



Experimental Investigations of Steel Welded Machine Tool Bodies Filled with Composite Material

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Abstract. Designing machine tool body elements is a difficult task, therefore manufacturers introduce minor changes of evolutionary rather than revolutionary character. Modern machine tools very often have a structure similar to the bodies of machines of the previous generation. The vast majority of currently manufactured machine tool bodies are made in the form of grey iron castings. However, their relatively high mass, high cost for unit production, and significant limitations in terms of the possibility of modifying the existing structure, force the search for new, more effective solutions. In presented paper new solution consisting in filling the steel welded structure with a composite material is proposed. Steel welded structure ensures the required stiffness, while composite material is improving the damping properties. The paper presents results of experimental modal analysis conducted for three variants of steel welded body filled with composite material with different filling locations. Obtained results were compared and contrast in terms of dynamical behavior and damping abilities.

Keywords: Experimental modal analysis · Machine tool bodies · Steel profiles · Composite · Mineral casting

1 Introduction

The functional properties of the machine tool depend significantly on its body, and main task is to provide a geometric configuration of individual machine tool elements under static and dynamic loads accompanying the cutting process. Probably the most popular material used in the field of designing machine body elements is gray cast iron. The advantages of gray cast iron include very good casting properties, good machinability and workability. This material also has a relatively low manufacturing cost and good vibration damping ability, which is one of the most important factors determining the dynamic properties of the machine tool and has a significant impact on the machining capabilities.

Despite the undeniable advantages of gray cast iron, the latest research and development trends show that there is a clear tendency to move away from traditional gray cast iron casts to new composite materials characterized by very good damping properties. However, composite materials, due to insufficient mechanical properties,

cannot be used separately. Therefore, hybrid solutions combining conventional materials like steel, aluminum or gray cast iron with composite materials are used [1–8].

In [9], the authors designed the slides of high-speed milling machines by joining high-modulus, carbon-fibre, epoxy composite sandwiches to welded steel structures using adhesives and bolts, which provided a significant increase in damping properties and a reduction in mass.

In [10], the authors presented a theoretical modal analysis of two machine tool bodies: one made of gray cast iron and the other made of a hybrid combination of cast iron and mineral casting. The analysis was carried out to determine the dynamic properties of two bodies made in traditional and innovative casting technology. In addition, an analysis of the static stiffness of both bodies was carried out. On the basis of the conducted simulation tests, the authors found an increase in dynamic and static stiffness of the machine body made of a hybrid combination of gray cast iron and mineral casting.

In [2], the authors inserted a friction layer between the aluminium-composite interface to increase the structural damping of machine tool structures, such as columns and spindle holders, which resulted in weight and static deflection reduction and much higher damping capacities than those of aluminium structures.

The article presents the alternative solution of hybrid machine tool bodies composed of steel welded construction filled with composite material. Steel welded construction ensures adequate stiffness while composite material provides high damping abilities. The paper contains the results of experimental modal analysis of three miniature steel welded machine tool bodies with different filling locations. Based on obtained research results, the properties of the proposed solutions were compared, indicating their advantages and disadvantages.

2 Test Objects

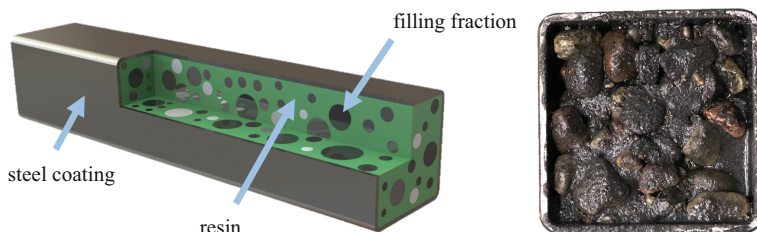
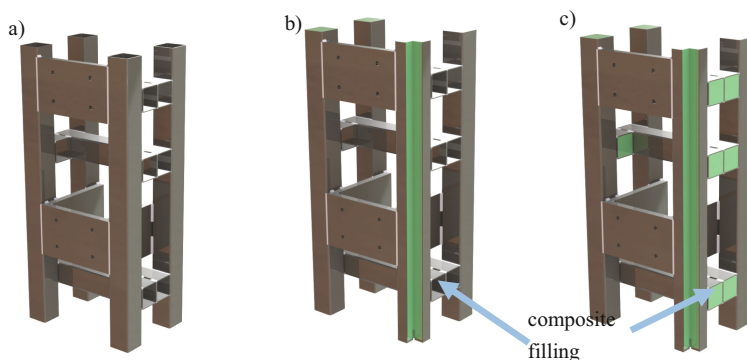
The test object is steel welded body and consists of profiles with a square cross-section of dimensions 50×50 and a wall thickness of 2 mm. The analyzed body is slightly modified reflection on the 1:3 scale of the body of the newly designed vertical lathe of light construction. The research object was tested in three variants differing in the location of composite filling to examine its ability to shape the dynamic properties of the structure, in particular related to the vibration damping ability. Composite material filling consisted of a filling with a different size of the filling fraction and a bonding resin fulfilling the task of the binder. The composition of selected material, based on previous studies [8, 11] focusing on the comparison of individual materials with respect to vibration damping abilities, is presented in Table 1. The method of filling a single beam which is the basic element that the examined body consists of, is shown schematically in Fig. 1.

As already mentioned before, three variants of the welded steel body were analyzed, differing in the location of the composite filling, they are as follows:

- steel welded body with no filling, weight: 21,33 kg (Fig. 2a)

Table 1. Composition of the composite material.

Specimen	Resin	Ash	Small fraction (0,25–0,2)	Medium fraction (2–10 mm)	Coarse fraction (8–16 mm)	Steel fiber
M05	26.1%	1.7%	15.7%	13%	30.5%	13%

**Fig. 1.** The method of filling a single beam being part of the examined body.**Fig. 2.** Machine tool body examined variants.

- steel welded body partially filled with composite material, weight: 31,85 kg (Fig. 2b)
- steel welded body fully filled with composite material, weight: 37,76 kg (Fig. 2c)

3 Experimental Investigations

To determine dynamic behavior of tested structures, an experimental modal analysis was conducted, using impact testing technique. To eliminate support influence on machine tool body damping capacity, objects were subsequently suspended on steel cables and then analyzed. A set of preliminary tests was conducted focusing on finding optimal stiffness of suspension [12].

To excite all the modes within the frequency range of interest, several impact locations were examined, and on this basis the most suitable points were chosen. Examined machine tool bodies were excited using a modal hammer in selected points at three orthogonal directions. In addition, excitation parameters (e.g. power spectral density, excitation force levels, double impact occurrence) and coherence functions were monitored during experiment.

To check the measurement quality, and accomplish a comprehensive modal analysis, which except natural frequencies, damping factors and scaled mode shapes and includes modal mass and stiffness as well, driving point measurements were made. The structure responses were measured in 260 points in three orthogonal directions using triaxial IPC accelerometers, characterized by high sensitivity, wide frequency range and small mass. The measure points arrangement was depicted in Fig. 3.

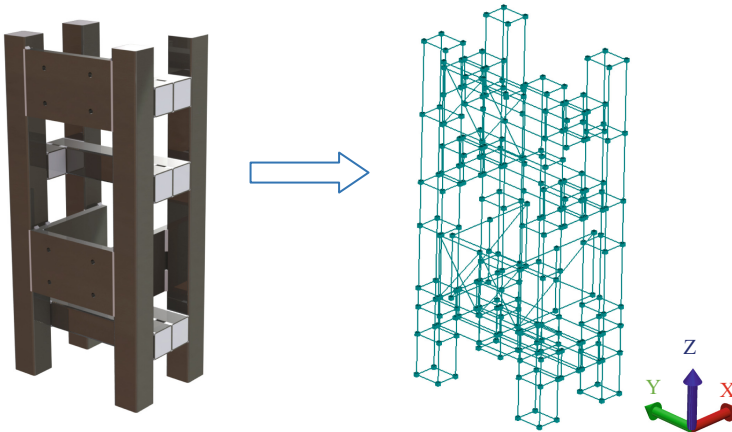


Fig. 3. Measure points arrangement.

After the preliminary activities, i.e. sensor connections, temperature stabilization of measuring equipment, setting a signal acquisition and processing parameters, verification of Maxwell's Reciprocity Theorem was conducted, results are depicted in Fig. 4.

The experiment itself consisted of measurements, data processing and analysis of vibration levels to select the relevant mode shapes. The structure was subsequently excited at selected points, using modal hammer PCB with 10.23 mV/N sensitivity. Dynamic response of the examined structure was measured using triaxial PCB ICP type accelerometers, characterized by sensitivity of 10 mV/(m/s²). Building and validating of modal model was realized using LMS TestLab software and Scadas III hardware. Modal parameters estimation process was realized using Polymax algorithm with default values of tolerance on frequency - 1%, damping - 2% and mode shapes vector - 5% and next validated using MAC criterion. Experimental setup is presented schematically in Fig. 5.

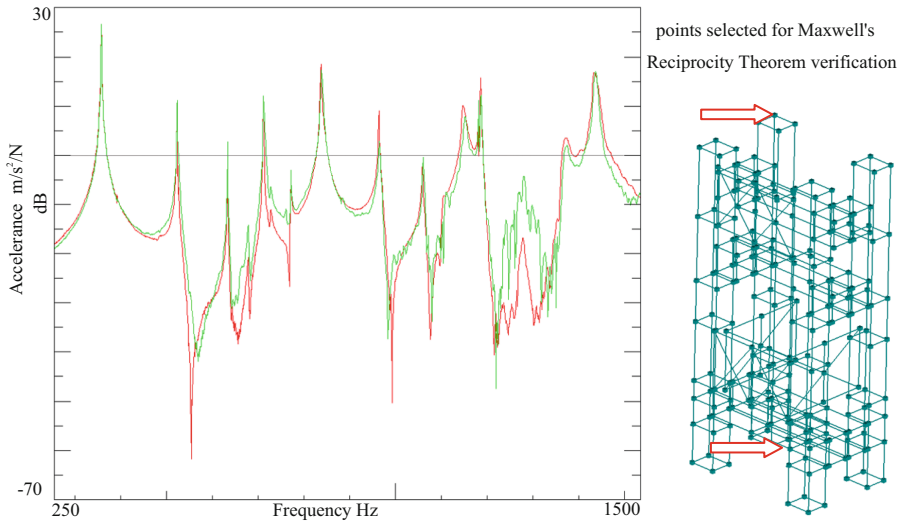


Fig. 4. Verification of Maxwell rule between indicated points at X direction.

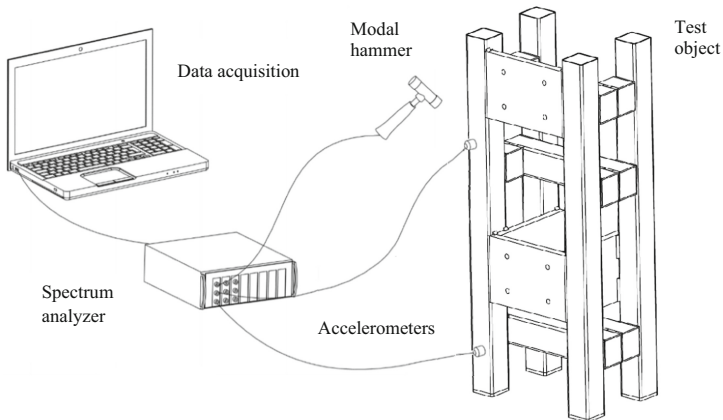


Fig. 5. Experimental setup.

4 Results

As a result of experiment, 780 frequency response functions were determined using H1 type of FRF estimator and on their basis, modal model was built. Modal parameter estimation was realized using Polymax method with values of tolerance on frequency – 1%, damping – 2% and mode shapes vector – 5%. Modal model poles were selected in the range 100–1500 Hz, and mode shapes were estimated using stabilization diagram. Modal Assurance Criterion (MAC) was used to indicate physical mode shapes with low orthogonality level. The final modal model of subsequent variants of examined steel welded body is presented in Table 2.

Table 2. Modal models of machine bodies variants.

Mode number	Variant 1		Variant 2		Variant 3	
	Natural frequency	Modal damping	Natural frequency	Modal damping	Natural frequency	Modal damping
1	356 Hz	0.15%	339 Hz	0.14%	390 Hz	0.22%
2	522 Hz	0.18%	484 Hz	0.16%	778 Hz	0.26%
3	632 Hz	0.06%	639 Hz	0.14%	779 Hz	0.10%
4	675 Hz	0.29%	685 Hz	0.22%	912 Hz	0.20%
5	711 Hz	0.11%	733 Hz	0.27%	968 Hz	0.30%
6	724 Hz	0.22%	760 Hz	0.17%	1012 Hz	0.33%
7	759 Hz	0.17%	780 Hz	0.15%	1031 Hz	0.28%
8	770 Hz	0.11%	857 Hz	0.07%	1135 Hz	0.25%
9	836 Hz	0.17%	1016 Hz	0.17%	1228 Hz	0.25%
10	963 Hz	0.06%	1031 Hz	0.11%	1285 Hz	0.34%
11	1104 Hz	0.08%	1083 Hz	0.21%	1371 Hz	0.27%
12	1150 Hz	0.27%	1098 Hz	0.18%	1418 Hz	0.27%
13	1059 Hz	0.18%	1177 Hz	0.17%		
14	1181 Hz	0.04%	1216 Hz	0.20%		
15	1274 Hz	0.35%	1320 Hz	0.08%		
16	1368 Hz	0.25%	1444 Hz	0.23%		
17	1436 Hz	0.18%				

Figure 6 depicts mode shapes estimated for examined variants that repeat regardless of the filling location, having also significant receptance function amplitude level. Signatures above graphic representations of presented mode shapes occur in the

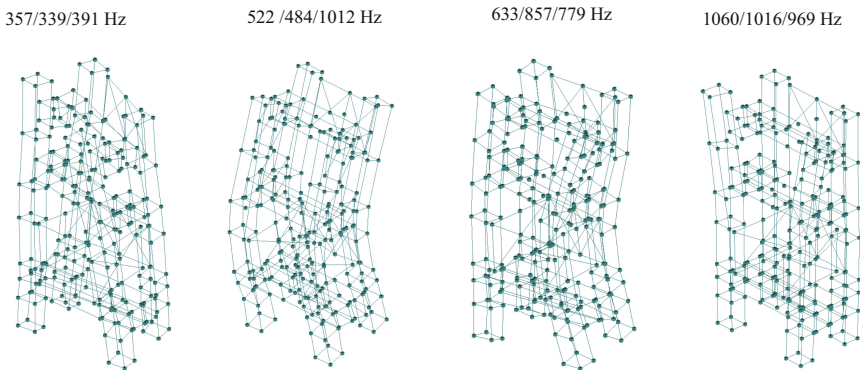


Fig. 6. Mode shapes estimated for examined variants.

following order: Variant 1/Variant 2/Variant 3, rounded to integer for clarity sake. Figure 7 depicts MAC (Modal Assurance Criterion) values obtained by comparing subsequent variants in order to determine the similarity of it.

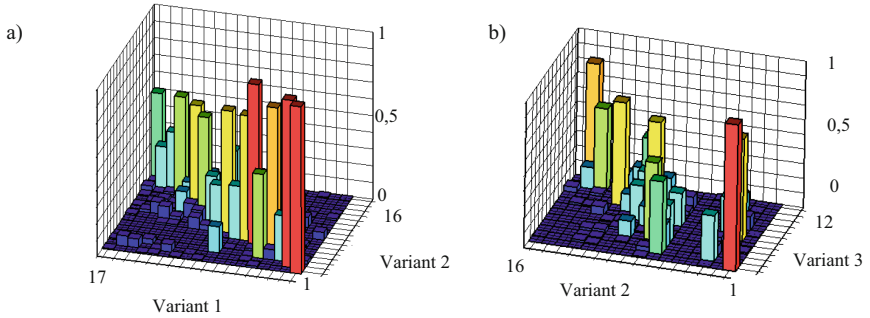


Fig. 7. MAC matrix for variant 1 and 2 (a) and for variant 2 and 3 (b).

The Figs. 8 and 9 present FRF comparison in selected points for examined variants. Point A was selected on top part of machine tool body (where the spindle is mounted), point B on bottom part of machine tool body (where the tool is mounted).

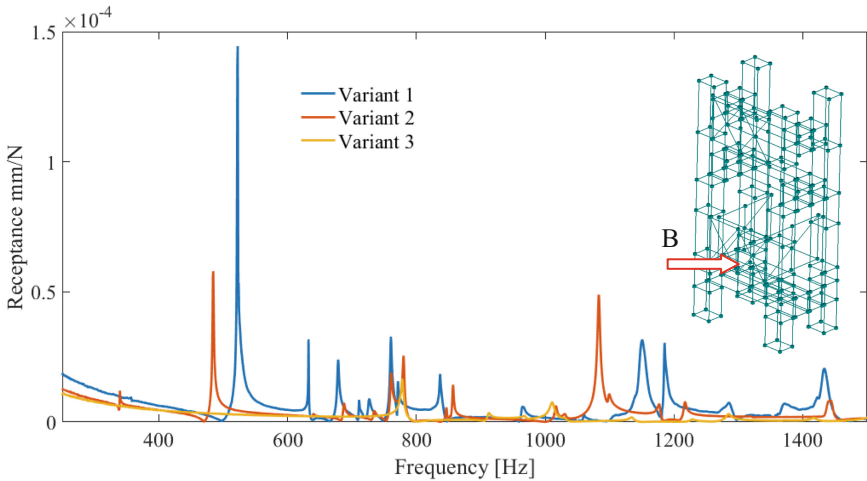


Fig. 8. Receptance function comparison for examined variants in point A in Y direction.

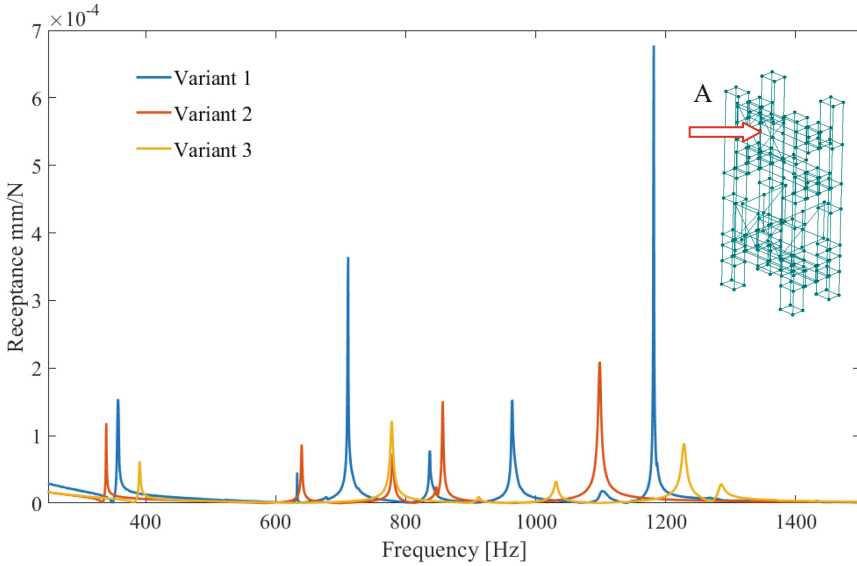


Fig. 9. Receptance function comparison for examined variants in point B in Z direction

5 Conclusions

Summing up the presented results, following conclusions can be reached: (i) the use of composite filling resulted in increase of damping abilities of machine tool body, which is clearly manifested in receptance functions amplitudes (ii) the use of composite filling resulted in a general increase in the natural frequency values of corresponding mode shapes, (iii) composite filling can also be used to increase the stiffness of some of the elements included in the body, while maintaining a lower mass similar structure made from gray cast iron.

Additionally, filling location has a significant influence on certain mode shapes in terms of increasing hollow section stiffness, which leads to conclusion, that this can be optimized in terms of minimization of relative tool – workpiece vibrations in certain frequency range. This should be analyzed in detail in future work.

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