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RESEARCHING METHODOLOGY AND RESULTS REGARDING SOME DEVICES INTEGRATION ON CNC MACHINE TOOL

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The paper presents some general considerations regarding the importance of using and integration of the devices on machine tools with numeric command. For highlighting its behaviour the experimental model of a fixing device D used for clamping a workpiece P on a milling machine-tool was designed and realised. The numerical and experimental researches emphasize the behaviour of the assembly workpiece-clamping device under the action of cutting forces and moments. The cutting force was developed and the deformations of the clamping arm, which is the most solicited element from the structure device, were measured. The evaluation of the clamping device strain was realised with the help of a sensor, which signal can be used for modifying the programmable parameters, in the numeric command equipment of the machine tool.

Keywords: cutting forces and moments, clamping device, device adaptation, sensors, experimental data and data acquisition.

1. Introduction

The domain literature [1, 2, 3] presents many researches which lead to the improvement of the processing precision, optimal machine tool operation, processing automation and productivity increasing. Clamping and training devices for the workpiece and/or the tool holder [4], with important role in the technologic system, could be equipped with one or more sensors, obtaining a mechatronic device. The sensors and the transducers have an important role in analyzing the system evaluation taking into consideration the measured parameters: strain, stress, and vibrations. Because of the big variety of sensors, taking into consideration the evaluated measure or the signal type, it is necessary to fulfil the hardware and software integration with the whole control system [5, 6].

As known from the literature [7, 8, 9], the orientation and clamping devices must meet several conditions, such as: a simple construction, stiffness, a degree of modularity, adaptation to the requirements of the flexible manufacture, maintenance of the position of the workpiece and the tool under the action of the cutting forces and moments. It is also important that the intensification of the

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vibrations which appear during the cutting process isn't caused. Clamping and training devices for the workpiece/tool holder must continuously adapt to the request of the increasing process parameters [10, 11, 12] and also to the cutting forces and moments, clamping safeness, and diversification of the processed materials and tools.

Integration of the clamping devices in advanced production systems requires taking into consideration two important aspects: spatial integration, namely the link between the electrical and mechanical system, and functional integration, the link with the control system.

2. Performances evaluation for a clamping device

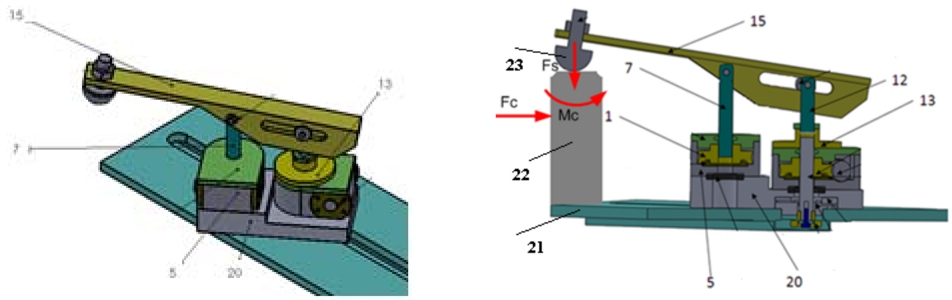
Performance analysis of the devices supposes going through a methodology that comprises the following steps: analysis of the workpiece, orientation surfaces, technologic processes and tools, production type, process parameters, knowing and determination of the elements loadings (cutting forces and moments, clamping forces), determination through modelling and simulation of the most stressed elements from the device structure taking into account the most unfavourable case. The analysis results help establishing the solution location for the sensor or transducer, which is considered the principal element of the mechatronic system [1, 4]. It is assumed that the signal produced by the sensor is processed so as to be compatible with the numeric control system of the machine tool. This kind of connection can be established with the help of a programmable logic controller.

The criteria established from the literature [7, 8, 9], on which the evaluation of the devices performances are based, are the following: the basic technologic process, machining allowance division, actuating type, automatisation and modularization grade, the machine tool type on which the device is adapted. Therefore a manufacturing device to perform the orientation and fixing role for processing must contain in its structure: elements with orientation role, supplementary locating elements, elements and fixing subassemblies, elements for tools adjustment and guidance, elements for the link with the machine-tool [1, 2, 3, 6, 10, 11]. Every component element of the device has an important functional role in the relative assembly. Both in the literature [7, 8, 9], and in the devices catalogues [13] different constructive solutions for the principal supports are described. These are fixed or mobile. These are designed for plane, cylindrical, spherical, conical or any other kind of surface; principle, adjustable or self adjustable, with subsequently alignment or auto alignment and blocking, which has the role to decrease the workpiece deformation and to prevent the displacements. From orientation achievement point of view, for improving the performances of the devices it could be used a multifunctional support [14] with auto alignment and blocking, which it is totally constructed from modular components, changeable, adjustable, which permit the obtaining of new characteristics and functionalities from kinematic, technologic, constructive and economic point of view. For evaluating the way of clamping function achievement are proposed fixing methodologies which take into consideration the technologic process, the shape and the dimensions for the processed workpiece, workpiece and tool material. When a workpiece is positioned and fixed with the help of a fixing device with sensors the system dynamic response could be used for characterizing the corresponding fixing state.

3. Stages for the performances evaluation of a fixing device adaptable on milling machine-tools

3.1. The analysis of the constructive solution

The analyzed fixing device, build in modular version, is used for the workpiece 22 fixing on the machine-tool table 21 or on a pallet with the help of the clamping element 23. This is realized from specific modules for every function required by the technologic process: longitudinal displacement, angular alignment, blocking on the machine-tool table, clamping the workpiece. The system is with worm-worm gear and bolt nut-nut mechanism and manual actuation. The modern actuation way is possible with the help of an electric screw driver, which can be manipulated using a flexible manufacturing cell robot. The device has a plate 20, case type, on which are mounted two cases 5, each of them containing a module that assures different device functions, every module contains a worm gear. The fixing on the machine tool table is done by rotating the worm axle of the worm gear 9, in the corresponding sense, until obtaining the desired clamping force, controllable with the help of the force transducer, from the dynamometer, fig. 4 a. The movement of the worm axle in the other sense disconnects the device from the machine tool table. Only after clamping the device on the machine tool table it is possible to clamp the workpiece. This is done by rotating the axle of the worm and the worm gear 1. The position of the clamping arm is adjustable by screwing or unscrewing the threaded rod 12 in the special nut 13. After establishing of the desired position, the threaded rod 12 is blocked by a tightening nut for preventing the clamping weakening during the cutting process.



a. b.

Fig. 1. Analised device: *a* - Perspecting view of the device, *b* - Section view of the device.

The device can be adapted to the conditions imposed by the cutting parameters, form and the dimensions of the workpiece, the positioning way on the machine table or on the device element. The device can be also adapted from dimensional point of view because of its modular structure.

3.2. Determining the clamping force developed by the device

After establishing the cinematic and constructive solution of the worm mechanism, the forces acting on it were determined with the help of the tangential force that acts on the clamping bar as a result of transmitting of the movement with the help of the mechanism nut 1- screw 7, which performs a descending movement. The clamping force developed by the clamping element 15 is determined with the help of the cinematic and organologic calculations.

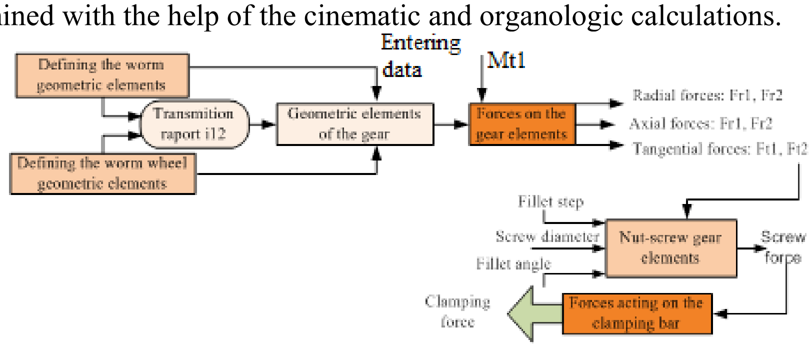


Fig. 2 Determining the clamping force developed by the device.

In fig. 2 is presented the algorithm for the calculation of the clamping force developed by the device [15]. Two programs, one in MathCAD and one in Excel, were developed and used in order to make the organlogic calculation faster. There were defined as string values, the actuation moment, M_{t1}, as input data, and the clamping force F_{st}, as output data. In fig. 3 are presented the results for the calculation methodology.

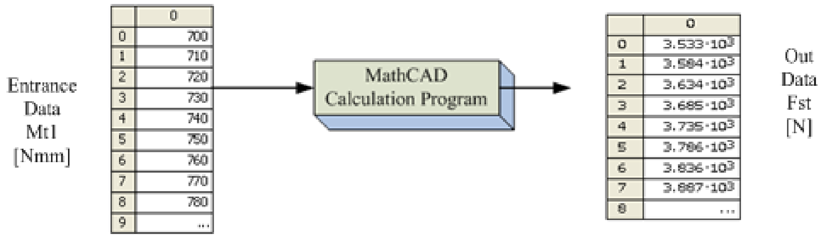
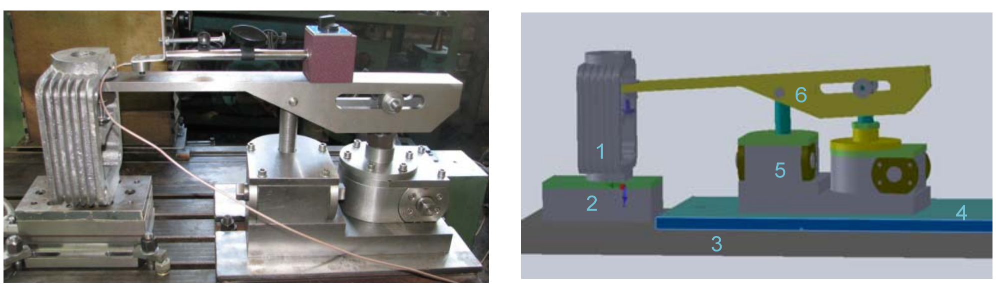


Fig. 3 Calculation example for the clamping force: Mt1 [Nmm] the actuation moment, Fst [N] the clamping force

3.3. Modelling and static simulation under the action of clamping forces

For the clamping function evaluation of the analyzed device the experimental devices in fig. 4.a was created. The processed workpiece 1 is clamped on the machine tool table 3, with the help of a dynamometer 2. The workpiece clamping on the machine tool table is done with the device 5 clamping arm 6, which is clamped on the machine tool worktable with the help of the adapting board 4. The experimental assembly was modelled in SolidWorks, see fig. 4 b, for the simulation of the clamping arm under the action of the clamping force and for the determination of the natural mode shapes and frequencies.



a. b.

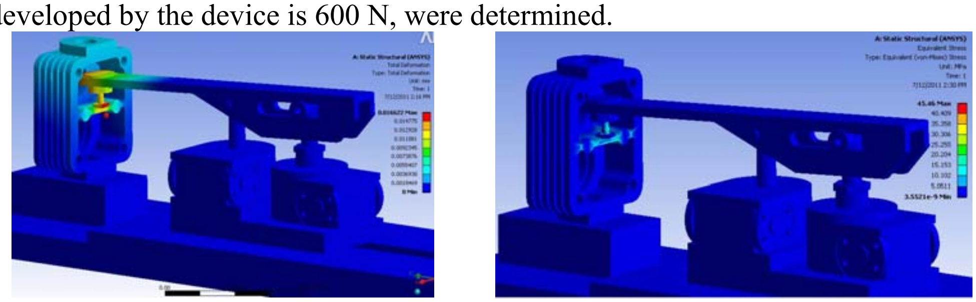
Fig. 4. Example of using the device: a. Device on the MT table, b. 3D model of the device.

The construction solution for the clamping arm was chosen in a unfavourable variance from rigidity point of view, but taking into consideration the possibility of applying the clamping force on o surface imposed by the shape of the workpiece, as shown in fig. 4 a. The displacement sensor was mounted on the clamping arm, for measuring its deformation under the fixing force action.

The clamping force represents the output of the clamping device and is established taking into account the cutting forces and moments. This must be limited, so it must not exceed a certain value in order to avoid the workpiece surface deformation in the clamping element contact zone, fig. 5 a.

Exceeding a certain limit can lead to permanent deformation of the surface of the workpiece or of the clamping element. The workpiece deformation may have negative consequences for the machining precision and the deformation of the clamping element can generate permanent deformations.

Limiting the clamping force can be associated with the deformation value in the case of using a displacement sensor. The results will be presented further in chapter 4. Another variance is the using of a coupled transducer that can be mounted on the worm-worm gear mechanism. The first solution was chosen because the measurements were realised in the most appropriate area where the clamping point is applied. With the help of the static analysis for a mechanical structure, stress and strain [16] can be determined. For the considered fixing device structure the maximum principal deformation (16.62 μm), fig. 5 a, and the maximum principal stress (45.45 MPa), fig. 5 b, when the clamping force developed by the device is 600 N, were determined.



a. b.

Fig. 5. Static structural analysis of the assembly workpiece clamping device: a. Total deformation (maximum); b. Equivalent stress (maximum).

In table 1 the results regarding the clamping arm, element and surface of the workpiece deformation, when the fixing force varies from 120N to 1200N are presented. Next stage in the numeric research for the analyzed clamping device of the workpiece is represented by the evaluation of the strain when the clamping force varies on a range from 0 to 1200 N, and on another from 1200 N to 0, for the clamping arm, clamping element, and the clamping surface for the machined workpiece.

In fig. 6 the deformation curve for the clamping arm at the ascending/descending of the device till 1200 N are presented. The two curves are identical. This fact demonstrates that the clamping arm, up to that force value, is solicitated in the elastic domain.

Table 1

Total maxim static deformation

Clamping force (N)	Workpiece total deformation (mm)	Total deformation (mm)	Bracket total deformation (mm)
0	0	0	0
120	0.0025	0.0033	0.0033
300	0.0063	0.0083	0.008

420	0.0088	0.0116	0.0114
600	0.0126	0.0166	0.0163
720	0.0151	0.0199	0.0196
900	0.0189	0.0249	0.0244
1200	0.0253	0.0332	0.0326

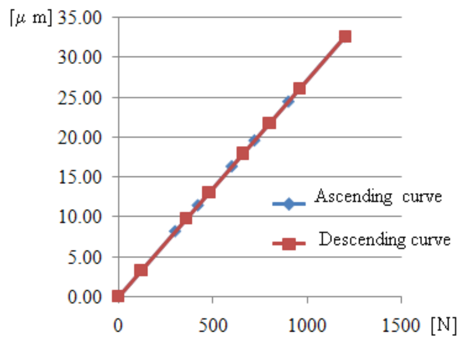


Fig. 6 Clamping arm deformation curve

3.4. Results of the modal analysis

Another important stage is the modal analysis, which is frequently used for the determination of the dynamic characteristics of the analyzed structure [16].

This type of analysis is linear and will not take in consideration the amortization or the exterior loadings, because the structure vibrates under its proper weight. In table 2 are presented the first 6 frequencies.

Preload modal analysis has as final scope the determination of the structure dynamic characteristics. For preload modal analysis, as initial conditions, the tensions created of the static loads are taken into consideration. This kind of analysis is preceded by a static analysis. In this way the contribution of the tensions produced by the static forces to the modification of the rigidity matrix is taken into consideration. After this analysis were also determined the first 6 frequencies. The values are presented in table 3.

Table 2

Modal analysis results

Vibration mode	Frequency (Hz)
1	708.57
2	1132.5
3	1320.6
4	1328.6
5	1574.1
6	1911.9

Vibration mode	Frequency (Hz)
1	711.56
2	1133.17
3	1324.31
4	1328.72
5	1577.29
6	1912.54

Due to the mechanism which forms the experimental device model (bolt nut-nut, worm-worm gear) and the multiple joints the rigidity is negatively influenced. Appropriated values for the natural frequencies of the device confirm the low level of rigidity for the experimental model. Considering the two sets of frequencies presented in tables 2 and 3 in this case study, the preload analysis it is not necessary, the natural frequency values being very close.

Analyzing the results through modal analysis it can be observed that the first vibration mode is the simplest, it corresponds to the static deformation and does not present inflection points. Taking into consideration the first vibration mode, figs. 7 and 8, the most stressed element from the clamping device structure is the clamping element. The element is stressed to torsion.

The second vibration mode, figs. 9 and 10, is a simple stress mode, in perpendicular plane on the first one. The element is stressed to bending and presents a single inflexion point.

Taking into consideration the third vibration mode, figs. 11 and 12, the most stressed element from the whole assembly is the machined workpiece, which is stressed to torsion along the *z* axis.

The fourth vibration mode, figs. 13 and 14, corresponds to the workpiece bending along plane *xoz*. The fifth (figs. 15 and 16) and sixth (figs. 17 and 18) vibration modes are complex stress modes, which act on the clamping element and namely on the workpiece. As the frequency degree increases the deformation of the vibration mode gets complicated but its contribution to total deformation decreases. The structure does not vibrate after the first or the second vibration mode, only after a linear combination of all modes, the most important being the first six ones.

Determining the natural frequencies resulted after the model analysis is important for avoiding the apparition of the resonance. These must be compared with the machine tool working frequencies on which the device is mounted. In this way it is not permitted its functioning with harmonics of the natural frequencies.

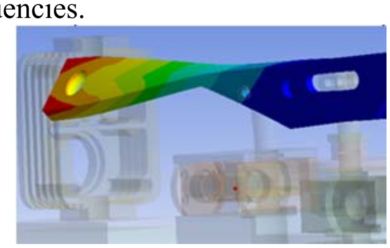


Fig. 7. Clamping arm vibration mode – the first natural frequency

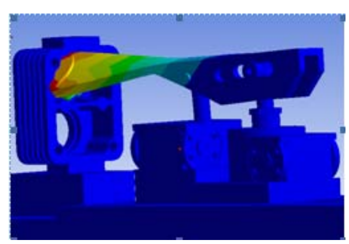


Fig. 8. Assembly vibration mode - the first natural frequency.

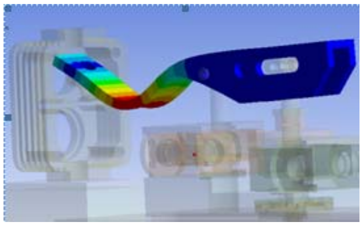


Fig. 9 Clamping arm vibration mode – the second natural frequency.

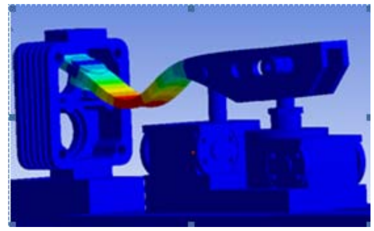


Fig. 10. Assembly vibration mode - the second natural frequency.

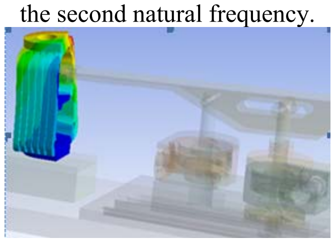


Fig. 11. Workpiece vibration mode – the third natural frequency.

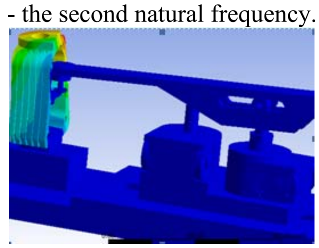


Fig. 12. Assembly vibration mode - the third natural frequency.

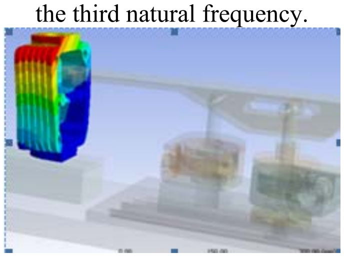


Fig. 13. Workpiece vibration mode – the fourth natural frequency.

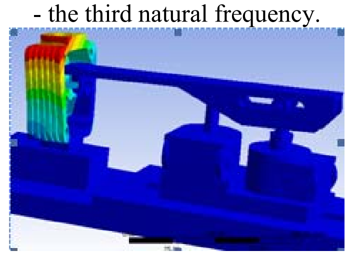


Fig. 14. Assembly vibration mode - the fourth natural frequency.

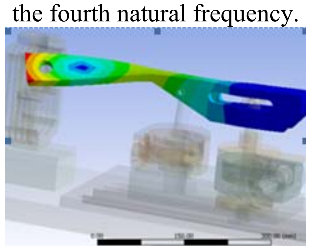


Fig. 15. Clamping arm vibration mode – the fifth natural frequency..

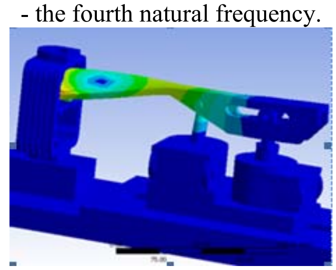


Fig. 16. Assembly vibration mode - the fifth natural frequency.

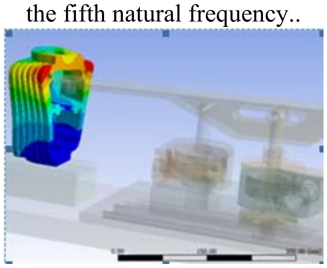


Fig. 17. Workpiece vibration mode – the sixth natural frequency.

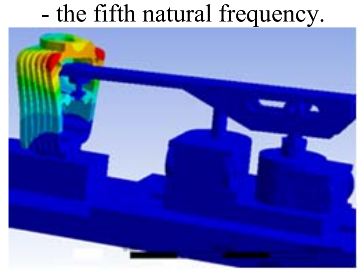


Fig. 18. Assembly vibration mode - the fifth natural frequency.

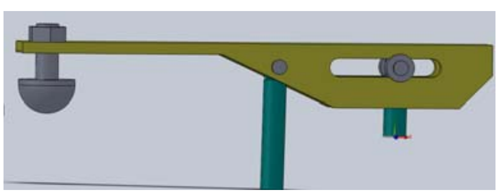
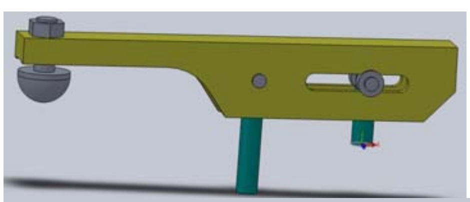
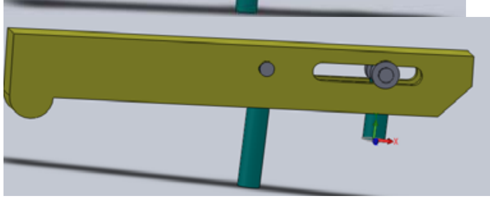
3.5. Methodology for choosing the clamping arm

The analyzed clamping device is being characterized by the fact that, on a common modular structure, named the device body, different clamping elements can be mounted. The clamping arms are different from the design, length and material point of view, as shown in table 4.

In this way the device can be easily adapted to different types of workpieces or cutting methods, assuring the corresponding machining precision. On the bases of these considerations a methodology of choosing the optimal clamping arm was proposed. The methodology is based on the creation of a database with different models for the clamping arm. For these models the deformations when these are tensioned with variable forces were determined. Fig. 19 presents, in a schematic way, the methodology of choosing the arm.

The simulations were realized for three different types of clamping arms, from design point of view, having different lengths (250, 200, 150 mm) and being made of different materials (AISI 1045, AISI 4340 and AISI 8740). The clamping elements were chosen for increasing the rigidity. When modifying the length of the clamping element, and so the clamping force, trying to obtain the maximum deformations as low as possible. For validating the solution is necessary to take into consideration the machining precision, the cutting process and the maximum deformations.

Table 4

	Clamping element of 250 mm. This variant was practically realized, and experimentally tested. It can be realized from different steel types: AISI 1045 AISI 4340 AISI 8740
	Clamping element of 250 mm, 200mm and 150mm. It can be realized from different steel types: AISI 1045 AISI 4340 AISI 8740
	Clamping element of 250 mm, 200mm and 150mm. It can be realized from different steel types: AISI 1045 AISI 4340 AISI 8740

For realizing the finite element analysis the well known stages, namely: preparing their model for analysis, the effective analysis and processing of the obtain results were respected.

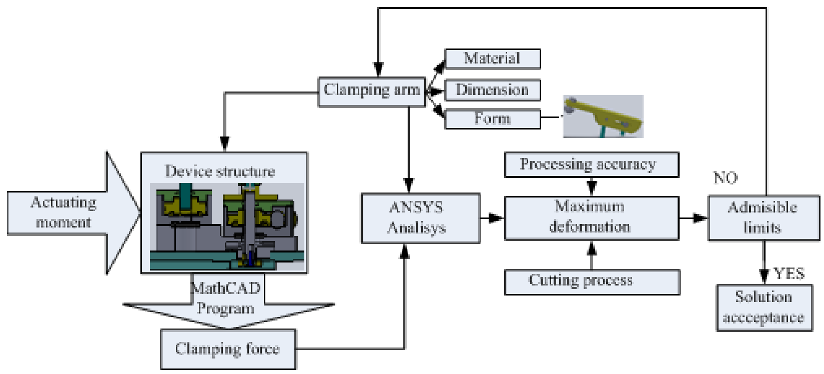


Fig. 19.Methodology of clamping arm choosing.

The most important criteria that are taken into consideration when choosing the clamping arm are: the workpiece form and dimensions, the clamping arm shape and dimensions, the material of the arm, the locating method, the machining type. When at the worm that actuated the clamping arm it is applied a motor moment, the device it is capable of generating a specific clamping force that can be calculated with the presented methodology. On the other hand to the basic device structure different types of clamping arms can be attached. After a clamping arm is chosen the given solution is analyzed with the help of a finite element program. For validating the final solution is necessary to take into consideration the machining precision, the cutting process and the maximum deformations. If they are below the admissible limits the solution can be validated, if not another clamping arm must be chosen.

4. Deformation measuring for a clamping device adaptable on milling machine tools

During experimental researches, for the cutting and clamping forces measuring a Kistler dynamometer type 9257B and also a data acquisition board NI USB 4432 and a Kistler 5070 amplifier [17] were used. In fig. 20 is presented the clamping forces variance when the worm does a course of 8 complete rotations.

The registered clamping force doesn’t represent the total clamping force, but the supplementary clamping force induced by the actuation of the worm with 8 complete rotations, in 60 sec. During data recording was observed an abnormal clamping force variation, which suddenly becomes negative.

This fact involves the apparition of an overheated moment, created by the reaction of the clamping force which tries rising the devices from the machine tool table, fig.21 a.

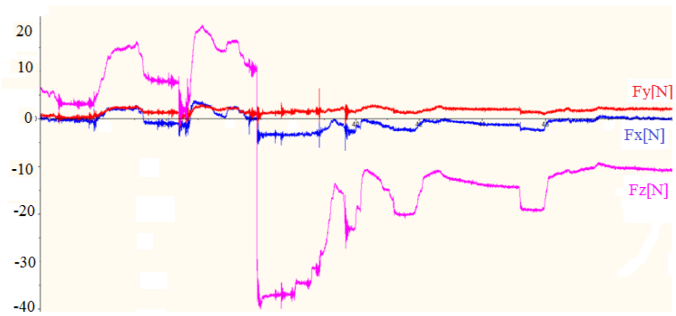


Fig. 20 F_z Component of the clamping force

The experimental analysis shows that the solution is unsuitable for a clamping force about 1200 N, so it was necessary to improve the clamping system used for fixing the device on the machine tool table, figure 21.b.

a. b.

Fig. 21. Clamping device during tests: a.- Rising the device from the machine table, b. - Assembly with supplementary stiffening elements

For the future constructive variance of the device was established that fact that the introducing of supplementary stiffening elements is necessary. These elements will not have influences on its functionality. For the complexity of the experimental tests and elaboration of some recommendations regarding the analyzed device, the device was tested on a milling machine, fig. 22.

During milling the components of the cutting force on the three principal directions F_x, F_y and F_z were measured and registered. Two types of face milling were conducted: longitudinal milling, x machine tool, y dynamometer, and transversal milling, y machine tool, x dynamometer, fig. 22. For the machining a Coromill ball nose end mill tool, R216.44-12032-AK26N [19] with the following cutting data GC 1610, z=4 teeth, r_c=6, γ_0=10°30′, α_0=12°, a_p=26 mm, D_c=12 mm was used. The cutting process parameters used are the following: spindle speed n_c=2000 rpm, cutting speed v_f= 96 mm/min, cutting depth a_p=1,2 mm, cutting width a_e=11 mm.

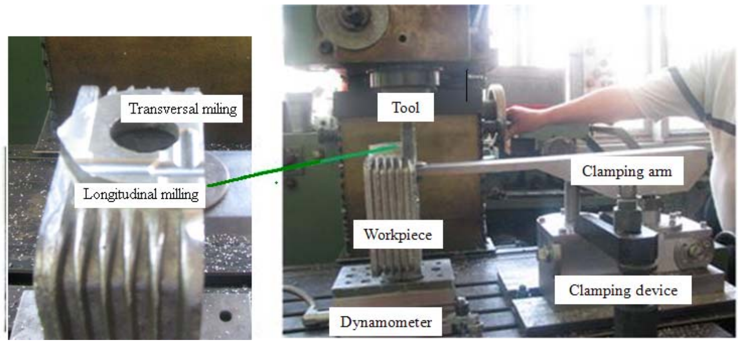


Fig. 22. Milling processing

The machining was done using a universal milling machine, on an aluminium alloy workpice, without cooling agent. The experiments were conducted in the Machine-Tools Laboratory, University Politehnica of Bucharest, Faculty of Engineering and Management of the Technological Systems, Machine and Production Systems Department. In figs. 23 and 24 the cutting forces recorded during longitudinal and transversal milling are presented.

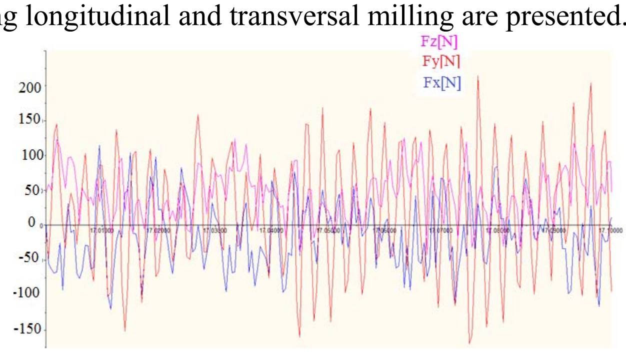


Fig. 23 Cutting forces for longitudinal milling

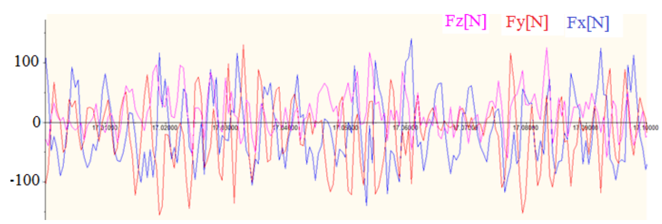


Fig. 24 Cutting forces for transversal milling

During experimental measuring of the clamping arm deformation, on its structure the dynamometer for registering the variation of the clamping force was also connected. The arm is relieved step by step corresponding to every rotation of the worm which contributes to its displacement. When increasing the clamping force, tests were done following successive stages. In the first stage on the worm was acted with four complete rotations. In this easy way was assured the first clamping stage, for which the 3 components of the force on the directions x, y and z, presented in fig. 25, were registered. Three zones in the clamping force variation are distinguished: the first one when the worm is not actuated, corresponding to range 1, the second one when actuating the worm with four complete rotations (range 2) and the last one when the clamping force is stabilized (range 3). The clamping arm total deformation measured with the help of the comparison gauges was 0.012 mm.

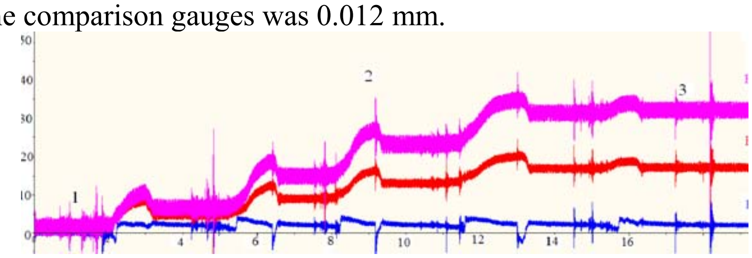


Fig. 25. Clamping forces components on the x, y and z for two rotations of the clamping mechanism spindle

The final stage for the device evaluation is represented by the measurement of the clamping arm deformation with the help of a displacement sensor and the clamping force using the Kistler dynamometer 9257B as in the experimental setup presented in fig 4,a. Fig. 26 presents the whole measuring chain and also the clamping device integration setup in an advanced production systems.

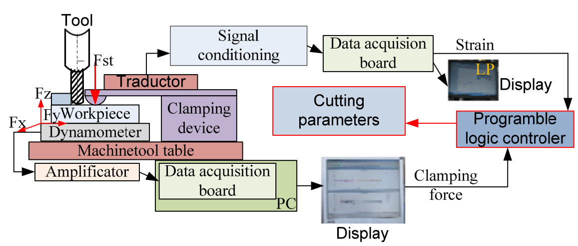


Fig. 26. Measuring deformation with the help of a transducer: integration scheme.

5. Conclusions

For evaluating the performances of some orientation and clamping devices it is necessary to go through some principal stages:

- analyzing the workpieces and of the technologic processing,
- analyzing of the process parameters and orientation and also the clamping surfaces,
- determination of the loads (cutting forces and moments, clamping forces, inertia forces, and the workpiece weight),
- static and dynamic analysis through modelling and simulation of the most tensioned elements from the device structure, in the most unfavourable case (the one when the clamping element has the length of 250mm),
- possibility of adapting the device for its integration in an advanced production systems.

The proposed methodology for determining the clamping force developed by the device, based on the known relations, gives a rapid and precise calculation of the clamping force when the actuation moment is known.

Limiting the clamping force of the device it is important to avoid the workpiece surface deformation in the contact zone with the clamping element. If the clamping force exceeds a certain limit a permanent deformation of the surface of the workpiece or of the clamping element can appears. This fact may have negative consequences for the machining precision.

With the help of the static analysis for the anlysed structure were determinded stress and strain, for a certain clamping force. By extending this analysis for different forces it ca be extablished the clamping force interval in which the device is used with out deformating the workpiece surface or the clamping element.

Numerical simulation using FEM, is an engineering instrument used previous to any scientific research concerning an assembly for designing. Taking in consideration the actual economic conditions, we can not afford first to execute the product and than to test it and find out what changes are necessary. So this stage it is useful in reducing the supplementary costs caused by the supplementary material consumption labour costs and for the design of the physical model that are needed for establishing the final solution after experimental test.

Taking into consideration the modular construction of the device, a data base with different clamping arms models of different lengths and made from materials with different mechanic characteristics was created. For this database the deformations when soliciting with different clamping forces were determined.

This is useful in establishing the optimal configuration of the device corresponding to the application, when this is used for clamping the workpieces that are processed using different technological processes.

The obtained experimental results are useful for the methodology validation for the analyzed device and for establishing the necessary clamping force in accordance with the process parameters, cutting forces, technological process, the form, dimensions and the workpiece material, the clamping device type etc.

Adapting deformation sensors was efficient for assuring a permanent signal regarding the deformation state for the most tensioned element in the device structure: the clamping arm.

Accidental modification of the deformation of the analyzed element will be useful to generate a signal alert for the command equipment of the machine tool, approach that can be considered as a new objective for further future researches for the development of the mechatronic clamping device.

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