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EXPERIMENTAL AND NUMERICAL RESEARCHES FOR UNIVERSAL MODULAR DEVICE

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Abstract: *The paper presents the stages of preparing the technologic system machine tool-device-tool-workpiece for creating a data acquisition system for registering the cutting forces and torque on the rectangular directions, during milling of carbon steel prismatic work-piece. Some considerations regarding the basic requests for the machine tool clamping devices and their behaviour under the cutting forces and torque are presented. We also established the evaluation methodology stages of o modular fixture device regarding construction and operation, loads, analyzing through modelling and simulation, data acquisition, interpretations and results validation for its integration on CNC machine tools.*

Key words: *cutting conditions, force and torque measurement, clamping system, stress analysis, sensors.*

1. INTRODUCTION

Performance analysis of the devices for the integration in advanced production system supposes going through a methodology that comprises the following steps: analysis of the work-piece, the technological processes and cutting tools, number of clamping points needed for the work-piece processing, establishing of the orientation surfaces and the production type [1]. It is also needed knowledge and determination of the process parameters, cutting forces and moments and clamping forces [2].

The device evaluation also needs numeric calculation stages, determination through modelling and simulation of the most stressed elements from its structure, in the most unfavourable case. The analysis results help in establishing the locating solution for the sensor or transducer, as principal element for transforming the fixture device in a mechatronic one. The signal produced by the sensor is assumed and processed in a way to be compatible with the numeric command system of the machine tool [3, 4].

2. WORKING CONDITIONS

The experimental researches are done using a 3-axis CNC vertical milling centre (Fig. 1) located in the Machine Tools Laboratory, of the Machine and Productions Systems Department, with the following characteristics: main spindle speed D_{nc}: 100–8 000 rpm, with infinite variable range, the power of the main spindle motor P = 7.5 kW, working travel on axes X = 610 mm, Y = 305 mm, $\underline{Z}$ = 460 mm, the maximum machining feed rate D_f: = 1–1000 mm/min and for high cutting speed till 2000 mm/min, AC motors for feed drives with 3–2000 rpm, M = 3/6 Nm for X / Y axes and M = 12 Nm Z axis, the milling centre has a CNC Fanuc controller.

Fig. 1. MCV 300 machine-tool: *a* – basic components; *b* – machine-tools dynamometer axis system.

The machine-tools axes are the similar as direction to those of the Kistler dynamometer [9] used for the force measurement.

The cutting force components F_x, F_y and F_z were measured taking into consideration the dynamometer directions and the specific influence for every processing.

For the measurements of the cutting forces and torque the next experimental stand was arranged (Fig. 2), composed of the next principal components: the work-piece (1), fixed on the machine tools table (3), with the help of the Kistler dynamometer 9257B (2), amplifier for Multi-component – Force measurement Multi-Channel Charge Type 5070 (4), data acquisition board PCIM-DAS1602/16, mounted in PC (5), cu Windows XP and data acquisition program DynoWare Type 2825A [6].

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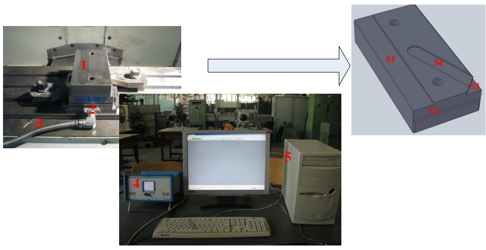

Fig. 2 The experimental stand.

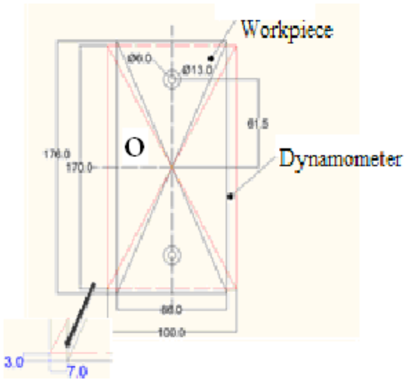

Fig. 3. The position of the work-piece axis and clamping holes.

The prismatic working piece is from carbon steel XC-45, with the following dimensions 86×176×56 mm. For the surfaces processing two different types of tools were used: a roughing end milling, with diameter D_c = 80 mm, z = 6 teeth (milling tool type Coro Mill R365-Q27-S15M080, square inserts PM) and a milling tool with diameter D_c = 18 mm and z = 3 teeth (cod R216.13-18030-BS18P) [10].

3. EXPERIMENTAL RESEARCHES AND RESULTS

On the work-piece were processed different types of surfaces *S*1…*S*4, differently orientated. During each surface processing were measured and registered the cutting forces and torques, in the dynamometer centre.

The components of the cutting force, F_x, F_y and F_z were measured with the dynamometer on the directions of the dynamometer reference system (Fig. 1). The component F_z is normal orientated on the surface of the machined wall. The component F_y in orientated on the direction of the feed movement, and the F_x component is normal on the tool's axis. The component F_z is normal orientated to the processed surface and the horizontal components F_x and F_y are orientated parallel.

The workpiece was fixed on the dynamometer with the help of an intermediary adaptor, as shown in Fig. 3.

The cutting forces were measured in conditions of roughing and finishing milling, with corresponding feed per tooth and cutting speeds [5]. Within each measurement it was acquired a file with machining data and results of the force components using the dynamometer. By processing the acquired data files with the DynoWare type 2825A, various diagrams of the cutting forces components previously selected by the user are obtained, and also the minimum, the medium and the maximum values on the chosen interval of time, as needed. The numerical values of each force component may be determined for each moment or interval of the determination using options from the program toolbar. Significant results selected from the experimental determinations are shown in Table 1.

The values measured forces are determined directly by the cutting depth a_e and a_p by the feed per tooth f_z and the cutting speed v_c. Based on geometric data for the tool and the processed surface *S*1, Fig. 4, in contact with the material processed are three teeth of the tool. Cutting force components on the three main directions, on the time interval 170.11–170.39 sec are represented in Fig. 5. Cutting moments in the centre O of the dynamometer are registered on time sec. 170.11–170.39 sec, are represented in Fig. 6.

For finishing milling, Fig. 7, as in previous processing, analyzing the trajectory, the number of teeth and the tool diameter, taking into account the cutting width, throughout the processing, in contact with the material will be three teeth. Cutting force components on the three main directions are represented in Fig. 8, and the moments recorded in dynamometer centre, in Fig. 9.

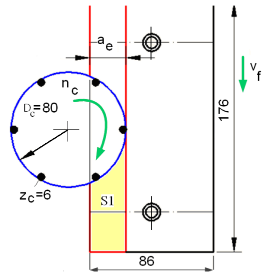

Fig. 4. Longitudinal roughing milling.

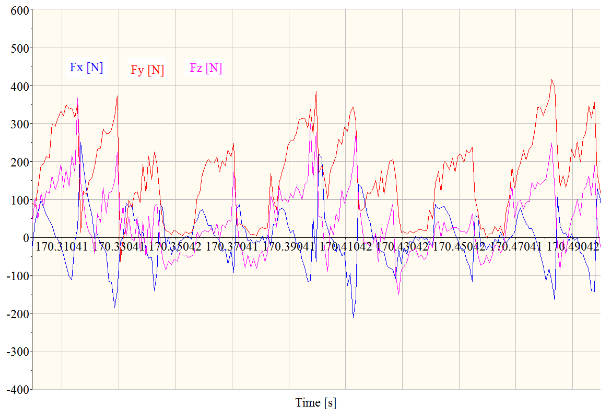

Fig. 5. Cutting forces on *X*, *Y* and *Z* directions.

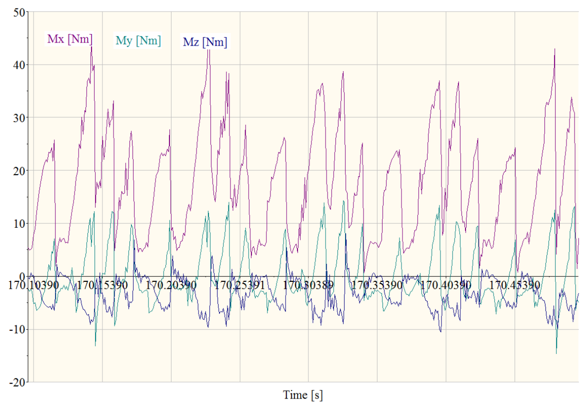

Fig. 6. Cutting moments on the principal directions.

Table 1

Cutting forces and parameters

	Cutting conditions							F_x [N]			F_y [N]			F_z [N]		
	D_c [mm]	z teeth	a_e [mm]	a_p [mm]	f_z [mm]	v_f [mm /min]	n_c [rot/ mm]	min	med	max	min	med	max	min	med	max
S1	80	6	25	1.5	0.06	43	437	–277	–8	312	–167	146	485	–279	32	465
S2	80	6	25	0.5	0.06	43	437	–176	–2	173	–34	23	196	–62	49	302
S3	18	3	2	18	0.03	90	1450	–37	88	273	–334	-124	38	–155	–27	45
S4	18	3	18	5	0.03	90	1450	–254	–30	47	–322	-85	24	–113	–25	56
S5	18	3	18	3	0.03	90	1450	–65	118	319	–367	-184	43	–98	–44	13

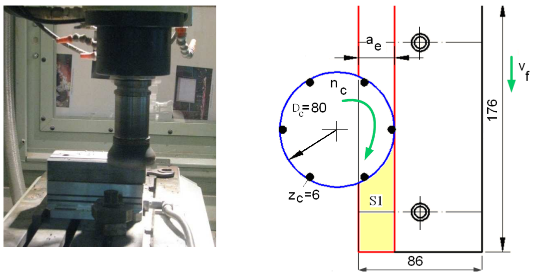

Fig. 7. Longitudinal finishing milling.

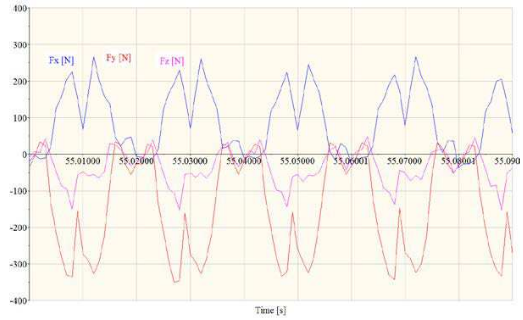

Fig. 11. Cutting forces on *X*, *Y* and *Z* directions.

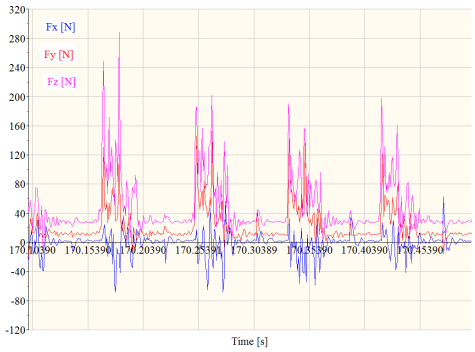

Fig. 8. Cutting forces on *X*, *Y* and *Z* directions.

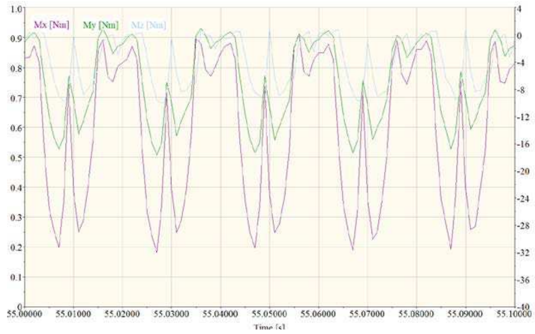

Fig. 12. Cutting moments on the principal directions.

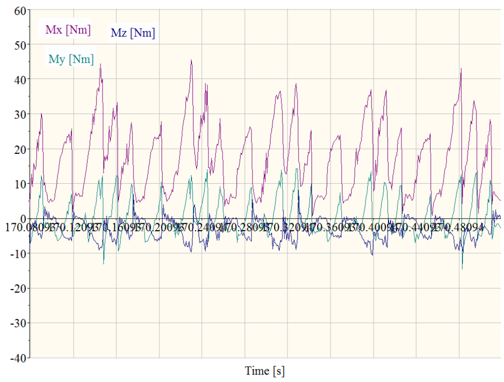

Fig. 9. Cutting moments on the principal directions.

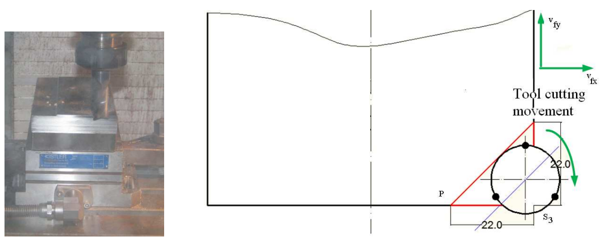

Fig. 13. *S*3 surface processing.

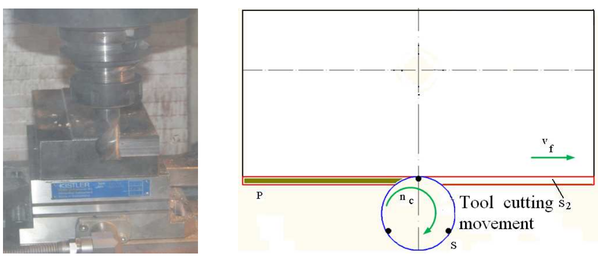

Fig. 10. Transversal milling.

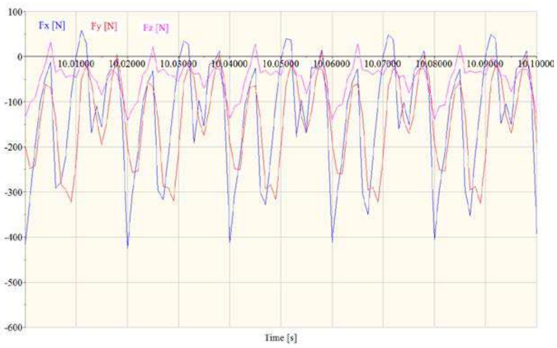

Fig. 14. Cutting forces on *X*, *Y* and *Z* directions.

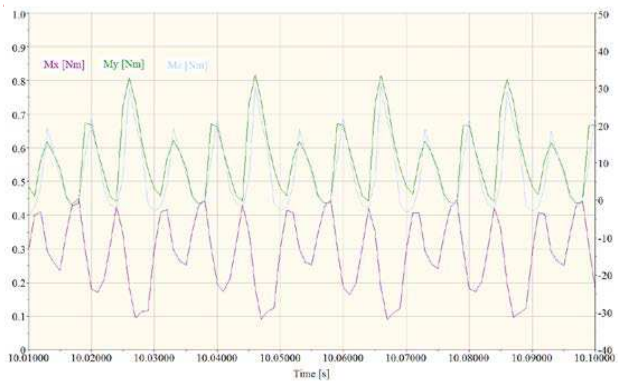

Fig. 15. Cutting moments on X, Y and Z directions.

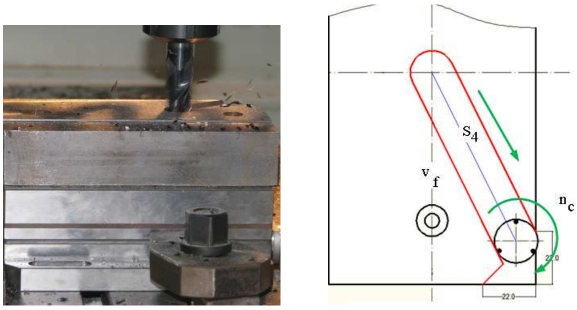

Fig. 16. *S*4 surface processing.

Analyzing from geometric point of view the processing case for the *S*2 surface, taking into account the processed surface, the number of teeth and the tool diameter, was demonstrated that only one tooth is in contact with the work-piece material, Fig. 10.Cutting force components on the three main directions are represented in Fig. 11, and the moments recorded in dynamometer centre, in Fig. 12.

Analyzing from geometric point of view the processing case for the *S*3 surface, taking into account the processed surface, the number of teeth and the tool diameter, was demonstrated that two teeth are in contact with the work-piece material, Fig. 13.

Cutting force components on the three main directions are represented in Fig. 14, and the moments recorded in dynamometer centre, in Fig. 15.

Analyzing from geometric point of view the processing case for the *S*4 surface, taking into account the processed surface, the number of teeth and the tool diameter, was demonstrated that two teeth are in contact with the work-piece material, Fig. 16. Cutting force components on the three main directions are represented in Fig. 17, and the moments recorded in dynamometer centre, in Fig. 18.

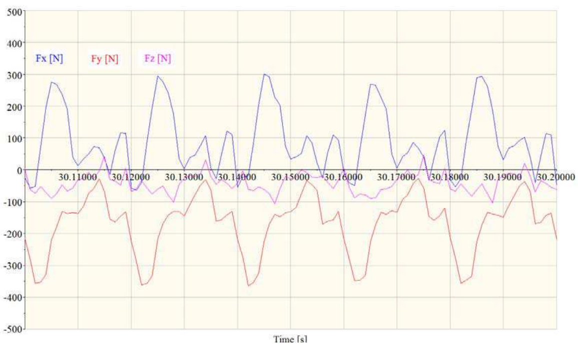

Fig. 17. Cutting forces on X, Y and Z directions.

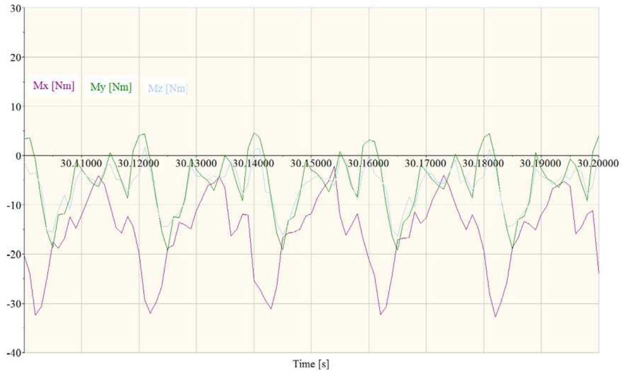

Fig. 18. Cutting moments on X, Y and Z directions.

As a case study for the work-piece of prismatic form, figure 19, the locators R_1 and R_2 are positioned in points *D* and *C*, the length *l*, respectively *m* from the surface *B* of the workpiece [7]. The locator R_3 is positioned at length y_1 and cutting force acts at the distance y_2.

The work-piece clamping is done on the surface parallel to the locators R_1 and R_2, at distance *n* from the surface *B*, in the point *A*.

Thus, starting from the formula (1), on a range of variation of cutting force can be determined the clamping force diagrams, Fig. 20, depending on the position of the positioning surface *B*, the point of application of fixture force and values from the processing process.

$$F_{cl} = \frac{k - \mu \cdot (y_1 - y_2)}{2 \cdot \mu \cdot n} \cdot F_c \,. \qquad (1)$$

These diagrams are useful for establishing the necessary clamping force to ensure the maintenance of the work-piece, in a stable position throughout the processing. In the following is analyzed the case when the locator R_3 is positioned at the half height of the work-piece, $y_1 = 44$ mm, cutting force acting at a distance $y_2 = 75$ mm from the surface acting the locators R_1 and R_2. The friction coefficient is considered $\mu = 0.1$ and $k = 30$.

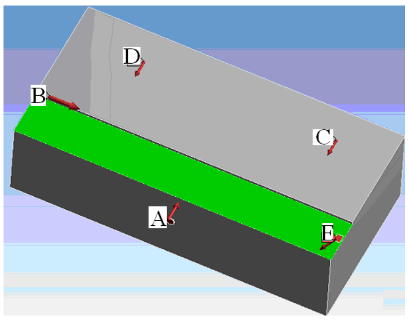

Fig. 19. Locating principle 3-2-1.

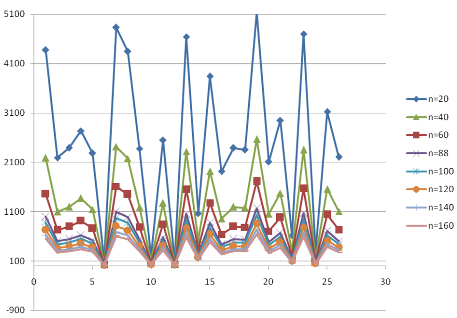

Fig. 20. Clamping force diagram.

4. NUMERICAL RESEARCHES REGARDING THE EVALUATION OF A CLAMPING DEVICE WITH NUT-SCREW MECHANISM

4.1. Modelling and functional-constructive analysis of fixture device with screw nut mechanism.

For a processing device to be used for work-piece fixture for processing must contain in its structure: elements with role orientation, additional supports, fixing elements or assemblies, control elements and guidance for tools, elements liaison with machine tools. Each component of the device fulfils a functional role in that assembly. The work-piece is positioned using three perpendicular planes, the principal one being the one on which the work-piece is laid [7]. This plane is realized by the motherboard 1 built in modular version, with T channels.

The secondary plane is the one on which a surface of the work-piece came into contact with 2 locators 2 and 3, and the tertiary is the one that contains a single support 4.

The orientation and fixation is done in a modular variant, with interchangeable components and reusable which are part of a set of modular elements SEM 64.

The locators 3, Fig. 21, are mounted in special bodies 4, which and are set on the motherboard 2 with the help of the screws and plates 5 which enters the T channels. Fixture is made with screw-nut mechanism, 6, which is mounted in a body (7) fixed to the motherboard. The boundary configuration used takes six degrees of freedom.

Because of the multidimensional modular elements to the device can be done certain adjustments required by the cutting parameters, work-piece shape and size, its position on the machine tool table, dimensional viewpoint adaptation, Fig. 22.

4.2. Determining the clamping force developed by the device.

The screw as a clamping element it is very used for manual clamping devices because of its advantages as: conservation of certain strength, the development of large forces, simplicity. The clamping force the device is able to develop is determined by the relationship:

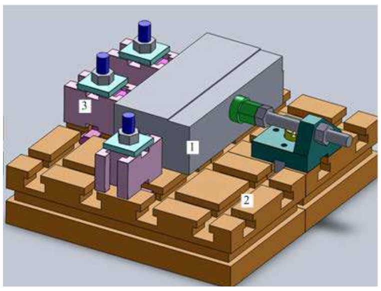

Fig. 21. Modular fixture device.

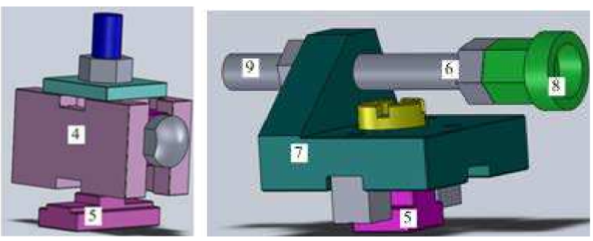

Fig. 22. Subasemblyes of the modular fixture device.

$$S = \frac{M}{\frac{d}{2}\tan(\alpha + \varphi_1) + \mu \cdot r} = k_1 \cdot M, \text{ [N]} \qquad (2)$$

where: M – clamping torque in Nmm; d – screw diameter, mm; μ – frictional coefficient, r – the contact section radius, mm, α and φ – geometrical parameters of thread.

4.3. The simulation of the analyzed device behaviour under the action of the forces.

With the help of the static analysis of mechanical structures can be determined the strain: specific, equivalent, maximum principal, minimum principal, tangential, maximum, strain, strain intensity, maximum specific strain, normal, tangential, strain energy, the main vector, thermal deformation, equivalent plastic strain specific tension: equivalent (von Mises), the main peak, the main medium, minimum main, tangential stress, intensity of stress, normal stress, tangential stress, the main error vector, response and local results [8]. For fastener structure were determined the total static deformation (Fig. 23) and equivalent stress (Fig. 24), when the clamping force provided by the device is 1 000 N.

4.4. The determination of the modal frequencies

Another important step in evaluating the performance of the device by numerical researches is the modal analysis, which is commonly used to determine the dynamic characteristics of structure analysis, namely frequencies and own vibrations modes [8].

This type of analysis is linear, and does not take into account the damping or external loads, the structure vibrating under the action of its own weight. After this analysis were determined its first six frequencies. The values are presented in Table 2.

Preload modal analysis aims to determine the dynamic characteristics of the structures, when considered as initial conditions due to static forces, which is preceded by a static analysis [8]. It is considered the contribution of the static stress due to changes in matrix stiffness.

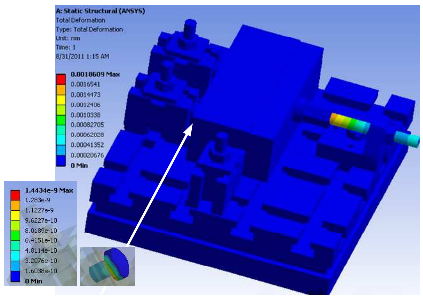

Fig. 23. Total static deformation.

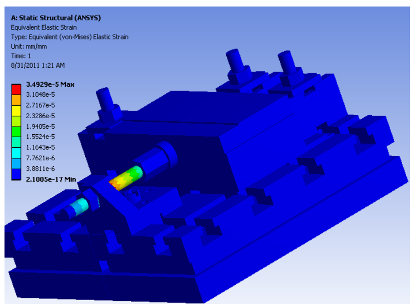

Fig. 24. Total equivalent stress.

Table 2

First six natural frequencies

No.	**Frequency** [Hz] **Modal analysis**	**Frequency** [Hz] **Preload modal analysis**
1	1 539.1	1 593.1
2	1 582.8	1 582.9
3	4 852.7	4 852.2
4	5 090.2	5 097.1
5	5 189.9	5 190.8
6	5 796.7	5 806.7

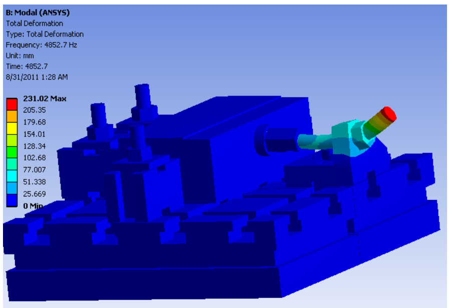

Fig. 25. The Third vibration mode.

This type of analysis is indicated for deep stressed structures or solicited to strong static compressive stress. After this kind of analysis the first six frequencies were determined and their values are presented in Table 2. From the analysis of obtained data by simulation, for the screw, it is found that the first vibration mode is the simplest, and corresponds to the static deformation and has no inflections points.

The second vibration mode is also a bending mode but in another plan. The third mode of vibration (Fig. 25) corresponds to the twisting of the front end. In mode 4 there is a first inflection point. As the mode of vibration increases its frequency, vibration mode of deformation complicates the contribution of total deformation mode decreases.

Structure does not vibrate after the first or the second mode, but after a linear combination of all modes of vibration. The first vibrations modes have the most important contributions.

5. CONCLUSIONS

In accordance with the actual standards the work-piece processing on CNC machine-tools is done by respecting dimensional precision, shape, quality and processing productivity conditions.

The assurance of these conditions it is influenced by the technologic system performances and the actuating, command and control equipment. Reason for that the fixture devices used for work-piece clamping must fulfil series of conditions such as simple construction, stiffness, flexibility, maintaining the work-piece position during processing under the cutting forces and moments action.

For evaluating the performances of some orientation and fixing devices it is necessary to go through some principal stages, like: analyzing the work-piece and of the technologic processing, of the process parameters and orientation and clamping surfaces, knowing and determine the loads, static and dynamic analysis through modelling and simulation of the most stressed elements from the device structure, in the most unfavorable case, the possibility of adapting the device for its integration in 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 developed by the device, when is known the actuation moment, applied with the help of a dynamometric key.

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 of processing, the form, dimensions and the work-piece material, the clamping device type.

Following the analysis of simulations results obtained and the current trend it is considered important the development of a methodology to ensure the monitoring of clamping force needed for safe operation of analyzed fixing device by including the basic structure of a strain sensor or transducer, providing a permanent signal on the state of deformation of the most requested item.

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