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ANALYSIS OF PORTABLE MACHINE TOOL CONSTRUCTION CONTAINING MODULAR COMPONENTS

Piotr Pawełko, Michał Dolata

S u m m a r y

The article presents the issue of designing portable machine tools in which module components are applied. Portable machine tools are mainly designed for machining of elements at the place of their final installation. Experience has shown that achieving high efficiency in the design of portable machine tools can only be reached through the use of mechatronic approach with the use of ready-made modular components (for example: ballscrew mechanisms, bearing units, linear guide systems). The designer of a machine tool must be aware of lack of information on selected parameters of these components. It is recommended to use simplified replacement models of these components and implement them to the model of entire machine tool to achieve desired static and dynamic characteristics. Authors of the article present an example of a modular component and its replacement model. They also present the results of calculations performed with the use of this.

Keywords: portable machine tool, mechatronic design, modular components, FEM

Analiza konstrukcji obrabiarki przenośnej z elementami modułowymi

S t r e s z c z e n i e

Przedstawiono problematykę projektowania obrabiarek przenośnych z zastosowaniem elementów modułowych. Obrabiarki przenośne projektowane są z uwzględnieniem ich użycia do obróbki elementów w miejscu montażu. Doświadczenie wskazuje, że uzyskanie wysokiej jakości obrabiarek przenośnych wymaga uwzględnienia w procesie ich projektowania kryteriów mechatronicznych oraz standardowych podzespołów modułowych (np. mechanizmów śrubowo-tocznych, węzłów łożysko-wych, modułowych prowadnic liniowych). Projektanci tych obiektów uwzględniają ograniczoną informację dotyczącą charakterystyki użytkowych komponentów modułowych. Dlatego zaleca się używanie uproszczonych modeli zastępczych i implementowanie ich do opracowanego modelu obrabiarki. Umożliwia to uzyskanie prognozowanych statycznych i dynamicznych charakterystyk obiektu poddanego analizie. Zaprezentowano przykładowy element modułowy i jego obliczenia.

Słowa kluczowe: obrabiarka przenośna, projektowanie mechatroniczne, elementy modułowe, MES

Address: Piotr PAWEŁKO, PhD Eng., Michał DOLATA, MSc Eng., West Pomeranian University of Technology in Szczecin, Faculty of Mechanical Engineering and Mechatronics, Institute of Mechanical Technology, 19 Piastów Av., 70-310 Szczecin; e-mail address: Piotr.Pawelko@zut.edu.pl, Michal.Dolata@zut.edu.pl

1. Introduction

A portable machine tool is a type of a machine that has several characteristics: among others, it can easily be transported and for the purpose of processing it should be mounted on the workpiece. Unlike portable power tools in a portable machine all movements are guided.

The impulse for the creation of portable machine tools were, as usual, the needs of the industry. Many of the industrial branches: energy industry, mining, shipbuilding, petrochemical, heavy industry, paper industry, have forced the designers of machine tools to change the way of thinking in terms of processing especially of large-scale workpieces. A significant problem has been noticed – the need for transportation of large-scale workpieces. The main problem is to transport these elements from the site of their production or assembly, to the factories which are equipped with appropriate machine tools to perform the required machining operations. The above process generates high transportation costs due to the necessary logistics and is also time-consuming. When constructing new elements, the transportation time is calculated in the production process itself, while when it comes to the recovering process, the time of transportation plays an important role. Moreover, it is sometimes impossible to transport an object. A very good example of such a case is regeneration and repair of components permanently connected with the main construction. These can be: cooling systems in nuclear power plants, offshore drilling platform components or the foundation of wind towers.

2. Requirements for portable machine tools

2.1. General characteristics

Portable machine tools are mainly designed for the machining of the elements at the place of their final installation. This type of service is determined by the terms "in place" or "in situ". Portable machine tools have been designed out of necessity to operate in extreme ambient conditions. They are required to carry out treatment, regardless of the environmental conditions of the workpiece, i.e. temperature, humidity, attachment methods and other factors. Conditions of use are extremely variable, hence it is difficult to assume the required accuracy of the machines. Currently, the quality of treatment is mostly affected by the machine operator who decides on the method and accuracy of the portable machine tool mounting process. The operator also determines the machining process parameters and performance of the machine, specifying its stability.

In portable machine tools, due to the design constraints, mainly related to the mass of machine, main motion drives with much less power are installed. This results in some restrictions to the processing parameters – an increase in the duration of the cutting operations. When we add the problem of laborious

installation of portable machine tools on the workpiece, it is surprising that market demand for this type of machine tools and service keeps growing. In practice, portable machine tools are used more and more frequently where it is necessary to meet the design guidelines during or after the assembly of large structural elements, while shortening the time of manufacturing new products and reducing its costs. These machines are used as devices for compensation technology – processing the workpiece during its installation. Often large elements are made at their destination.

Experience has shown that achieving high efficiency in the design of machine tools can only be reached through the use of mechatronic approach [1-10] with the use of ready-made modular components. It is clear that the approach based on mechatronics, which presumes the simultaneous consideration of knowledge in various fields, makes it theoretically possible to design and manufacture products with significantly improved quality. However, the question arises – can a designer blindly trust manufacturers offering modular components without analyzing thoroughly the mechanical properties? During the design process engineers need to pay special attention to the basic criteria. Meeting these criteria will allow to create a portable machine tool which will effectively fulfil its machining tasks.

When analyzing the requirements for portable machine tools the main criteria for the design can be determined, and the less important remain subordinate. The primary criterion is, as usual, to make it possible to transport the machine. In this case the sub-criteria are: minimal weight, compact design and the kinematics of the machine tool. The second criterion is the ability of the machine to perform machining – vibration stability. It is important, above all, to obtain the appropriate dimensional and profile precision and the surface quality; the duration of treatment is less important.

2.2. Vibration stability

Self-excited vibrations occur in mechanical systems quite frequently. Every mechanical system can be potentially unstable, provided that the variable force which causes its vibration is dependent on the parameters of the motion of this system (displacement, velocity). This, however, is not a sufficient condition for the self-excited vibrations to develop in the system. Variable force depending on the motion parameters must do such a positive work that the corresponding energy is equivalent to the energy dissipated as a result of motion resistances in the system [11, 12]. There is a cause and effect relationship between the mass-dissipation-spring system (MDS) of a portable machine tool – workpiece (PM-WP) and the machining process (cutting process) which takes place in this system. The load (cutting force component) which causes oscillatory movement depends on the parameters of the movement and vice versa. The vibrations in an examined MDS system can cause irregularities on a cut surface in the form of waves. When the cutting edge goes through the waves, the cutting parameters

change (mainly the thickness of the cut layer – h). These parameters influence the cutting force.

The cutting process parameters in which the system is stable can be determined. A stable system is one which returns to its stability after it has been excited. The appearance of self-excited vibrations in certain ranges of parameters naturally excludes the possibility of their practical application, which can reduce the technological capabilities of the machine tool.

Portable machine tools, due to their special use, must comply with the condition of low weight and mobility. This is why their construction is often designed on the edge of stability. Structures based on long profiles or openwork structures usually have huge problems with vibrations. For this reason, the design of such machine tools is extremely difficult, and dealing with the problem of vibrations often requires high speed tools and thin layers which are being machined.

2.3. Modularity

The conceptual design is the presentation of an overall design concept. It shows the distribution, shape and mutual position of the most important elements of the designed device. It provides the legal framework of the project and assessment criteria. The conceptual design must meet the desired requirements. Conceptual design is very important for successful implementation of construction projects. It has been noticed that significant and relevant decisions taken early – during the conceptual design accelerate engineering tasks and have a tremendous impact on the quality of the final product. It has been reported that about eighty percent of the costly decisions are made at the stage of conceptual design [13]. At this very stage of the design process it is essential to use a mechatronic approach.

The costs of a portable machine tool in relation to its functionality are of lesser importance. Taking under consideration difficult conditions in which a portable machine tool operates, its wear is much faster than that of a standard machine tool. It is therefore necessary to design it in such a way that all used components can be quickly replaced. In the light of the above mentioned points, it is reasonable to use modular components as they are commonly available. It significantly reduces production downtime and its costs.

3. Modular design of portable machine tools

Finding the best solution for structural support system of the portable machine tool begins with an analysis of the form of geometric and physical structure, or topology of the machine (distribution of kinematic pairs) [14]. The second step is to determine the geometry of the designed kinematic pairs. Determining overall dimensions of the machine, defining the ranges of

movement, indicating cooperation zones geometryand assembling designed pieces of structure with ready elements (e.g. motors, clutches, guides, bearings) must appear in the form of design documentation.

The goal of each project is to obtain solutions which meet the assumptions of the design. For this purpose, the design criteria and methods of their verification are being defined. Machine tools for metal machining, apart from utility must meet the basic work criterion which is the stability of the machining process (vibration stability) [15-18]. The necessary information needed to carry out the stability analysis is practically given only in the final stage. In order to make it possible to computationally verify the structure due to the stability criteria it is necessary to obtain the information about topology, geometry, materials, masses, inertia elements, stiffness of connections, load capacity, static and dynamic properties of the workpiece, as well as loads resulting from the cutting process.

Each model has some simplifications, that is why one can expect the uncertainty of the results. Hence one ought to make the final experimental verification of the stability criterion. Designing a portable machine tool according to current trends (as a mechatronic device), should prompt the designer to apply well-proven solutions (ready-made construction modules). Such as: integrated bearing units, linear-guide systems, drive units, spindles, electrospindles, power systems and control systems. This technique has been successfully used by designers of modern CNC machine tools, robots, manipulators, and that is why it seems to be a reasonable approach. At the early stages of the project some pieces of information about properties of the modular components can be obtained from the manufacturers. In addition to information about the mass and geometry of the elements, one can obtain other relevant data. It is evident that the quantity and quality of the information is insufficient to carry out reliable design calculations. This is especially true when determining static and dynamic stiffness of a designed system.

It is clear that it is not possible to build a portable machine tool using only commercially available components. Part of the support system in the form of body elements is almost always designed individually for the needs of the design. Parameterized models built in the convention of finite elements method (FEM) allow to carry out the so-called parametric optimization. It implies the solution of a constrained problem in which geometric and material parameters are the decision variables (e.g., density, Young's modulus and damping). For example in the process of optimization of the ribs in the body of a machine tool: thickness, width, height, as well as their location and number are determined. This optimization is designed to reasonably distribute the material. It leads to the optimal shape of the design, in which properties such as: established static stiffness, frequency and mode shapes, etc. are achieved.

4. Modeling of portable machine tools with the use of replacement models

4.1. Newly designed elements

In portable machine tools, unlike the stationary ones, the basic criteria for their evaluation are the mass and vibration stability. Material and geometry properties of a part are its structural variables. Analyses of components with parameterized variable geometry in the calculation process are currently made with the use of the most effective Computer Aided Design modeling software (CAD) while Finite Element Method (FEM) is used for the system calculations. It is important at this stage to define the interaction between design components of the portable machine tool. One ought to identify the ways of setting and fixing of analyzed structure fragments and properly constrain the degrees of freedom in the prepared model. It is also necessary, like in the previous case, to take loading forces into account – loading the model with gravitational forces, cutting process forces and the forces of inertia including pre-established dynamics of the drives. The specificity of the description of the boundary conditions significantly affect the reality of the cresults of the analyzes.

By the initial phase of the corpus system analysis one understands a situation in which the constructor prepares the initial geometrical form of the body. At this stage only geometric properties of cooperation zones of a machine tool and technological limitations are given. The kinematics of the machine tool is determined and its functionality is verified. Efficient and effective realization of this process depends on the experience of a constructor and the proper preparation of the initial parametric model of the machine tool body.

Carrier components of portable machine tools (designed or chosen) should be characterized by high stiffness at low weight. This can be achieved by designing a special form of geometric elements of the machine body (modulus of rigidity) and the selection of appropriate material properties (Young's modulus).

A portable machine tool project shown in Fig. 1 is an example of such a model which is made of two main load-carrying components (designed machine tool body parts) – vertical beam (V) and horizontal beam (H).

The deformation of beams for the simplest geometric form of the model without structural reinforcements was analyzed (providing only the main dimensions and appropriately shaped cooperation zones with the chosen modular elements). In following calculation sequences, places with increased stress were stiffened by additional elements (ribs). Dimensions of the ribs and their location were further parameters of the models in addition to thickness and width of the bodies. Figure 2 shows the calculation results of the analyzes carried out for two body elements. The analysis has resulted in obtaining ten times stiffer elements, which are only one and a half time heavier compared to the initial models.
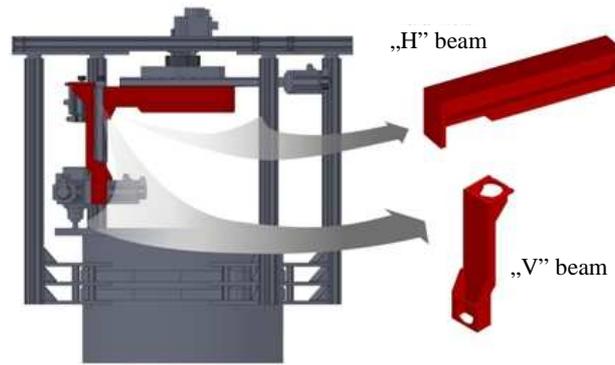
Fig. 1. The portable machine tool model detailing vertical "V"
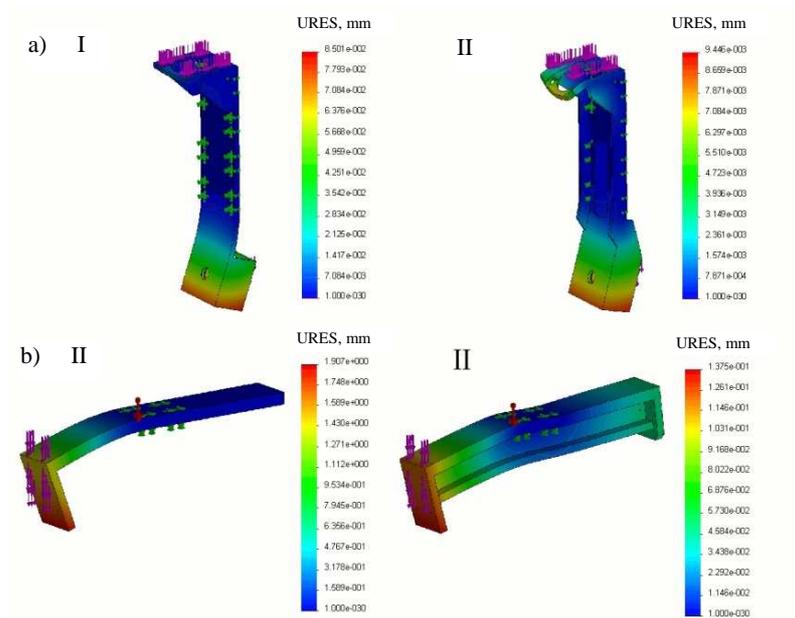and horizontal "H" beams

Fig. 2. Results of analyses performed on computational models of beams using FEM:
a) vertical "V", b) horizontal "H", I – before optimization, II – after optimization

To complement the design calculations the analyses of the dynamics of the designed elements were performed, especially for the frequencies and mode shapes. Examples of the mode shapes for the vertical beam are shown in Fig. 2. Particular attention was paid to the behavior of the construction in the so-called force chain – parts of the structure directly responsible for the transfer of cutting forces. The sixth form in Fig. 3 concerns drive motor mounting point and not the

previously described force chain, that is, only the first five forms are significant. The mode shapes can significantly affect the behavior of the tool during cutting.

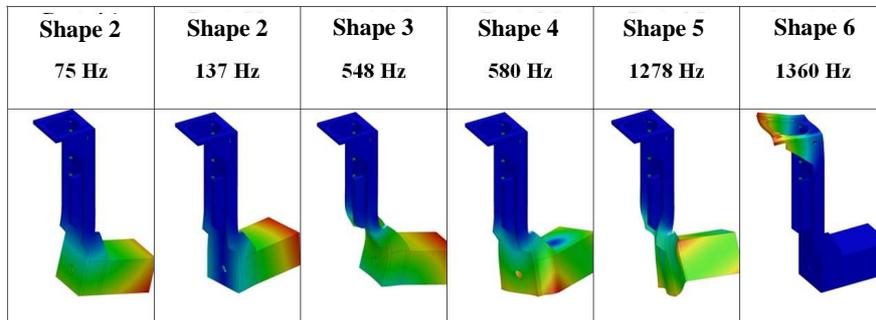| Shape 2 75 Hz	Shape 2 137 Hz	Shape 3 548 Hz	Shape 4 580 Hz	Shape 5 1278 Hz	Shape 6 1360 Hz

Fig. 3. Examples of the mode shapes of vertical beam "V"

Modeling body elements of machine tools [19] does not require applying replacement elements. Monolithic elements of the body of machine tools do not represent a significant burden in terms of power and time of the calculations.

The situation is different when it comes to the range of mechanical components (for example: ballscrew mechanisms, bearing units, linear guide systems). In those cases, an accurate representation of system geometry is only effective for conducting calculations of isolated components, not for the final product. It is recommended to use simplified replacement models of these components and implementing them to the model of entire machine tool. The replacement models should have the smallest dimensionality as well as the ability to imitate behavior of real components. This type of modeling has already been successfully used in the design of stationary machine tools [19].

4.2. Ready-made modular elements

Ready-made components in the form of profiled rails with carriages (guides) are currently used in the design of modern linear guides. They are fixed to a machine tool body with screw connectors. Such systems are characterized by their very high efficiency, of up to 95%, high load ratings and a wide range of possible applications. Mainly ballscrews are used as the drive elements in machine tools for changing the rotation of the motor shaft to linear motion of the system. The described transmission is also very efficient. The disadvantage of both outlined structural solutions is a very low damping factor, appearing in resonances at high frequencies.

One of the assumptions in terms of mechatronic design, especially important for portable machine tools is to reduce the time dedicated to the design and manufacture. In order to achieve this goal, it is suggested to apply ready-made compact axle drive assemblies in the designed systems. Such an approach

seems to be reasonable considering global trends in machine tool design, and the range of ready-made solutions in the linear motion technology offered by its producers [20-24]. It is possible to select a complete compact drive assembly, where the housing comprises linear guide system, a ballscrew, bearing units and a connector for the drive motor.

During the initial design phase one of the main goals is to provide appropriate accuracy of dimensions and shape of workpiece surfaces. This is reflected in parameters characterizing the selected systems and components of linear motion technology. This includes acceptable error values occurring in: ballscrews (for instance the cyclic pitch error), profiled rails and ensuring their correct assembling. The system being selected should also be characterized by proper carrying capacity, while maintaining compact dimensions and low weight.

Basing on a Bosch-Rexroth compact linear guide one can see examples of data required by the manufacturer and included in the phase of selection of a mechanism. Equivalent load (Fig. 4) is determined from the formula:

$$F_{comb} = |F_y| + |F_z| + C\frac{|M_x|}{M_t} + C\frac{|M_y|}{M_L} + C\frac{|M_z|}{M_L}$$

where: F_{comb} – equivalent load, N, F_x – x-axis load, N, F_y – y-axis load, N, F_z – z-axis load, N, C – dynamic load rating, N, M_x – x-axis torque, Nm, M_y – y-axis torque, Nm, M_z – z-axis torque, Nm, M_t – permissible x-axis torque, Nm, M_L – permissible y-axis torque, Nm.
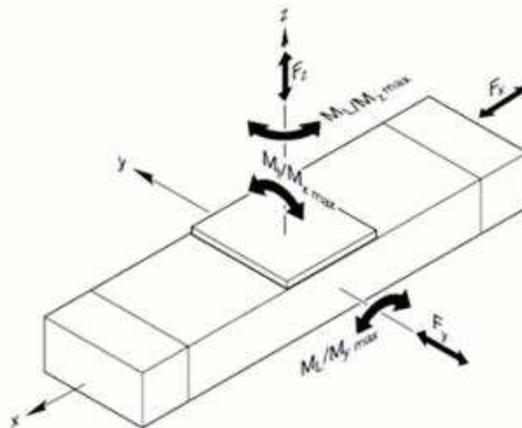

Fig. 4. View of constituent loads acting
on a compact linear module [18]

It is possible to carry out preliminary selection of components of the machine tool taking into consideration only carrying capacity and positioning accuracy with the use of a simplified geometrical model of the machine. Such a model can be created on the basis of the geometry-movement selection (G-MS), based on preliminary calculated masses of individual elements included in the design. There are no other selection criteria such as stiffness (static or dynamic). One should also bear in mind that it is an iterative process. Therefore, the process needs to be controlled. The design variables should be validated in the adopted solutions of the further phases of the project. In order to obtain additional information about a machine tool component (stiffness, resonant frequencies, mode shapes) one should conduct experimental studies. Another way of obtaining above mentioned data is to model the component basing on the geometric data from catalogues and perform calculations with the use of FEM techniques.

According to available information, compact linear modules have very good functional properties [20, 25]. The mechanism is made with two body elements combined with linear guides and a ballscrew (Fig. 5 and 6).
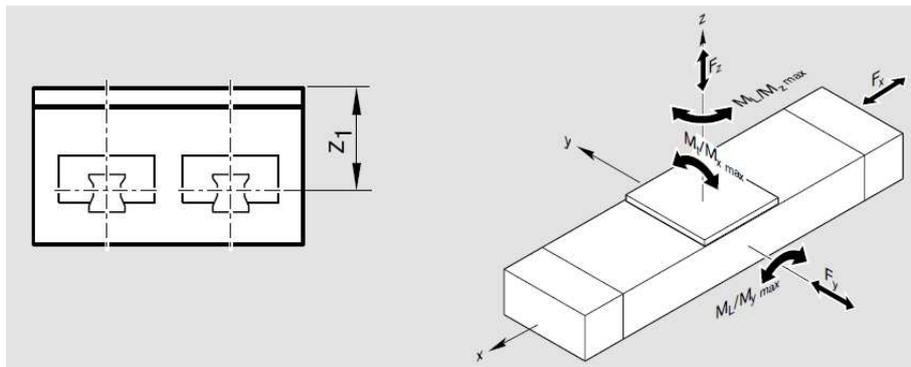

Fig. 5. General scheme of a compact linear module

A Bosch-Rexroth compact linear module (type eCKK 110, the long carriage version) has been used in the design of a portable machine tool. The module has been disassembled in order to accurately map its geometry and then modeled with FEM techniques (Fig. 6).

Selection of the module is based on calculation formulas available in the catalogue [25]. These formulas are based on external loads and allow only to calculate lifetime of the module. During the analysis the most unfavorable permissible loads acting on the module were assumed.

During the final assembly of the portable machine tool high deformability of the module was noted. It turned out that despite being under the maximum permissible load this linear guide has a low static stiffness.
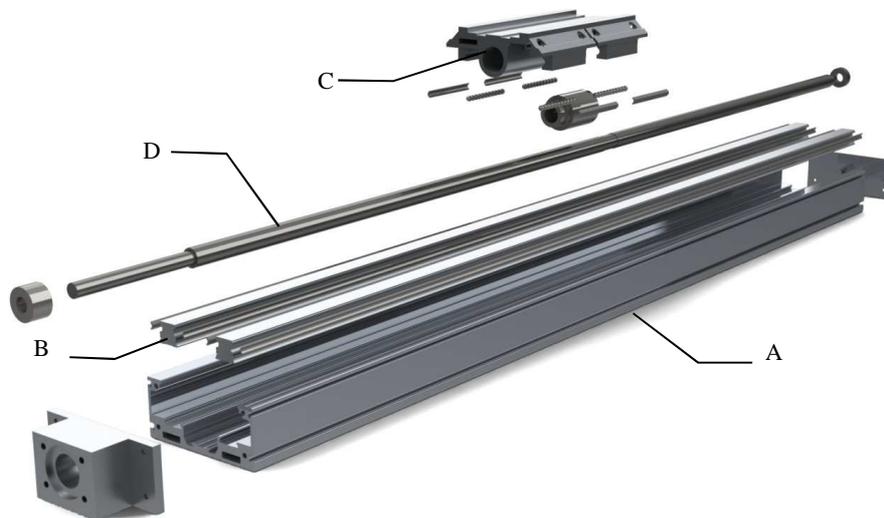
Fig. 6. View of a compact linear module. A – aluminium housing (body 1), B – a set of rails, C – table (body 2), D – ballscrew mechanism with bearings

The problem about those type of elements (ready-made modular) is the lack of manufacturers' information about the rigidity. The information on the maximum permissible loads is available. Yet, there is not any information on the behavior of the product under the load. Seemingly, the module is an assembled set of parts (roller guides, ballscrews) which can easily be bought separately. Yet, in the light of the above analysis it is not so. In the case of a modular linear guide its body frame components seem to be the main source of problems. A modular linear guide consists of a housing which is made out of an extruded aluminum profile. The housing is a support for two aluminum rails. The rails have steel inserts which are in contact with steel balls. Each rail has two inserts but only one insert is active. This is because there is no standard carriage in the modular guideway. There are four places of contact between rails and an aluminum table. The carrier system looks like a normal carriage but is cut into halves. There are four half-carriages and they are all part of an aluminum table. The carriages have the same inserts as the rails. There are two covers at each end of the housing. The covers have bearing sockets for the ballscrew. The table is attached to the ballscrew, which is connected to an end tip by a coupling. The low weight of the system is an important advantage of the described solution. The disadvantage is that the above mentioned linear guide has low rigidity.

This experience has proved the need for modeling such highly specialized modules. This is the only way to determine their static and dynamic characteristics. These characteristics are the base for creating a replacement model of a modular guideway which can be effectively used in the machine tool model.

FEM is used as a method of calculation. The first step in the analysis was to exclude irrelevant elements from the geometric model of the module as they do not affect the behavior of the guide under load. The next step was to discretize a geometric model. This process has been made with special emphasis on the contact elements and contact zones. Then, a static analysis was performed. The component was loaded with maximum permissible loads (890 N of force and 70 Nm of torque). The boundary conditions and the method of loading of the mechanism are shown in Fig. 7.
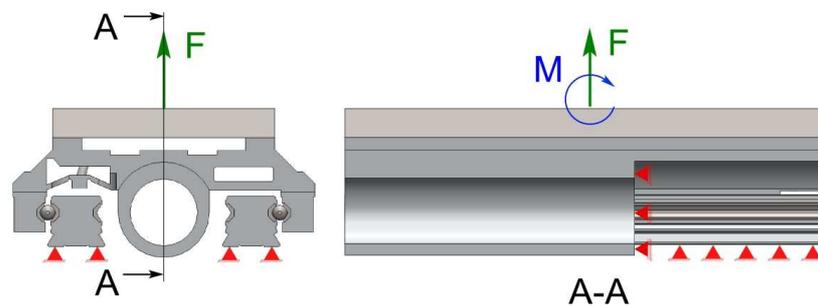

Fig. 7. Linear guide boundary conditions and loads

As a result of the calculations the spatial distribution of displacements in modular linear guide is achieved (Fig. 8).

The above example clearly determines large and uneven displacements of the table. When analyzing the cross-section of the table its lack of symmetry is noticed. In one part of the table the openings are larger than in the other. A hole is located so close to the edge of the element that it creates a significant narrowing. The narrowing affects the rigidity of the table and causes the asymmetry of its deformation (Fig. 8, the place marked with A). The table is reinforced by two screws. Despite the reinforcement the carrier part of the table is still bent outside.

Displacement values are significant (0.03 mm), especially when referred to the usage in machine tools. Moreover, the modular guideline is one of the first elements of the construction chain of this portable machine tool, which makes the spindle tip even more displaced (Fig. 9).
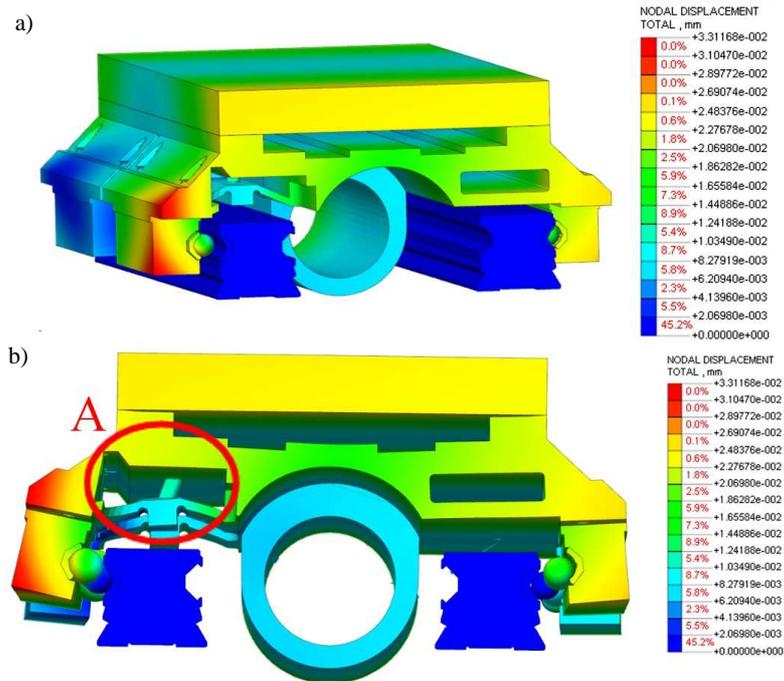
Fig. 8. Samples of the results a compact module calculations: a) isometric view
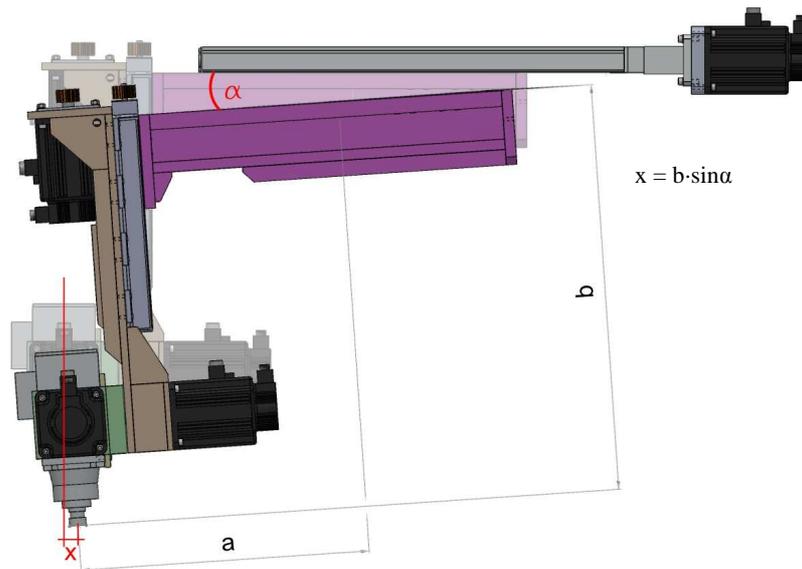b) side view Circle A shows a low rigidity part of the table

$$x = b \cdot \sin\alpha$$

Fig. 9. Diagram showing the position of the spindle tip after deformation
of the analyzed linear guide

5. Summary

Modern portable machine tools are supposed to be used for machining large components at their installation site or at the place of work of a workpiece. Their design must primarily allow stable machining with predetermined parameters. These machines have to obtain a desired level of accuracy. Hence, the design process should be conducted in terms of mechatronics, and the construction should be based on ready-made modular components. It shortens the time of design and also makes the potential repairs easier (entire modular components can be replaced).

Such an approach has its limitations despite its usefulness. The designer of a machine tool must be aware of lack of information on selected parameters of a modular component. In the above mentioned example of a portable machine tool one can see how large the displacements of a loaded linear guide can be. Despite the fact that the permissible load is not exceeded, the module should not be used in this machine tool. The position of the tool tip is far from the assumed. The information outlined in the article is very important for the designers as it evidences the needs for analyzes of the modular components.

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