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ANALYSIS OF STATIC STIFFNESS OF MACHINE TOOLS FOR RAILWAY AND SHIPBUILDING INDUSTRIES

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Abstract: The article presents static stiffness investigation of a rather specific group of machine tools characterized by a unique construction type which are made for railway and shipbuilding industries. Machines of that type are rarely tested in terms of their static stiffness, so consequently the knowledge about their static stiffness properties is fairly limited. The investigation was conducted involving two methods, traditional (conventional) one and the other originally developed method using dynamically changeable signal (DDSS). The results obtained represented stiffness characteristics and stiffness indicators. The static stiffness tests of the machine tools presented in the article are very rare. Therefore, in this case, the knowledge base is very poor. Based on the results obtained, the machining accuracy can be predicted. In many cases, the obtained results are the only source of information needed to validate FEM calculation models, compare similar machines, verify and optimize the stiffness of the structure at the design stage. In addition, due to the lack of appropriate standards for conducting this type of research, the presented unique procedures are helpful for subsequent researchers of this issue.

Key words: machine tools, static stiffness, DDSS method.

1. INTRODUCTION

The static stiffness of machine tools is a feature that has a great influence on the accuracy of these machines. Issues related to it are discussed in various aspects in many publications e.g. [1-6]. The article presents experimental studies of the static stiffness of machine tools characterized by a specific design that requires the use of an unusual approach to this type of research. The presented research was conducted including two methods used in machine tool studies:

a) conventional method,
b) Dynamic Determination of Static Stiffness method (DDSS).

The conventional method is based on simulating the cutting force or its components on an idle machine tool and measuring the static displacements of selected selected machine tool units along the given directions with the use of classic displacement sensors. This method is well known and widely used in this type of research.

The DDSS method is based on the equality of displacement brought about by a dynamic force with an amplitude of displacement caused by a variable dynamic force the amplitude of which equals the value of the static force. This is the case when the frequency of the excited force is much lower than the first frequency of the free vibrations of the object. Graphically this can be illustrated by the curve of the multiplication index of the amplitude at low frequencies of excitation as shown in Figure 1.

The application of seismic sensors mounted on the body of the machine tool by means of stable magnets is the most essential advantage of this method. The DDSS method eliminates the necessity of constructing scaffolds as bases for the displacement sensors, as has been the case when applying conventional methods. Another advantage of the application of seismic sensors is that the arduous zeroing of the sensor indications preceding the respective cycles of investigations becomes unnecessary.

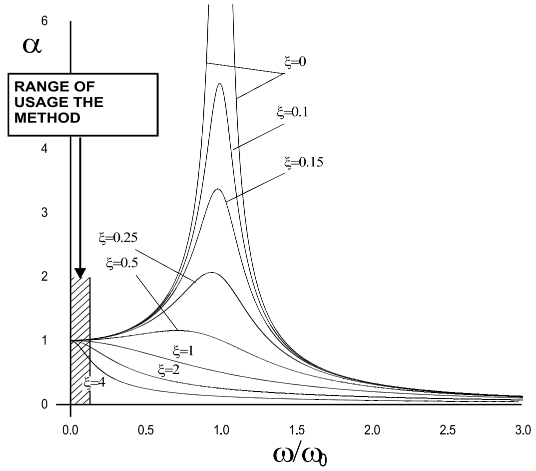

Fig.1. Graph of the multiplication index in the function of the relation of frequency of force exciting to frequencies of free vibrations; ω_0- frequency of free vibrations [rad/s], ω - frequency of the dynamic force [rad/s], ξ - dimensionless damping coefficient, α - dimensionless multiplication index of the amplitude [7]

DDSS method performed a dominant role in our research plans due to its universality. The main reason for that was the possibility of increasing the number of measurement points on a machine tool, which in turn extended the range of analysis of properties of an investigated machine tool construction. The second method, conventional one constituted a supplement. Its main role was to focus on critical construction points of the machine tool.

2. HEAVY MACHINE TOOLS TV 240 CNC

The first machine tool included in the stiffness research was a heavy lathe for wind turbine shafts TV 240 CNC series. Lathes of the TV series can be produced as machining centers with a manual exchange of the tool and automatic systems measuring the tools and a machined detail. This particular type of a lathe is able to perform machining, boring and milling operations. Figure 2 presents an overview of a TV 240 CNC lathe.

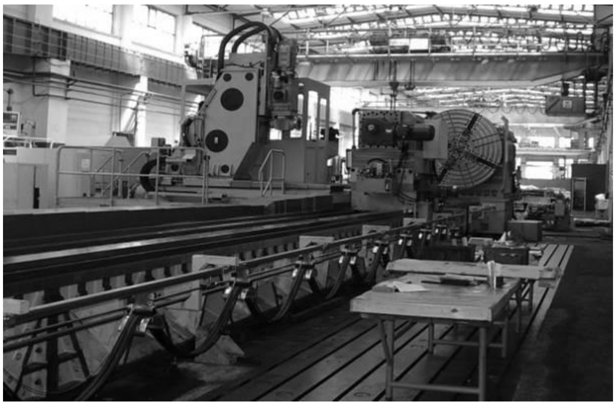

Fig. 2. General overview of the lathe TV 240 CNC [10]

The lathe's base is the bed equipped with four runways. The headstock is fixed permanently on the left side of the bed. The machining, and boring-milling carriages are moving along bed's runways together with a tailstock and back stays. The machined detail rests in a chuck mounted on the headstock and the tailstock. TV series lathes are meant for making wind turbine shafts, with the surplus of 5 mm/side skinned beforehand.
The machine material comprises carbon steel and alloy steel, improved thermally to 300 HB. Detailed technical specification of the investigated machine tool can be found in internet references [10]. The characteristic parameter of the investigated machine tool was its maximum turning diameter of 2400 mm.
In case of this particular construction while creating the plan of the investigation we focused on determining stiffness of basic elements of the investigated machine which were responsible for the precision of the machining process. The crucial constructional elements of the investigated machine TV 240 CNC include: tool holder, the disc of the tool holder**,** tailstock, lathe carriage, boring and milling carriage. In the case of lathes, the deformation in the direction of the Y axis determines the accuracy of machining. For example, deformation of the tailstock quill in the direction of this axis causes twice the deformation of the diameter of the turned workpiece. In addition, the deformation of the tailstock quill also causes an error in the conicity of the turned shaft. Figure 3 presents a sample measurement system applied during the investigation of the tailstock stiffness in relation to the lathe carriage.
Following the presented scheme, the force loaded onto the lathe was applied between the tool holder and the tailstock quill. It assumed the maximum value determined at 30 kN.
The diagram depicted in Figure 4 presents characteristics of relative stiffness of the tailstock body in relation to the lathe carriage (sensor 1Y) marked in red. Blue color represents the characteristics of relative stiffness of the tailstock quill (pinola) in relation to the lathe carriage (sensor 2Y).
The study of the investigated lathe assumed (similarly to other cases) - taking into consideration existing time and technical limitations - repetition of the sensor arrangement for both methods (conventional and DDSS) in case of critical points of the construction.

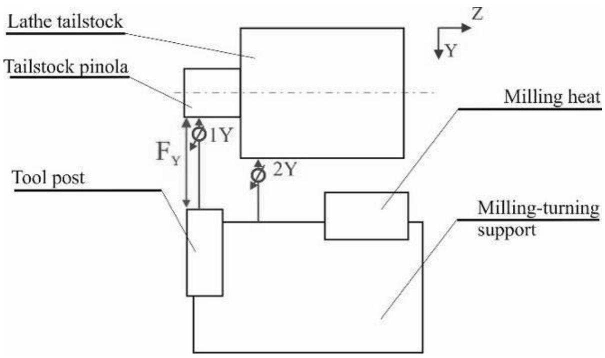

Fig. 3. Distribution of measuring points during the investigation of the quill (sensor 1Y) and tailstock (sensor 2Y) of the lathe TV 240 CNC

The study of the investigated lathe assumed (similarly to other cases) **-** taking into consideration existing time and technical limitations - repetition of the sensor arrangement for both methods (conventional and DDSS) in case of critical points of the construction.
As based on the conducted measurements it is possible to argue:

- that the machining precision using TV 240 CNC lathe depends mainly on static stiffness of the tool holder and the stiffness of the lathe carriage (relative stiffness of the tool holder in relation to the tailstock quill equaled approximately 200 kN/mm; stiffness in relation to the lathe chuck disc along Y axle was about 200 kN/mm, and in Z axle about 76 kN/mm).

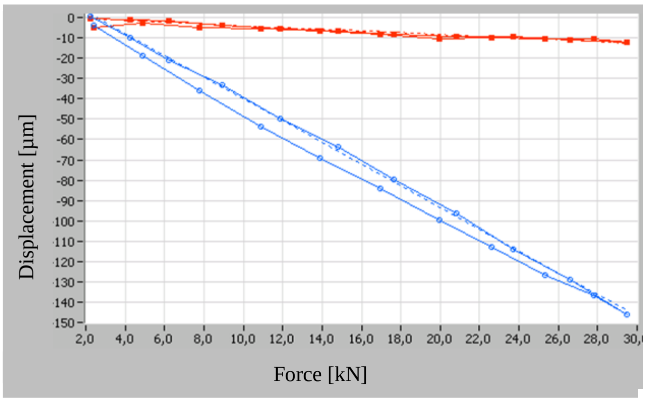

Fig. 4. Stiffness characteristics of the quill and the body of tailstock, as relative to lathe carriage: sensor 1Y – blue, sensor 2Y – red

- both tailstock body stiffness in relation to the carriage (about 2000 kN/mm), and tailstock quill stiffness in relation to the body (about 3500 kN/mm) are satisfactory.
- the stiffness of the tool holder's disc, which is the element used to hold the machined detail, was satisfactory and it exceeded the value of 600 kN/mm.
- the precision of the milling process is determined by the stiffness of the lathe's carriage, for axle Y oscillating from about 150 to about 250 kN/mm (relative stiffness in relation to tailstock body).
- extortion along axle Y may entail a slight raise of the carriage's base in the X axle at runways (stiffness in the X axle is about 550÷750 kN/mm).

3. MILLING MACHINE FS-550 CNC

The following heavy–duty milling machine characterized by an unusual construction of is load frame that underwent the research was milling machine meant for shipbuilding industry identified with the symbol of FS - 550 CNC. This machine, with cutter diameter of 5500 mm, is dedicated for machining crank arms used in crankshafts of ship engines. Figure 5 shows the view of the milling machine during operation. Figure 6 presents CAD model including the key dimensions.

Fig. 5. Milling machine used for cranking FS-550 CNC during operation [8]

Due to unusual nature of the machine's frame the main focus of the study was to determine stiffness properties of the cutter and the table.

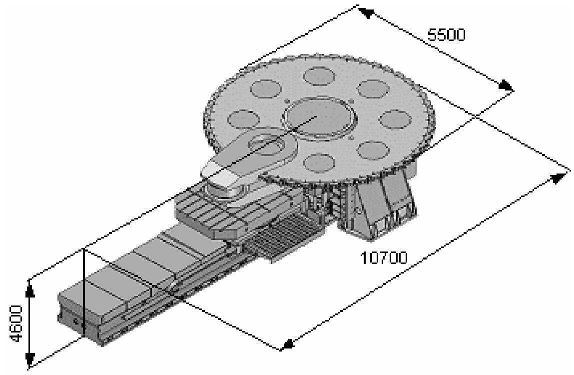

Fig. 6. Milling machine used for cranking FS-550 CNC CAD model with marked overall dimensions [8]

This assumption was influenced by the fact that the machining accuracy of the inner surfaces of the crank arms is affected by cutter's deformations in both directions X and Z axle.

The measurement scheme allowing the analysis of such deformations is presented in Figure 6. In order to achieve a better clarity of the picture, omitted some of the dislocation sensors in the lower diagram. The location of 7Z sensor corresponded to the location of 2Z sensor, 860 mm from the cutter's edge. In case of determination of stiffness characteristics due to conventional method, used an independent support stand mounted under the machine's cutter to position induction dislocation sensors (Figure 7). The research included two extreme positions of the cutter in Z axle (for two tool advancements).

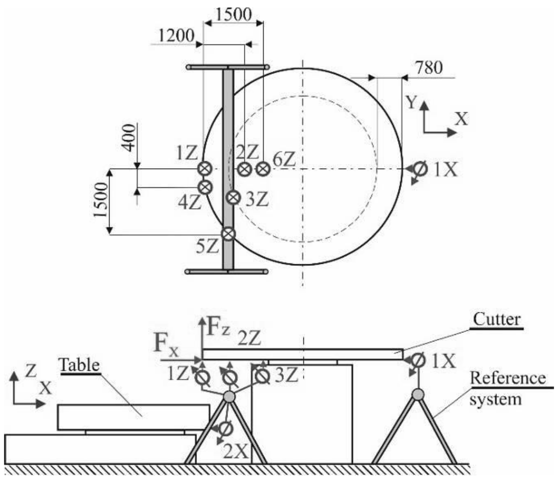

Fig. 7. Scheme of the measurement system used for investigation of a milling machine FS-550CNC

Following the accepted plan, the maximum value of the loading force was determined at the level of 10 kN (it was based on manufacturer's recommendations). Consequently, have obtained stiffness characteristics of the cutter. A sample characteristics is presented below (Figure 8).

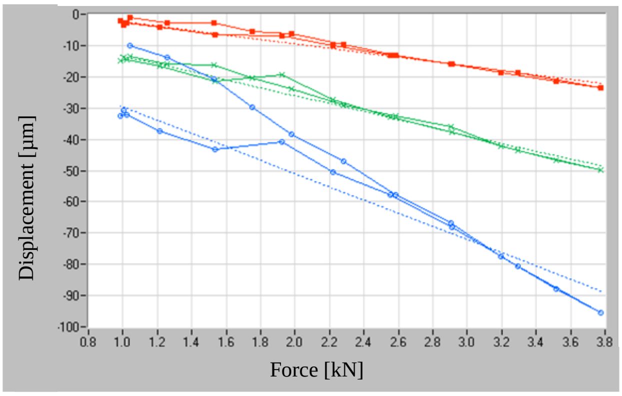

Fig. 8. Stiffness characteristics of the cutter determined with the load applied towards Z axle and the extreme lower positioning of the cutter: blue – sensor Z4, red – sensor Z6, green – sensor Z5

Using the stiffness characteristics, it was possible to determine static stiffness indicators presented in Table 1. The coefficients of stiffness can be calculated making use of three different methods.

Method A: Index of the static stiffness calculated as the quotient of the maximum loading force and the maximum displacement brought about by this force. This method is recommended in standards in the case of a linear characteristic of the stiffness of the investigated object.

Method B: Index of the static stiffness calculated for the increments of loads corresponding to the segments (sections) with a constant inclination of the stiffness curve. This method is recommended in standards in the case of a non-linear stiffness characteristic.

Method C: Index of the (averaged) static stiffness determined by interpolating the point obtained by measurements applying the least squares method.

Methods B and C were used to evaluate the results contained in the article.

In order to present a better visualization of the findings Figure 9 shows the comparison of stiffness indicators in relation to the distances between the measurement points and the cutter's edge. The analysis of conventional method findings, stiffness diagrams in particular, clearly shows a rather high linearity of characteristics and a small hysteresis field, which proves the that contact stiffness impact on the resulting stiffness of the milling machine is insignificant.

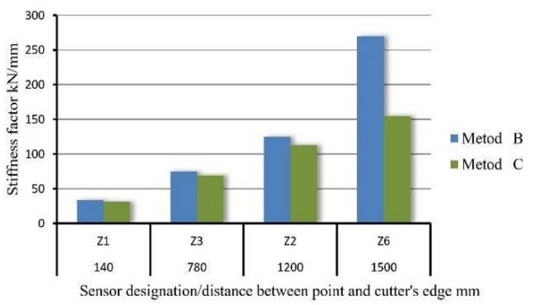

Fig. 9. Comparison of stiffness factors of the cutter in relation to the distance between measurement points and the cutter's edge

Table 1. Static stiffness indicators of the FS-550 CNC milling cutter, determined by conventional method

Sensor mark	Cutter's stiffness. Upper position of the cutter. Maximum force value 10 kN in Z axle.	
	Stiffness indicator kN/mm	
	method B	method C
Z1	34	32
Z2	115	111
Z3	72	68
Z4	33	32
Z5	55	52
Z6	277	276
Z7	78	73
Cutter's stiffness. Lower position of the cutter. Maximum force value 10 kN in X axle.		
X1		
X2	1164	787
Sensor mark	Cutter's stiffnss. Lower position of the cutter. Maximum force value10 kN in Z axle.	
	Stiffness indicator kN/mm	
	method B	method C
Z1	33	31
Z2	125	113
Z3	75	69
Z4	34	31
Z5	49	46
Z6	279	257
Z7		
Table's stiffness. Upper position of the cutter. Maximum force value 10 kN in X axle.		
X1	422	400

The scope of static stiffness research using DDSS method was, as in the case of other machine tools, very much similar to the scope of research conducted using the conventional method. Similarly as in case of measurements made following the conventional method, the main emphasis was put on determining the static stiffness of the cutter. Determining the stiffness by the use of dynamic method resulted in stiffness indicators identified in each case for three different (3, 5 and 7 Hz) frequencies of the extortion force. Figure 10 presents a comparison of results obtained due to conventional and DDSS method for the upper position of the cutter. While investigating the milling machine for cranking, could observe a very high similarity of the results obtained due to both methods: conventional and DDSS one. Lack of major differences between the findings can be explained by a rather small, as compared to shape stiffness, participation of contact stiffness in the resulting stiffness of the machine.

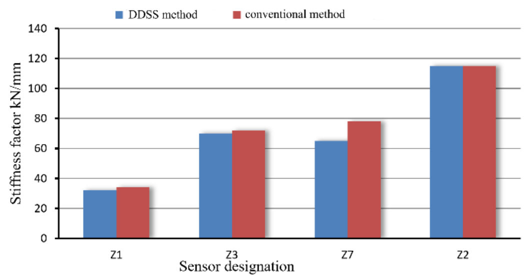

Fig. 10. Comparison of stiffness factors determined according to conventional method and DDSS method for the top position cutter of milling FS-550 CNC

Basing on the conducted research it is possible to argue that:

- the tool stiffness towards X direction which fluctuates from 337 to 414 kN/mm, plays a decisive role in precision of the machining process,
- cutter's stiffness on its perimeter in Z axle is significantly lower (minimum 25 kN/mm), yet it does not influence greatly the precision of the machining process. However a relatively low stiffness of the tool in Z axle may cause excessive vibrations of the cutter during its operation.

4. MACHINE TOOLS FOR RAILWAY INDUSTRY

Machine tools produced for a railway industry constitute a considerable part of a machine tool industry. Nevertheless, due to their dimensions they cannot be straightforwardly included in a group of heavy machine tools. They are however included in the present article, since the measurement methodology characteristic for heavy machine tools was successfully applied in their case.

There are the following machines intended for the railway industry:

- roll-on-roll-off type machine tools (above floor type), such as UBF 112 N with a double – saddle, dedicated to re-profiling of wheels used in rail vehicles.
- underfloor wheel lathes (underfloor type) such as UGD 150 N model (Figure 11), which are a double - saddle CNC special machine tools dedicated to re-profiling of wheels used in rail vehicles. They are particularly meant for reconditioning wheel surfaces of light rail vehicles (underground trains, trams), without the necessity of dismounting them from the vehicle.

Within the scope of the investigation on stiffness properties of various types of machine tools dedicated to railway industry, studied two machine tools of UBF 112 N. The article presents only a selected test results characterized with the widest scope of conducted measurements. A thorough description of the study involving UBF 112N machine tools is presented in detail in other papers by the authors. Static stiffness results related to the underfloor wheel lathe UGD 150 N are presented in other paper by the authors. As it has been already mentioned the research plan was similar to the scope of research dedicated to heavy machine tools. Conventional static stiffness investigation included load application in three directions (axle X, Y and Z), corresponding to components of force of the lathing process. The research included diversification of the value of the extorting force as well as the points where it was applied (maximum value of the extorting force reached up to 17 kN).

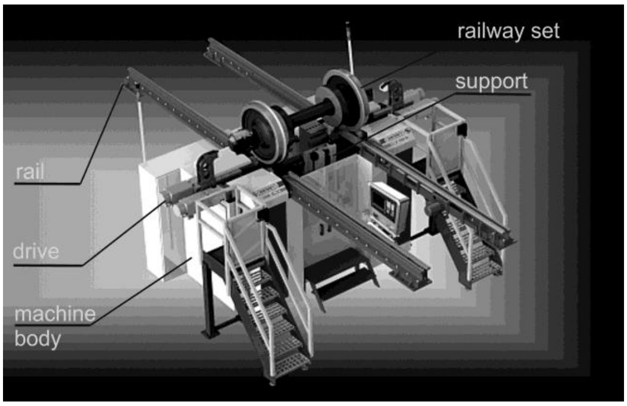

Fig. 11. Underfloor wheel lathe UGD 150 N [9]

Relative displacements of selected points, located both on the lathe and on the machine detail, were measured. Thus were able to determine static stiffness indicator in points that were considered to be the most crucial for the precise operation of the machine:

- while load application towards X axle the loading force was applied between the wheel set and the lathe's carriage (the point of application was located on the tool holder). The lathe was loaded with force of maximum value of 15 kN. Measurement points were located as presented in Figure 13:
  - on the carriage in relation to lathe's body (sensor 1X),
  - on the carriage in relation to the headstock's body (sensor 2Z),
  - on the carriage in relation to lathe's body (sensor 3Y),
  - on a set near the chuck in relation to the spindle's disc (sensor 4X),
  - on a set near the chuck in relation to the chuck (sensor 5X),
  - on a spindle's disc in relation to the headstock body (sensor 6X);
- while loading the lathe towards Y axle, the force was applied between lathe's body and the wheelset (the point of application of forces was on wheelset surface). The force applied on to the lathe reached its maximum of 17 kN. The deployment of measurement points is presented in Figure 12:
  - on the wheelset surface in relation to lathe's body (sensor 7Y),
  - on the spindle's disc in relation to the headstock body (sensor 8Y),
  - on the set (near the chuck) in relation to the spindle's disc (sensor 9Y);
- while loading the lathe towards Z axle the loading force was applied between the lathe's body and the guideway of the carriage (the point of application was on the guideway). The maximum force applied equaled 6 kN. The arrangement of measurement points is presented in Figure 12:

- on the carriage in relation to the lathe's body (sensor 10Z),
- on the carriage in relation to the headstock of the lathe (sensor 11Z),
- on the guideway in relation to the lathe's body (sensor 12Z).

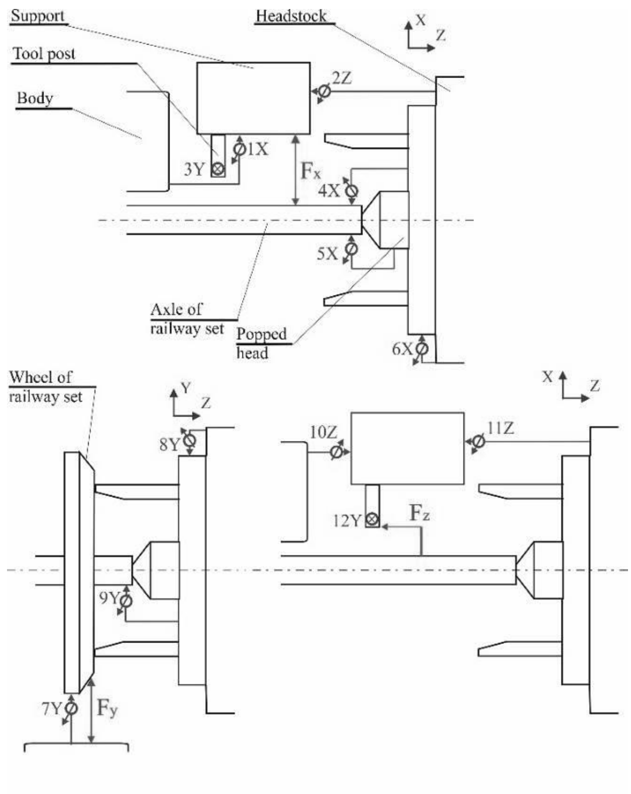

Fig. 12. Schemes of measurement systems during the investigation of circular mill UBF 112 N:
a) for the forcing along X axle, b) for the forcing along Y

As based on the conducted experimental investigation, it is possible to conclude that circular mills UBF-112 N type represent a relatively high stiffness. In case of the other lathe that was investigated more thoroughly, none of the determined stiffness indicators dropped below 200 kN/mm. However, intended maximum dislocations did not exceed 55 µm. The research including application of force along X axle, proved that it was the carriage that represented the lowest stiffness (the value was determined on the basis of measurements of carriage dislocation in relation to lathe's body, sensor 1X). The stiffness indicator assumed then the value of about 300 kN/mm. Comparable values of stiffness indicators were observed while applying the load along Y axle. The highest relative dislocations occurring then were between the surface of the wheelset and the lathe's body (sensor 7Y). In the course of the research along Z axle again it was the carriage that displayed the lowest stiffness indicator (the value determined was based on measurements of the dislocations of the carriage in relation to lathe's body, sensor 10Z).

Table 2 presents static stiffness indicators obtained while investigating the circular mill UBF 112 N using a conventional method.

Table 2. Results of measurements of the static stiffness index of a lathe UBF 112 N obtained by conventional method

Force value kN	Value of static stiffness indicators kN/mm		
	method C	method B	method C
Load application along X axle			
	1X (j_{xx})		2Z (j_{xz})
~12	314	293	1692
~14	296	277	1412
	4X (j_{xx})		5X (j_{xx})
~7	450	438	2417
~14	511	519	1292
Load application along Y axle			
	7Y (j_{yy})		8Y (j_{yy})
~11	251	333	3343
~17	231	286	2239
Load application along Z axle			
	10Z (j_{zz})		11Z (j_{zz})
~6	285	455	478
Force value kN	Value of static stiffness indicators kN/mm		
	method B	method C	method B
Load application along X axle			
	2Z (j_{xz})	3Y (j_{xy})	
~12	1714	350	333
~14	1182	359	325
	5X (j_{xx})	6X (j_{xx})	
~7	2333	2148	2333
~14	1400	2651	2800
Load application along Y axle			
	8Y (j_{yy})	9Y (j_{yy})	
~11	5500	3356	5500
~17	2667	2666	3200
Load application along Z axle			
	11Z (j_{zz})	12Y (j_{zy})	
~6	714	881	1250

5. CONCLUSIONS

As based on the presented findings of our research involving machine tools meant for railway and shipbuilding industries, one cannot provide unequivocal value ranges of stiffness indicators that should characterize all the aforementioned machine tools. It is mainly due to an insignificant number of the investigated machines representing the same type or at least of a similar construction. However, as based on the presented findings it is possible to formulate conclusions of a general nature:

- because of specificity of the heavy machine tool production process as well as the shortness of their availability, it is necessary to conduct static stiffness measurements in their natural operating conditions.
- the range of the obtained static stiffness results suggests that the way heavy machine tools are assembled has a crucial impact on their stiffness properties. Developing a list of technical recommendations or standards determining acceptable values of stiffness indicators would

allow a quick review of the accuracy of the assembly process,
- because of the dynamic nature of cutting forces, the indicators determined by the DDSS method can provide more accurate measurement results of machine tool stiffness properties.

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