermal Effects for a Machine-tool Structure Based on Modal Analysis, Precision Engineering, 72-78 (1986).

[3] B. Li, H. Cai, X. Mao, J. Huang, B. Luo, Estimation of CNC Machine-tool Dynamic Parameters Based on Random Cutting Excitation Through Operational Modal Analysis, International Journal of Machine Tools & Manufacture, 26-40 (2013).

[4] I. Zaghbani, V. Songmene, Estimation of Machine-tool Dynamic Parameters During Machining Operation Through Operational Modal Analysis, International Journal of Machine Tools & Manufacture, 947-957 (2009).

[5] G.P. Zhang, Y.M. Huang, W.H. Shi, W.P. Fu, Predicting Dynamic Behaviours of a Whole Machine Tool Structure Based on Computer-aided Engineering, International Journal of Machine Tools & Manufacture, 699-706 (2003).

[6] V. Gagnol, T.P. Le, P. Ray, Modal Identification of Spindle-tool Unit in High-speed Machining, Mechanical Systems and Signal Processing, 238-2398 (2011).

[7] A. Vivo, C. Brutti, J. Leofanti, Modal Shape Identification of Large Structure Exposed to Wind Excitation by Operational Modal Analysis Technique, Mechanical Systems and Signal Processing, 195-206 (2013).

[8] S. Rahmatalla, K. Hudson, Y. Liu, H.Ch. Eun, Finite Element Modal Analysis and Vibration-waveforms in Health Inspection of Old Bridges, Finite Elements in Analysis and Design, 40-46 (2014).

[9] R. Ebrahimi, M. Esfahanian, S. Ziaei-Rad, Vibration Modeling and Modification of Cutting Platform in a Harvest Combine by Means of Operational Modal Analysis (OMA), Measurement, 3959-3967 (2013).

[10] Ch. Brecher, S. Baumler, A. Guralnik, Experimental Modal Analysis Using a Tracking Interferometer, CIRP Annals – Manufacturing Technology, 345-348 (2014).

[11] B. Chomette, J-L. Carrou, Operational Modal Analysis Applied to the Concert Harp, Mechanical Systems and Signal Processing, 81-91 (2015).

[12] N.F. Nangolo, J. Soukup, L. Rychlikova, J. Skocilas, A Combined Numerical and Modal Analysis on Vertical Vibration Response of Railway Vehicle, Procedia Engineering, 310-319 (2014).

[13] G. Vratnoski, V. Dukovski, Design of Polymer Concrete Main Spindle Housing for CNC Lathe, 13th International Scientific Conference on Achievements in Mechanical and Materials Engineering, 695-698 (2005).

[14] V. Ducatti, R. Lintz, J. Santos, Comparative Study with Alternative Materials for Manufacture of Machine Tool Structure International RILEM Conference on the Use of Recycled Materials in Building and Structures, 925-934 (2004).

[15] L.N. Lopez de Lacalle, A. Lamikiz, Machine Tools for High Performance Machining, Springer (2009).

[16] L.V. Kostyleva, L.V. Palatkina, V.A. Il'inskii, Gray cast iron primary structure detachment crack propagation resistance, Metal Science and Heat Treatment **50**, 5-6, 248-251 (2008).

[17] C. Bruni, A. Forcellese, F. Gabrielli, M. Simoncini, Hard Turning of an Alloy Steel on a Machine Tool with a Polymer Concrete Bed, Journal of Materials Processing Technology, 493-499 (2007).

[18] N. Kepczak, W. Pawłowski, Application of Mineral Casting for Machine Tools Beds, Mechanics and Mechanical Engineering **17**, 3, 3-7 (2013).

[19] H. Haddad, M. Al Kobaisi, Optimization of the Polymer Concrete Used for Manufacturing Bases for Precision Tool Machines. Composites: Part B, 3061-3068 (2012).

[20] T. Erbe, J. Król, R. Theska, Mineral Casting as Material for Machine Base-frames of Precision Machines. Twenty-third Annual Meeting of the American Society for Precision Engineering and Twelfth ICPE, October 2008, Portland, Oregon (2008).

[21] F. Cortés, G. Castillo, Comparison Between the Dynamical Properties of Polymer Concrete and Grey Cast Iron for Machine Tool Applications. Elsevier, Materials and Design **28**, 1461-1466 (2006).

[22] B. Zoltowski, Badania dynamiki maszyn (Machine Dynamics Research) in Polish, Wydawnictwo MAKAR, Bydgoszcz (2002).

[23] N. Kepczak, W. Pawlowski, W. Blazejewski, The Study of the Mechanical Properties of the Mineral Cast Material, Archives of Mechanical Technology and Automation **34**, 2, 25-32 (2014).