Study of the stiffness of modular fixtures using the finite element method

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Abstract. Modular fixtures are some of the most used fixtures for orientation and fixing of the workpieces in the cutting process. It is also know that the precision of the machining process is influenced by the overall stiffness of the modular fixtures, which, in turn, depends on the stiffness of each module, connecting elements, contacts etc. This paper comprises a study of the stiffness of modular fixtures based on the multifunctional holes system. We shall determine the influence of the applied force, of the pretension force, of the friction coefficient at sliding between surfaces in contact and of the number of joints on the normal stiffness and tangential stiffness for an orientation subassembly consisting of modules in a set based on the multifunctional holes system.

1. Introduction

A constant visible trend in the last decades has been the orientation of the manufacturing towards the ever more diverse needs of the consumer. The effect was, and it still is, the switch of focus of manufacturing towards small, medium, group-organized series. As such, technologies and flexible equipment have developed, that have the capacity to respond fast and efficiently, from an economic perspective, to the demands of a very dynamic competitive market with claims for high quality [1].

Within flexible manufacturing equipment, clamping fixtures are connecting links which are in a functional interdependence with the other links of the technological systems (machine-tool, workpiece, tool, etc.) [2], thus the importance they have in applying an automated, efficient manufacturing flexibility.

Clamping modular fixtures are increasingly used within flexible manufacturing equipment, especially because they have the common precision of dedicated fixtures and a cost which is comparable to the cost of universal fixtures [3]. From a structural point of view, these are made of standardized modules (elements) that are part of a complete set of standardized modules, executed in a wide variety of types. By assembling the modules, various fixtures can be built for orientation – positioning and clamping of the workpieces with various forms and dimensions, under various manufacturing conditions. From a constructive point of view, the modular clamping fixtures are differentiated by positioning and orienting of the modules.

A first category is represented by the modular fixtures where positioning and orienting of the modules is made by guidance on flat surfaces, using T-slots systems (Figure 1, a). The component fixtures are provided with T-bolts and for fixation studs, T-bolts and T-nuts are generally used.

The second category is represented by modular fixtures based on the multifunctional hole system (Figure 1, b), which uses bores and bolts for orientation-positioning, and the fixing is made with screws,
nuts and studs. The baseplates and modular fixtures that are part of the modular sets of “bore-bolt” contain a series of simple or threaded bores, set in a rectangular or circular manner, which allow orientation-positioning of the modules within the modular fixture.

As per [3] and [5], for the manufacturing of the basic components, wear resistant alloyed steel is used, with a hardness of 60 – 65 HRC, processing in the precision classes 5..7 ISO. Regardless of the system, the components acting as support modules have dimensional tolerances of ± 0.01 … ± 0.02 mm, including at distances between centering bores or T-nuts and deviations from flatness of 0.01 mm/ 150 mm. Under flexible manufacturing, modular fixtures based on the multifunctional holes system have many advantages compared to those based on the T-nut system. According to [3], [5], [6], these advantages are: low production cost, higher orientation – positioning precision, high repeatability, higher safety in exploitation, low assembly time, higher durability and higher stiffness.

An important standard of evaluating the performances of the modular fixtures is their stiffness.

2. Static stiffness of the modular fixtures

Regardless of the type of the clamping fixture, in order to minimize the displacement of the workpiece form its nominal position during clamping and machining, thus maintaining the machining error in tolerance, a high stiffness is required. Also, high stiffness of the clamping fixtures, in general, as well as of modular fixtures, in particular, is requested by the need to increase the productivity of the machining by using intense cutting regimes.

The static stiffness, as per formula (1) is defined by the ratio between force \( F \) invariable in time, which requires elastic structure in a certain direction and deformation (displacement) \( \delta \) of this structure in the same direction or not.

\[
K = \frac{F}{\delta} \left[ \frac{N}{mm} \right]
\]

In the case of assembled modular fixtures, the stiffness is negatively influenced by the presence of T-nuts machining or bore in the bodies of the modular elements in their componence. Also, the large number of joints present in the structure of the modular fixtures causes the latter to have high deformations, thus decreasing stiffness. In general, the joints between the elements making up the modular fixtures are friction joints, required in the axial or transverse direction, with pretension force on axial direction. The total deformations of the friction joints required in the axial direction of static forces, are composed of: contact deformations of joints and elastic deformations of the elements of the modular structure.

Analytically, contact deformations can be expressed by taking into account the Hertz theory of contact between elements of a structure [7, 8]. The elastic deformations of the elements of the structure are calculated based on the formulas known from the Strength of materials.

The deformation of a structure of modular fixture, required on transverse direction, can be divided into four groups of individual deformations [9]. These individual deformations are: bending deformation of the
baseplate, bending deformation of the vertical support, contact deformation between the vertical support and the baseplate, stiff displacement of the vertical support.

A multitude of studies and researches on stiffness of the fixtures, in general and modular fixtures, in particular, can be found in the literature [10-14]. Many of these have focused on determining, experimentally, through analytical calculation or using the finite element method, the stiffness of the modular fixtures, where positioning and orienting of the modules is made by guiding on plane surfaces, using T-slots systems.

This paper presents a study on the stiffness of the modular fixtures based on the multifunctional holes system, which uses bolts and bores for orientation and positioning, and the fixation is made with screws, nuts and studs.

3. Aspects regarding the determination of the stiffness

The stiffness of the modular fixtures can be analytically calculated, determined experimentally or using the finite element method. Analytical computational formulas have a low degree of confidence because of the simplifications and approximations and they lack data specific to contact deformations. Also, the experimental determination of the stiffness of the modular fixtures requires experimental stands, which are often costly, the results are obtained only in a small number of points/zones/sections, and the contact deformations are hard to measure.

The finite element analysis is recommended for the study of the stiffness of the modular devices because it provides an overview of the distribution of the stresses and deformations across the analyzed structure and its joints. The finite element method is currently the most used numerical simulation method in computer implemented engineering due to multiple types of analysis which can be achieved (static, dynamic, thermal etc.) and the advantages it provides [15-19]. In the field of clamping fixtures, the finite element method is used successfully for calculating the precision of the machining, of the clamping forces, of the stiffness, for position optimization and size of the clamping forces etc. [20-23]. The paper uses a static analysis with finite elements, made using Ansys Workbench software, to determine the stiffness of some standard module units within Norelem set, mainly used as orientation elements.

4. Model development

In order to carry out the study, elements of a modular set produced by Norelem (France) are used to make a modular fixture for the machining of a workpiece from the automotive area (Figure 2). For centering and fixing, the modular set uses grids with rectangular multifunctional bores, provided with a cylindrical hole for centering and a threaded hole for fixing. For fixing it uses screws/stud M10, for centering cylindrical outer/inner surfaces $\varnothing18$ $E6/n6$, and the grid step is $40\pm0.1$ mm [24].

![Figure 2. Modular fixture.](image)

![Figure 3. Technical drawing of the studied subassembly.](image)
For the study of the stiffness we shall take into account a LS oriented subassembly (Figure 2), made for the purpose of positioning of the active surfaces of the support pins at a distance of about 80…90 mm from the baseplate. Thus, support pins are mounted on supports, made of elements from the modular system, so as to enable this condition.

The Norelem modular system allows the creation of supporting towers of support pins (1) by using the adjustable supports (6) and the high distant piece (4 and 5) or short distant piece (2) – Figure 3 and 4. The centering is realized on cylindrical surfaces $\varnothing 18$ mm, and their fixing is made using a M18 x 66/11 stud (3). The adjustable supports (6) are centered using sleeve (8) and they are fixed on the baseplate using cylindrical head screws and hexagonal slot (7). This subassembly is symbolized by A. To study the influence of the number of joints in the structure on the stiffness, the set of workpieces (2), (4) and (5), was replaced with the workpiece (9), thus eliminating a number of 2 joints (Figure 4, b), obtaining subassembly B.

![Figure 4. Studied subassemblies: type A (a) and type B (b).](image)

![Figure 5. 3/4 section view of 3D model.](image)

![Figure 6. Loads and constraints.](image)

The 3D model of the assembly (Figure 4) under analysis was done in CATIA and then transferred to Ansys Mechanical for static analysis. The materials used in simulation are: tool steel for support pin and carbon steel for the other modules. The driving force (which can be clamping force, machining force, control, assembly etc.) is applied to the upper surface of the support pin, having the direction towards the baseplate – for the study of normal stiffness – and tangential on the surface, having the direction in Figure 6, for the study of the stiffness in transversal direction.

The pretension force is applied to the stud using Bolt Pretension option in Ansys Mechanical and has values ranging from 0…5000 N. Maximum forces values are limited to 5000 N in order for the equivalent stresses and contact pressure in the joints not to exceed allowable stresses of materials. The contact between the surfaces of the component modules is considered to be frictional, the coefficient of
friction having values ranging from 0.05…0.2. The contact between the stud and the support, respectively, the adjustable support in plane is of type Bonded. Deformations according to the normal/tangential directions of the upper surface of the support pin (S1) and the joint between the adjustable support in plane and the distant piece (S2) are determined– Figure 6. The deformation in the S1 section contains both contact deformations between component workpieces, and elastic deformation of the component parts.

5. Results
The purpose of the study is to determine the dependence of applied force – deformation (deformation curve or stiffness) for subassemblies A and B, under the condition of variation of the following parameters:

- the applied force will act in the axial direction and in the transverse direction, having values between 500 and 5,000 N, with a step of 500 N;
- the pretension force will have values of: 0, 500, 1000, 2000, 3000, 4000 and 5000 N;
- the friction coefficient between the surfaces in contact, with values between 0.05…0.2.

Table 1. Cases analyzed through finite elements method.

| Case | Subassembly Name | Force | Contact Type | Results |
|------|------------------|-------|--------------|---------|
| I    | A                | x     | Frictional, μ=0.15 | Figure 7 |
| II   | A                | x     | Frictional, μ=0.15 | Figure 9 |
| III  | B                | x     | Frictional, μ=0.15 | Figure 8 |
| IV   | B                | x     | Frictional, μ=0.15 | Figure 10 |

Table 1 summarizes the cases under the finite element analysis. Following the analysis, the results represented in Figures 7…10 were obtained, as dependencies between normal/tangential applied force and the normal/tangential directional displacements. Figure 11 presents the force – deformation dependencies resulting from the analysis of the modular subassembly A, considering that the force is acting in the normal direction, pretension force 5000N, for different values of the coefficient of friction. Figure 12 shows the deformation curves in sections S1 and S2 for the subassemblies A and B, assuming that the force is acting in the normal direction, the pretension force is 5000 N and the friction coefficient is 0.15.

Figure 7. Deformation curve for case I, under the conditions of variation of pretension force.
Figure 8. Deformation curve for case II, under the conditions of variation of pretension force.

Figure 9. Deformation curve for case III, under the conditions of variation of pretension force.

Figure 10. Deformation curve for case IV, under the conditions of variation of pretension force.
Figure 11. Influence of the coefficient of friction on stiffness, under the following conditions: modular subassembly A, force acts normally, pretension force of 5000 N.

Figure 12. Influence of the number of joints on the stiffness, when force acts normally, friction coefficient $\mu=0.15$, pretension force of 5000 N.

Figure 13. Influence of the number of joints on the stiffness, when force acts tangentially, friction coefficient $\mu=0.15$, pretension force of 5000 N.
Figure 13 presents the deformation curves in tangential direction, in sections S1 and S2 for subassemblies A and B, taking into account that the force acts on tangential direction, the pretension force is 5000 N and the coefficient of friction is 0.15. The following notations were used in Figure 13: A_S1, B_S1, - total deformation in section S1, in the direction of the normal/tangential force for subassembly A, respectively B; A_S2, B_S2 – contact deformation in section S2, in the direction of normal/transversal force for subassembly A, respectively B.

6. Conclusions
Following simulations and results generation presented graphically in the figures above, the following conclusion can be drawn. By analyzing Figures 7 and 9, we can observe that the pretension force strongly influences the stiffness in the normal direction of the modular subassemblies, which decreases along with the pretension force. The situation can be explained by the fact that the two forces (driving and pretension) have the same direction, and once the value of the pretension force exceeds the value of the applied force, it further deforms the elements of the modular subassembly. Regarding the stiffness in the transverse direction, we can observe in Figures 8 and 10 that it increases along with the increase of the pretension force, for both subassemblies. Figure 11 shows deformation curves obtained for different values of the coefficients of friction. It can be observed that the normal stiffness is insignificantly influenced by the variation of the friction coefficient in the area of the small driving forces, whereas, in the area of the larger driving forces, it increases slightly along with the decrease of the coefficient of friction. Figure 12 shows that, in section S1, total deformations for subassembly A (A_S1), are lower than for subassembly B (B_S1), which means that the stiffness in the normal direction decreases with the increase of the number of joints (interfaces contact). Regarding the stiffness on the transverse direction, according to Figure 13, it can be stated that there is no significant influence of the number of joints on it.

References
[1] Păunescu T, Bulea H and Păunescu R 2006 Dispozitive modulare. Construcție și exploatare, vol. I, Universității ”Transilvania’’ Brașov
[2] Gherghel N and Seghedin N 2006 Conceptia și proiectarea reazemelor dispozitivelor tehnologice, Tehnopress
[3] Păunescu T 2012 Tendințe în construcția dispozitivelor de prindere reconfigurabile, Buletinul AGIR 1 61-67
[4] http: //www.halder.com (accessed on February 2018)
[5] Chitariu D F 2014 Contribuții privind influența rigidității dispozitivelor modulare asupra preciziei de prelucrare, Univ. Tehnică ”A. I. Cuza” Iași, PhD Thesis
[6] Brăgaru A, Pănuș V, Armeaua A and Dulgheru L 1982 SEFA – DISROM. Sistem și metodă I. Teoria și practica proiectării dispozitivelor pentru prelucrări pe mașini-unelte, Tehnică, București
[7] Jonhson K L 1987 Contact Mechanics, Cambridge University Press
[8] Cioata V G and Kiss I 2009, The Machining Error Due to Contact Deformation of Workpiece-Fixture System, Acta Technica Corviniensis – Bulletin of Engineering 2(1) 33-36
[9] Zheng Y 2005 Finite Element Analysis for Fixture Stiffness, Worcester Polytechnic Institute, PhD Thesis
[10] Rong Y, Huang S H and Hou Z 2005 Advanced Computer-aided Fixture Design, Elsevier
[11] Segal L 2003 Contribuții privind proiectarea asistată de calculator a dispozitivelor modulate de prindere a semifabricatelor din construcția de mașini, Universitatea Tehnică „Gheorghe Asachi” Iași, PhD Thesis
[12] Chitariu D and Gherghel N 2013 Experimental Research Regarding Static Rigidity in Axial Direction of Normal Modules from Modular Fixtures Structure. I Research Methodology, Measuring Equipments, Researched Modules and Test Stand, Buletinul Institutului Politehnic Iași LIX (LXIII) 101-110
[13] Chitariu D and Gherghel N 2013 Experimental Research Regarding Static Rigidity in Axial Direction of Normal Modules from Modular Fixtures Structure. II Results, Buletinul
[14] Dulgheru L 1992 Contribuții privind rigiditatea dispozitivelor din elemente modulate, Institutul Politehnic București, PhD Thesis
[15] Chen X and Liu Y 2014 Finite Element Modeling and Simulation with ANSYS Workbench, CRC Press
[16] Miklos I Z, Miklos C and Alic C 2017 Dynamic Simulation of Road Vehicle Door Window Regulator Mechanism of Cross Arm Type, *IOP Conference Series: Materials Science and Engineering* **163** 012019
[17] Miklos I Z, Alic C I and Miklos C C 2016, Computer Aided Design of Welded Assemblies Current Trends, *Annals of the Faculty of Engineering Hunedoara* **14**(3) 153-156
[18] Dumitrescu I, Cozma B Z and Itu R B 2016 Safety Mechanisms for Mining Extraction Vessels, 16th GeoConference on Science and Technologies in Geology, Exploration and Mining SGEM, Albena, Bulgaria, June 30 - July 6, pp. 759-766
[19] Dumitrescu I, Cozma B Z and Itu V 2016 Study the Mining Winches using the CAD/CAE Software, 16th GeoConference on Science and Technologies in Geology, Exploration and Mining SGEM, Albena, Bulgaria, June 30 - July 6, pp. 833-840
[20] Ivanov V, Mital D, Karpus V, Dehtiarov I, Zajac J, Pavlenko I and Hatala M 2017 Numerical Simulation of the System “Fixture–Workpiece” for Lever Machining, *The International Journal of Advanced Manufacturing Technology* **91**(1) 79-90
[21] Kumbhar N M, Patil G S, Mohite S S and Sutar M A 2012 Finite Element Modelling and Analysis of Workpiece-fixture System, *International Journal of Applied Research in Mechanical Engineering* **2**(2) 60-65
[22] Cioată V G, Kiss I, Alexa V and Rațiu S A 2017 The Optimization of the Position and the Magnitude of the Clamping Forces in Machining Fixtures, *IOP Conference Series: Materials Science and Engineering* **200** 012015
[23] Cioată V G 2008 Determining the Machining Error due to Workpiece-Fixture System Deformation using the Finite Element Method, 19th International DAAAM Symposium, Brno, Czech Republic, October 22-25, pp 253-255
[24] http: //www.norelem.com (accessed on February 2018)