Research Article

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Dynamic properties of hybrid machine tool body – Theoretical and experimental investigation

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Abstract: The article presents theoretical and experimental investigation in order to obtain dynamic properties of hybrid machine tool body in comparison with cast iron body. For this purpose, the theoretical and experimental modal analyses were carried out. The influence of the mineral cast material for filling voids on the dynamic properties of the machine tool body was discussed. During the analysis, the modes and frequencies of free vibrations, the amplitude values and the damping ratios were compared. Despite lowering the free vibration frequency of the hybrid construction, compared to the cast iron body, in some cases, the dynamic properties were affected. This could be determined on the basis of decreasing the amplitude value of the transfer function (from 12.16% to 58.66%) and the increasing the vibration damping coefficient ratio (from 12.22% to 75.24%) in the case of a hybrid body as compared to a cast iron body. The final conclusions were drawn about the application of mineral casts in the construction of machine tools and its impact on the dynamic properties of the structure.

Keywords: Polymer concrete, cast iron, machine tool body, dynamic properties, modal analysis

1 Introduction

In the twenty-first century, modern machine tools require high machining accuracy, good surface quality and high productivity. In the machining process, vibrations may occur, which negatively affect the shape and dimensional parameters of the workpiece [1–3].

In the design process, and the construction and manufacturing of machinery and devices, the solutions should minimize the generation of vibrations. In order to reduce the impact of vibrations on the cutting process, various methods of reducing the vibration amplitude are used. These methods can be divided into two main groups: those related to the machine tool construction and those related to the cutting process [4]. One of these methods is to ensure adequate vibration damping both in terms of construction and material properties. Until now, in the field of machine tool construction, the commonly used material was cast iron, due to its very good vibration damping properties. The latest research and development trends show that there is a clear tendency to move away from traditional cast iron castings towards mineral casts due to their more advantageous (from technological point of view) dynamic properties, that is, higher damping.

Regarding dynamic properties of the machine tool structure in terms of the vibration response and its resistance to dynamic forces it induces, the conclusion that the high damping property of the structural material is more beneficial for the machining outcomes (qualitatively better results of the machined surfaces). The higher modal damping of main vibration modes indicates the lower amplitude of dynamic response and consequently higher quality of the machined workpiece. That may be considered as dynamic properties' improvement of the machine tool structure as far as the machining results are taken into account.

A solution that can combine the advantages of traditional (cast iron) and modern (mineral cast) construction materials is the application of both materials in the hybrid construction of machine tool bodies. Such a way of constructing large machine elements—for example, beds—requires maintaining certain rules and technological procedures to eliminate or minimize the disadvantages of both materials effectively, while at the same time ensuring the most effective use of their advantages. Both technological possibilities and limitations resulting from the properties of the materials used in a hybrid machine body have been thoroughly analyzed in this work.

Polymer concrete (mineral cast) is a complex material composed of particles of inorganic aggregates, such

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as basalt, spodumene, fly ash, river gravel, sand, chalk, and so on, connected by resin (usually epoxy resin) [1, 5, 6]. The current development trends include the application of mineral casting instead of cast iron in the construction of machine tools [7–9]. In some cases, such as in the precision industry, mineral casting is used only in selected components of machine tools, such as guides. This is due to the inadequate strength properties of mineral casting [6]. In other cases, where the precision of the object does not need to be so high, and strength considerations permit, the entire bed can be made of cast mineral [10, 11].

One method to investigate dynamic properties of the construction is modal analysis. It is divided into three areas (theoretical, experimental, and operational). Theoretical research is very often used at the design stage, not involving the production of an expensive prototype. It has been successfully applied to solve structural dynamic problems in mechanical [12–14] and aeronautical engineering [15]. Recently, modal analysis has also found broad applications in civil and building structures [16], biomechanical and harvest problems [17], space structures and electronics [18], acoustical instruments [19], transportation [20] and nuclear plants. Modal analysis in this research has divulged the modes and their natural frequencies and damping ratios. Modal analysis is used for modifying the structure, the diagnostics of the condition of the structure, the synthesis of control systems of active vibration reduction, as well as the verification and validation of numerical models, such as finite and boundary element models [21].

Experimental modal analysis is a technique often used in practice to study the dynamic properties of mechanical objects, both during the construction, as well as the operation of machinery. The identification experiment in experimental modal analysis involves exciting the vibration of the object, with the simultaneous measurement of the excited force and the response of the system, usually in the form of the spectrum of vibrations acceleration [21, 22]. Experimental modal analysis can be realized by the SISO (single input single output), SIMO (single input multiple outputs) and MIMO (multiple inputs multiple outputs) techniques. These methods are different not only in the requirements of the measuring devices, but also in the accuracy of their results.

This paper presents the results of theoretical and experimental modal analysis of the cast iron and hybrid machine tool bodies. The influence of the polymer concrete material for filling hollow spaces on the dynamic properties of the machine tool bed was discussed. During the analysis, the occurring modes of free vibrations, the amplitude values of the transfer function, as well as the damping coefficients were compared. Finally, conclusions about the usage of mineral cast in the construction of machine tools and its impact on the dynamic properties of the structure were drawn.

2 Theoretical Modal Analysis

In order to conduct the theoretical modal analysis, 3D models of cast iron and hybrid machine tool bodies were created in the Autodesk Inventor software. Figure 1 shows the isometric view of the machine tool body, which has been analyzed. It was the bed of the lathe machine tool, which was produced by Koluszki Foundry and Machinery. Its dimensions were 330 mm × 300 mm × 1950 mm (height × width × length). The thickness of ribs was 12 mm.

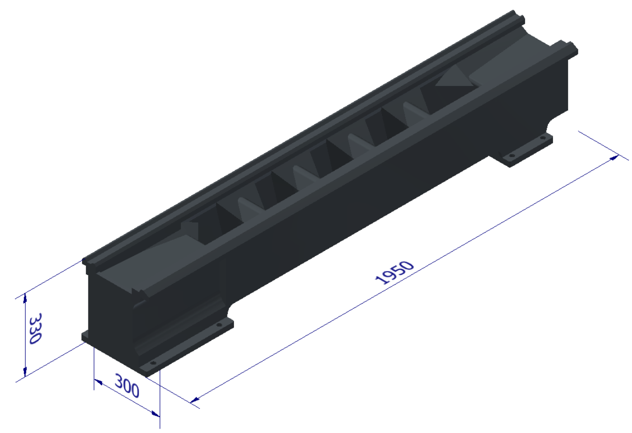
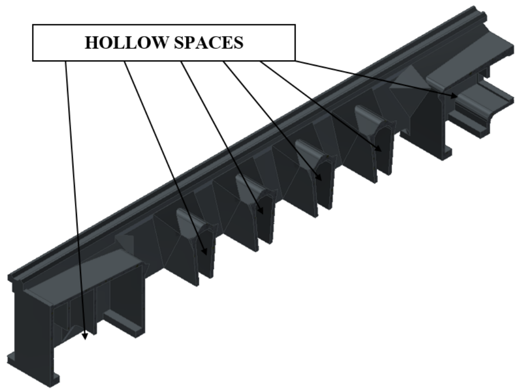


Figure 1: The isometric view of the machine tool body

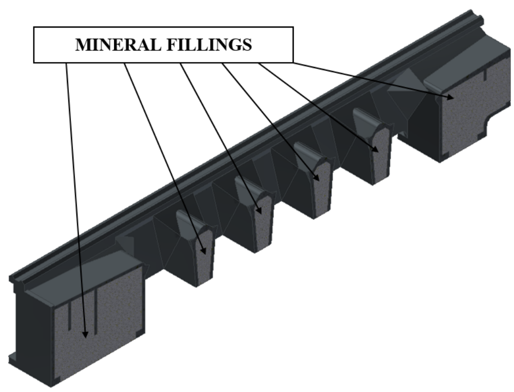
Figure 2 shows the cross-section views of both analyzed beds. The cast iron body (Figure 2a) in the cross-section had some hollow spaces, which in the following analyses were filled with mineral cast material in order to create a hybrid body (Figure 2b). The material used in research was polymer concrete offered by RAMPF, available on under the name EPUCRET 140/5 [23]. It is a material used for casting small parts of machines, for example, guideways, tables or beds, with a weight not exceeding 500 kg. It consists of aggregates with dimensions ranging from a few micrometers up to 5 mm.

During the research, the theoretical modal analysis was carried out in a frequency domain up to 1600 Hz. In an analysis, the following mechanical properties were set, which are included in Table 1.

The finite elements mesh setting was another very important problem during the analysis. In order to conduct the numerical study, tetrahedron elements were chosen.



(a)



(b)

Figure 2: Cross-sections of the machine tool bodies: a) cast iron body, b) hybrid body

Table 1: Mechanical properties of iron cast and polymer concrete.

Property	Iron Cast*	Polymer Concrete**
Tensile strength [MPa]	500	18
Compressive strength [MPa]	1600	106
Young's modulus [GPa]	160	30
Poisson ratio [—]	0.30	0.22
Kirchhoff modulus [MPa]	65000	12000
Density [g/cm^3]	7.15	2.30

* Values of mechanical properties of cast iron were given from the Autodesk Inventor materials library.

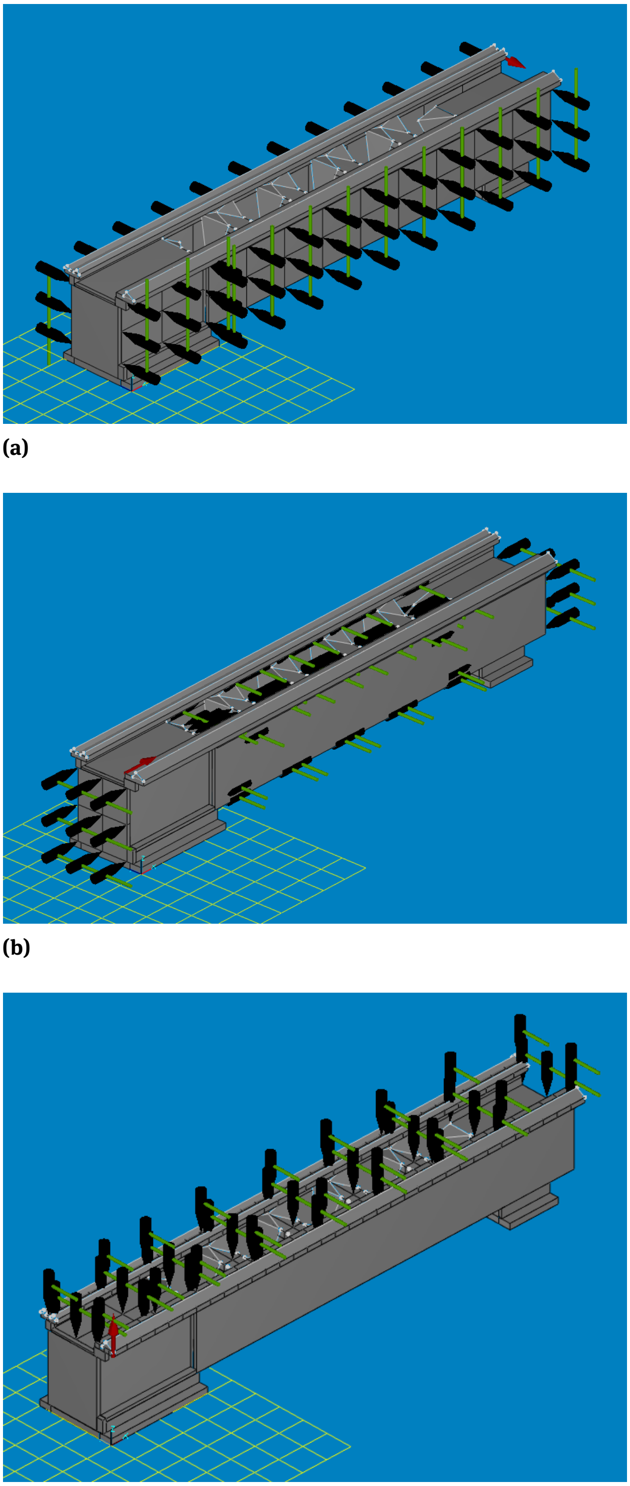
** Values of mechanical properties of polymer concrete were given from experimental research [24]

The smaller size of the mesh element resulted in increase of elements, nodes and number of equations to solve. In the case of smaller elements, the time of meshing was longer but the results were more accurate. The iron cast body mesh had 407,740 nodes and 231,853 elements when the hybrid body mesh had 475,499 nodes and 277,603 elements. The increase in the number of elements and nodes is a result of meshing the spaces of the body filled with the mineral cast material.

3 Experimental Modal Analysis

In order to conduct the experimental modal analysis, it was necessary to model the tested element in the Pulse LabShop program. The geometry model of the analyzed machine tool body is required in the experimental modal analysis system in order to plan and carry out properly the experiments, and to determine the modes of vibrations and their graphic representation.

The experimental modal analysis was carried out for three directions: transversal, longitudinal and vertical. The signal of the force course from the modal hammer and the acceleration signal from the accelerometer sensor were collected and processed in the PULSE data acquisition system. A Pulse Lite package from Brüel and Kjær was used including: a 3560 L measurement module, a 2-channel FFT analysis program, a 4514 acceleration sensor and a modal hammer type 8206-003. Parameters of acquiring the force and acceleration signals were determined by the settings of the PULSE system. The resolution of the measured signals allowed analysis in the frequency range up to 1600 Hz with step of 1 Hz. In order to reduce the spectrum leakage in Fourier Transform converting of the data from the time domain into the frequency domain, the Hanning windowing method was applied. The coherence function was determined by means of the Pulse LabShop system on the basis of five repetitions of the excitation. The bodies were tested three times. In the case of body tests in the transverse direction, 75 measuring points were selected for the analysis. In the case of longitudinal body tests, 77 measurement points were selected for the analysis and for vertical body tests, 45 measurement points were selected. During the modal analysis, SISO (Single Input Single Output) method was applied. It means that each measuring point was excited for vibration one by one in the selected order. This approach is called Rowing Hammer (Fixed Accelerometer). Figure 3 shows the excitation points (black-green hammers) and fixing points of the accelerometer (red arrows) for all the directions. The measuring stand is shown in Figure 4. During the tests, the bodies were mounted to the ground by mounting holes located on both sides of the beds. Experimental modal analysis was carried out in a frequency domain up to 1600 Hz similar to the theoretical modal analysis.



(a)

(b)

(c)

Figure 3: View of excitation points (black-green hammers) and fixing points of accelerometer (red arrows): a) for transversal direction, b) for longitudinal direction, c) for vertical direction

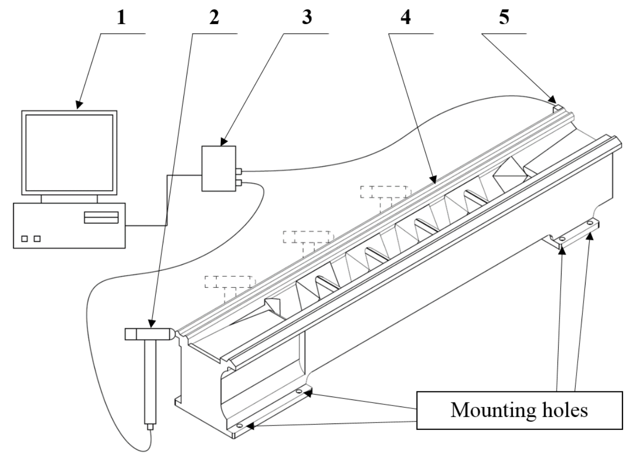


Figure 4: View of the testing stand: 1 – computer, 2 – modal hammer, 3 – data system acquisition, 4 – machine tool body, 5 – accelerometer

4 Results and Discussion

A comparison of the theoretical and experimental modal analysis results is presented in Table 2. The obtained modes are schematically marked, and also the values of free vibration frequencies were entered for each mode. In order to visualize the test results in Figures 5 and 6, the first mode of free vibrations obtained with the theoretical and experimental methods for the cast iron and hybrid body is presented.

The comparison shows that the dynamic properties, taken as an increase in modal frequency, were not improved in every case of free vibrations modes of the hybrid structure. Therefore, for each of the presented modes and frequencies of free vibrations, the values of the amplitude and the vibration damping coefficient were plotted from the graphs for the measurement points with the biggest amplitude value observed.

Figures 7 to 18 present the modes of free vibrations obtained in the experimental research with marked measurement points from which the values of amplitude transfer function and damping ratio were read. Additionally, the amplitude and vibration damping graphs were created to illustrate the improvement of dynamic properties.

Figure 7 shows the first mode of free vibrations with a marked measurement point (number 57 for the transversal direction). Figure 8 shows the values of amplitude and the damping ratio. In the case of a cast iron body, this mode was at the frequency of 211 Hz, while for the hybrid construction, it was 232 Hz. The value of the amplitude estimate of the transfer function for the cast iron solution was 943 (mm/s2)/N, while in the case of the hybrid body, this value

Table 2: Results of theoretical and experimental modal analysis

Mode	Shape for transversal direction	Shape for longitudinal direction	Shape for vertical direction	Frequency for cast iron body (theoretical)	Frequency for hybrid body (theoretical)	Frequency for cast iron body (experimental)	Frequency for hybrid body (experimental)
1				189 Hz	195 Hz	212 Hz	232 Hz
2				364 Hz	356 Hz	322 Hz	302 Hz
3				393 Hz	425 Hz	363 Hz	453 Hz
4				476 Hz	473 Hz	529 Hz	521 Hz
5				765 Hz	782 Hz	754 Hz	762 Hz
6				1026 Hz	1048 Hz	975 Hz	1000 Hz

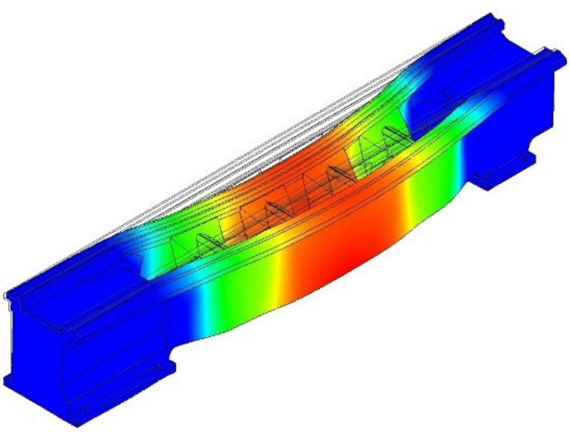


Figure 5: Theoretical first mode of cast iron body with a frequency of 189 Hz and hybrid body with a frequency of 195 Hz

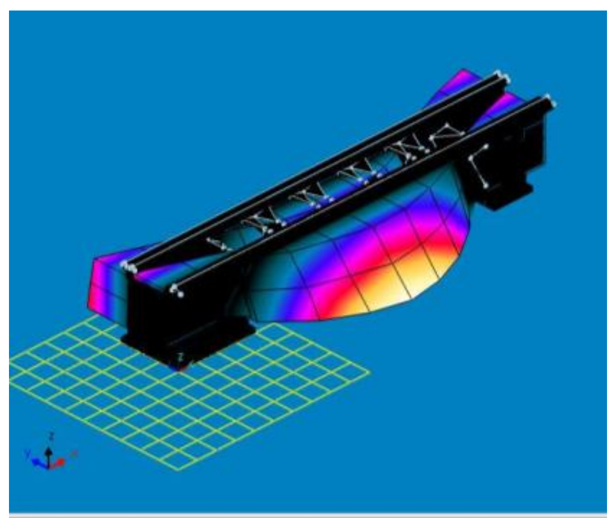


Figure 6: Experimental first mode of cast iron body with a frequency of 212 Hz and hybrid body with a frequency of 232 Hz

was 756 (mm/s2)/N. In this case, the amplitude dropped by 19.8% for the hybrid construction. The value of the vibration damping ratio for the cast iron body reached the value of 0.450%, where for the hybrid solution the value was 0.505%. In this case, the damping ratio increased by 12.22%. A similar situation can be observed for all the modes of the body. For mode 2 (Figures 9 and 10), the value of amplitude decreased by 53.33% and damping ratio increased by 59.54%. For mode 3 (Figures 11 and 12), the value of amplitude decreased from 12.16% (for #27 measurement point) to 31.89% (for #58 measurement point) and damping ratio increased from 23.42% (for #27 measurement point) to 26.56% (for #58 measurement point). For mode 4 (Figures 13 and 14), the value of amplitude decreased from 25.90% (for #71 measurement point) to 58.66% (for #13 measurement point) and damping ratio increased from 23.90% (for #13 measurement point) to 66.43% (for #71 measurement point). For mode 5 (Figures 15 and 16), the value of amplitude decreased from 29.11% (for #18 measurement point) to 34.41% (for #51 measurement point) and damping ratio increased from 33.48% (for #18 measurement point) to 41.20% (for #64 measurement point). For mode 6 (Figures 17 and 18), the value of amplitude decreased from 20.10% (for #3 measurement point) to 47.66% (for #18 measurement point) and damping ratio increased from 31.27% (for #69 measurement point) to 75.24% (for #3 measurement point). For all the modes, a decrease of the value of the amplitude from 12.16% to 58.66% was observed, while for the damping ratio, the increase was from 12.22% to 75.24%.

Below are the abbreviations used:

- Amp. C.I.B. – Amplitude of Cast Iron Body
- Amp. H.B. – Amplitude of Hybrid Body
- D.R. C.I.B. – Damping Ratio of Cast Iron Body
- D.R. H.B. – Damping Ratio of Hybrid Body

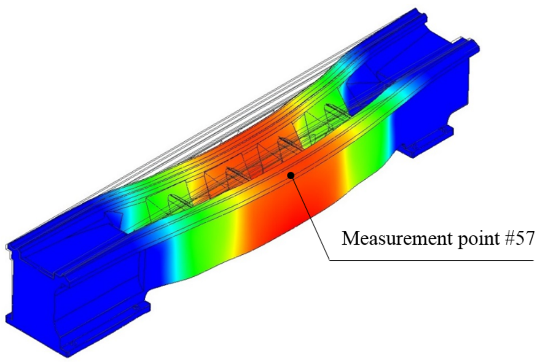


Figure 7: Measurement point for first mode

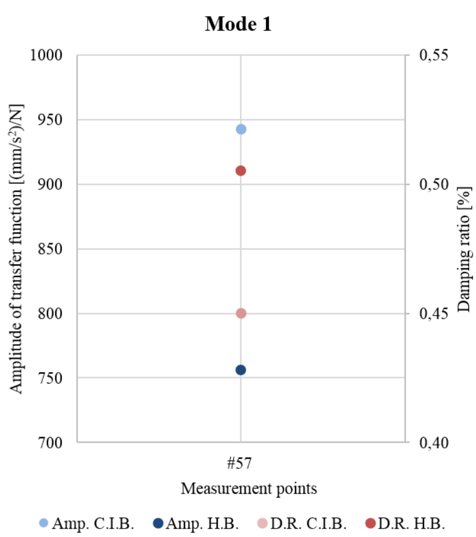


Figure 8: Graph of amplitude and damping ratio for first mode

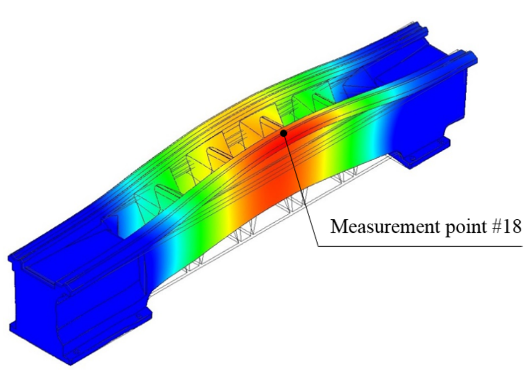


Figure 9: Measurement point for second mode

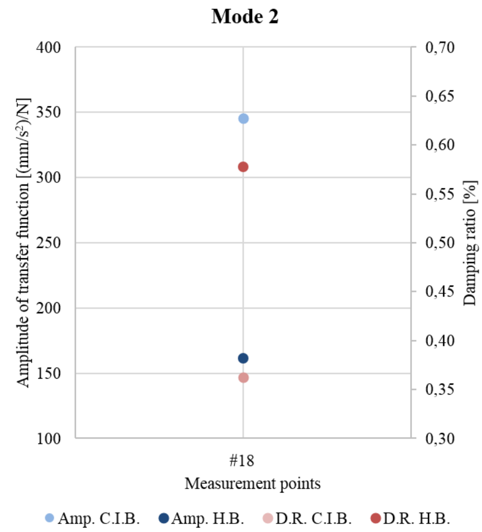


Figure 10: Graph of amplitude and damping ratio for second mode

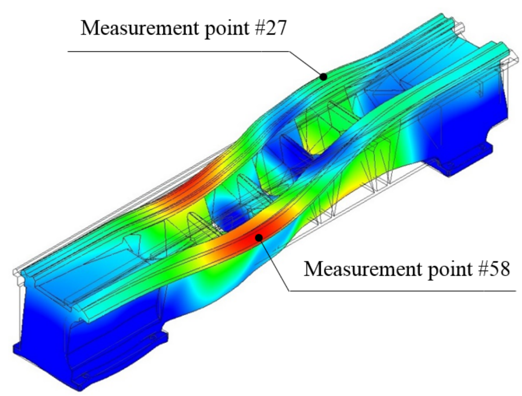


Figure 11: Measurement point for third mode

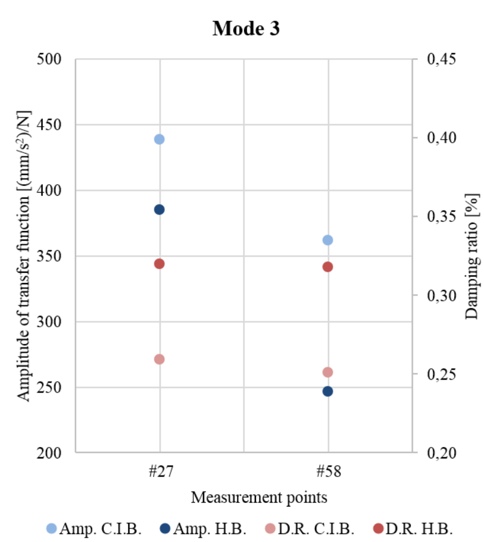


Figure 12: Graph of amplitude and damping ratio for third mode

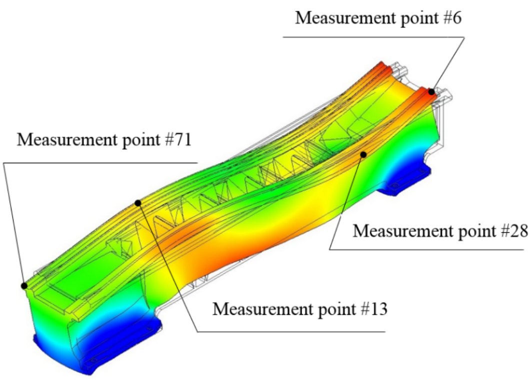


Figure 13: Measurement point for fourth mode

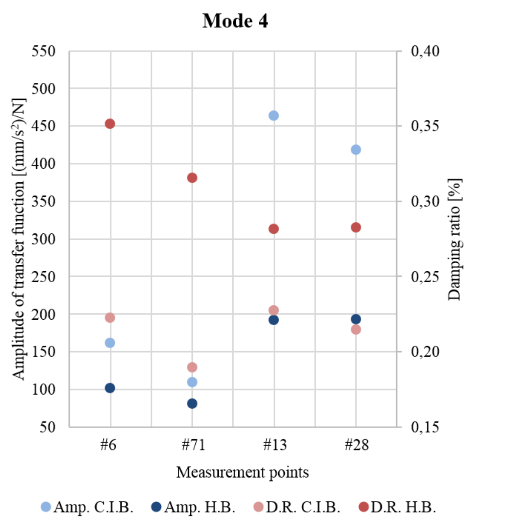


Figure 14: Graph of amplitude and damping ratio for fourth mode

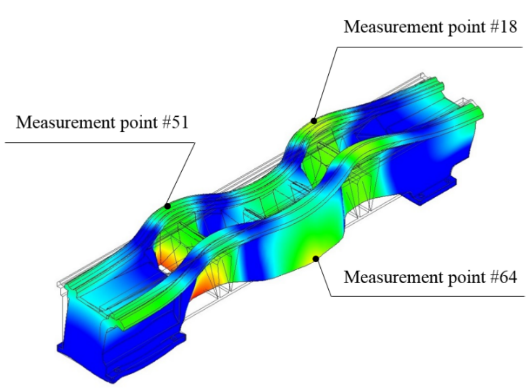


Figure 15: Measurement point for fifth mode

As it can be seen from Table 2, and the presented diagrams and drawings, in spite of the decrease, in some cases, of the free vibrations frequency of the hybrid construction in comparison with the cast iron body, the dynamic properties improved. This can be determined on the basis of the

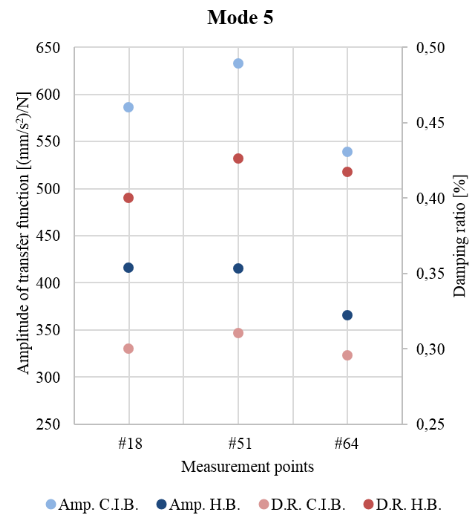


Figure 16: Graph of amplitude and damping ratio for fifth mode

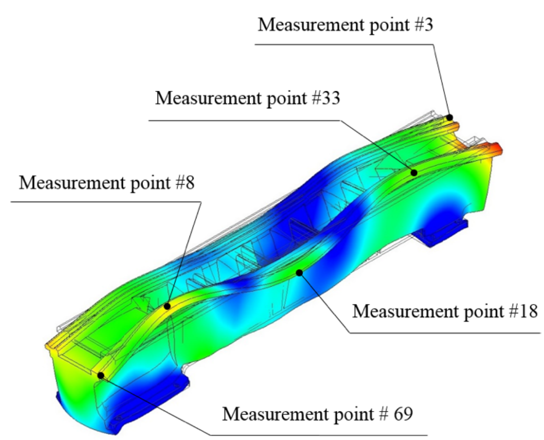


Figure 17: Measurement point for sixth mode

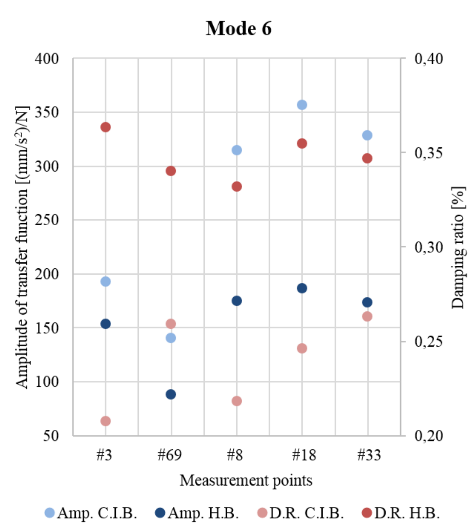


Figure 18: Graph of amplitude and damping ratio for sixth mode

decreasing amplitude value of the transfer function and the increasing vibration damping ratio in the case of a hybrid body compared to a cast iron body. The dynamic effect stated above is directly connected to the use of mineral cast as a construction material. The properties of this material combined with the cast iron used for the body structure results in the improvement of the dynamic properties of the machine bed made as a hybrid element (cast iron-mineral).

5 Summary and Conclusions

The article presents the results of the influence of a polymer concrete material for filling voids on dynamic properties of the lathe machine tool body. During the analysis, the six modes and frequencies of free vibrations, the amplitude values and the damping coefficients were compared. Despite lowering the free vibration frequency of the hybrid construction, compared to the cast iron body, in some cases, the dynamic properties were improved. This can be determined on the basis of decreasing the amplitude value of the transfer function (from 12.16% to 58.66%) and the increasing vibration damping ratio (from 12.22% to 75.24%) in the case of a hybrid body as compared to a cast iron body. The conducted research showed that the dynamic properties of new and existing machine tool bodies can be easily improved by filling the void spaces with a mineral cast material. This is particularly important during the renovation of old machine tools. In addition to the basic activities that restore the nominal parameters of the motion accuracy of machine elements (repair of guides, bearings, transmission systems, etc.), one can plan relatively simple work to fill the free spaces of cast iron bodies with a mineral cast material. In this way, the dynamic properties of the renovated machine tool can be improved in comparison with a similar, new machine with a classic design. From the point of view of the requirements regarding the dimensional and shape accuracy of the workpiece, it may turn out that machining with a hybrid machine tool is even more precise, which in turn may lead to the elimination of finishing operations, such as grinding processes. At the design stage of the new machine tool body, it is possible to ensure that the empty spaces in the cast iron construction element are filled with a polymer concrete material in order to improve its dynamic properties. It should be noted that filling the hollow spaces of a cast iron body with a mineral cast material should not disturb the conditions of its proper functioning and the course of the cutting process, ensuring proper coolant drainage, chip evacuation, proper cooling conditions, and so on.

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