OPTIMIZATION ELEMENTS OF THE ADVANCE SLEDGE WITH NUMERICAL CONTROL

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În lucrare se prezintă unele contribuţii originale şi realizări practice ale autorului privind optimizarea unităţilor de lucru pentru realizarea mişcării de avans şi/sau poziţionare. Lucrarea investighează unele probleme pornind de la concepţia funcţională a unui produs şi continuă apoi cu aspecte care au în vedere: evaluarea optimizării structurii mecanice; analiza lanţului cinematic de avans; utilizarea metodei elementului finit la evaluarea unor variante constructive. În final se prezintă unele soluţii constructive performante concepute de către autor. Acestea au fost fabricate şi aplicate pentru unii clienţi din România.

The paper presents some of the author's original contributions and practical results regarding the optimization of work units for feed and/or positioning movement. It tackles some problems beginning with the functional conception of a product, and then continues with some issues regarding: evaluation of the mechanical structure optimization; analysis of the advanced kinematic chain; use of the finite element method to evaluate some constructive variants. The final part presents some constructive performance solutions that had been designed by the author. These had been manufactured and applied for some customers in Romania.

Keywords: product functional conception and design; optimization; advanced kinematic chain; finite element method; constructive performance solutions.

List of symbols

Symbol	Significance	
Fav	advance force	N
F_{Pr}	cutting force	N
F_i	inertial forces	N
F_f	friction forces	N
M_S	momentum needed to advance the screw axis	N· m
p	the pace of the feed screw	m
η_s	efficiency screw-nut mechanism	
i	the transmission ratio	
η_{mec}	efficiency of mechanical transmission	
M_M	momentum of the motor shaft	N· m
M_{SL}	momentum due to work load	N· m
n_s	screw speed	rot/min
n_{acc}	the electric motor speed	rot/min
v	speed for the screw-nut mechanism	m/sec

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$n_{max\ M}$	the maximum engine speed	rot/min
Ma	the momentum at acceleration	N· m
M_M	maximum moment of the advance electric motor	N· m
l_s	screw lenght between bearings	m
l_{TS}	total screw lenght	m
m_T	total mass in advance movement	kg
J_{RM}	moment of inertia of wheel from the electric motor axle	kg·m^2
J_M	the moment of inertia of the axle motor	kg·m^2
J_{Mred}	the moment of inertia reduced to motor shaft	kg·m^2
J_{TM}	the total moment of inertia of the motor shaft	kg·m^2
J_{TredM}	the total moment of inertia reduced to motor shaft	kg·m^2
J_{Mred}	*the* moment of inertia reduced to motor shaft	kg·m^2
M_{acc}	the total rotational moment during acceleration	N· m
J_{Tred}	the rotational moment of inertia reduced to the screw axis	kg·m^2
J_{Rs}	the moment of inertia of the wheel axle feed screw	kg·m^2
J_{TS}	the total moment of inertia at the center screw	kg·m^2
$Jred$	the moment of inertia reduced to the axis of rotation	kg·m^2
ε	angular motion	rad/sec^2
ω_M	motor angular velocity	rad/sec
ω_s	screw angular velocity	rad/sec
t	time	sec
φ_m	motor angle	rad
φ_s	screw angle	rad
x	the linear motion for the plate	m
φ_s	the angular motion of the screw	rad
J_S	the moment of inertia of the feed screw	kg·m^2
d_s	screw diameter	m
D_{RM}	diameter wheel on the motor shaft	m
$d_{i\ RM}$	inner diameter of the wheel on the motor shaft	m
l_{RM}	length of the wheel on the motor shaft	m
D_{RS}	diameter wheel on the screw shaft	m
$d_{i\ RS}$	inner diameter of the wheel on the screw shaft	m
l_{RS}	length of the wheel on the screw shaft	m
$i_{\text{opt acc}}$	the optimal transmission ratio to acceleration	
$p_{\text{opt acc}}$	the optimal pace of the feed screw to acceleration	m
C	stroke	m
a_{max}	maximum of acceleration	m/sec^2

1. Introduction

The main objective of this paper is to illustrate the author's original contributions and practical results regarding the optimization of work units for feed and/or positioning movement. Based on a brief literature review, the paper highlights the state of knowledge regarding the choosen subject. Optimization of some constructive performance solutions is one favourite topic in many papers dedicated to this subject [1]. The author applies the finite element method [2] for the evaluation of some constructive variants (presented in paragraph 6). AutoCAD is also used like in other papers [3].

2. The functional conception of a product

Within the functional conception frame, the researcher-designer, creator of new products, looks for optimum solutions to materialize every product functions and by joining elementary products (or the assembly as superior hierarchic levels made up of elementary products) obtains the new product, constructively optimized, so the new product conception is made on functions and it can be called functional conception. A member or a group of members can correspond to a function or it can materialize many functions, so the cutting up in pieces of product can be done based on technical judgements, but in some cases it can be made physically.

The optimization [4], [5] is done by denying present solutions (denying the present constructive shape, the technical level of the component elementary product), so the activity can be free of constraints and easy to be improved.

The difference between redesigning an existing product and designing a new product is given by the comparison between financial efforts and technical performances of the product in these two constructive variants.

Evaluation of optimization of specific work units to achieve the movement of advance and / or positioning

Further we will adapt the methodology and the principles used in value analysis to highlight the effects of optimising the mechanical structure specific to feed and/or position units through research-development-design [6], [7] by increasing their technical-economic level.

For the evaluation of feed and/or position units specific to the mechanical structures, the technical-economic level of the product that illustrates the relation between the technical level of the product (measured by varying the technical dimensions of the product functions in the two variants) and the financial effort done in order to obtaine the product (expressed in monetary units) are introduced as an optimization criterion. This ratio must be maximized. Calculating the technical level variation between two variants of sled advance (classical building and construction CNC) one finds that the technical level of sledge advance with CN, is 2.9 times higher than the level of a classic technical construction sled advance.

3. Analysis of advanced powertrain specific work units to achieve the movement of advance and / or positioning

In the following analysis it will be considered an advance driveline [8], from the forward kinematic chain of sled advance (Fig.1) designed by author and made a machine tool for working-group aggregate caps for the automotive industry levels.

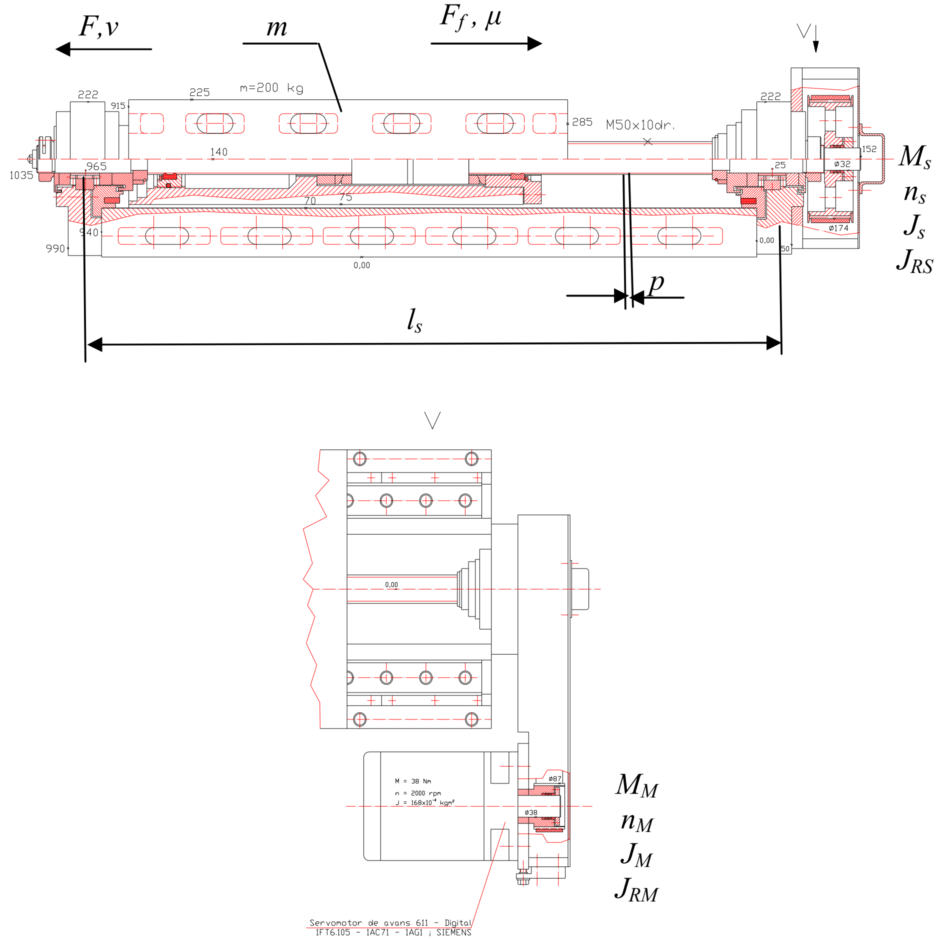


Fig.1. Kinematic chain of advance sledge SAN 500x250

As measured by kinematic, movement is transmitted from the advance actuator (the advance actuator can be characterized by M_M , - when the electric motor shaft, n_M (rpm) - electric motor speed, J_M , - the moment of inertia at motor shaft power) through a toothed belt reducer comprises a fixed wheel axle electric motor (characterized by J_{RM} - the moment of inertia of the wheel axle electric motor) and a wheel (characterized by J_{RS} - the moment of inertia of the wheel axle bolt) fixed on the screw shaft screw-nut mechanism advance.Advance Force (Fav) , is determined by taking the necessary process of cutting force (F_{Pr}), inertial forces (F_i) and the friction (F_f).

The moment needed to advance the screw axis (M_S) is determined by applying the condition that the mechanical work in the rotation is equal to work done of translation considering the pitch of the feed screw (p) and efficiency of screw-nut mechanism (η_s):

$$M_s \cdot 2\pi \cdot \eta_s = F_{av} \cdot p \tag{1}$$

Knowing the transmission ratio (i) and toothed belt reducer efficiency of mechanical transmission (η_{mec}) one can determine the moment due to work load (M_{SL}):

$$M_{SL} = 1/\eta_{mec} \cdot 1/i \cdot M_s \tag{2}$$

and the momentum of the motor shaft (M_M) is chosen greater than or equal to momentum due to work load (M_{SL}).

Taking into account the transmission ratio (i) and screw speed (n_s) it is possible to determine the speed of the electric motor speed (n_{acc}):

$$n_{acc} = i \cdot n_s \tag{3}$$

The speed for the screw-nut mechanism (v) is:

$$\mathrm{v} = n_s \cdot p \tag{4}$$

$$n_s = \mathrm{v}/p \tag{5}$$

Thus, it results that the electric motor speed (n_{acc}) in acceleration is:

$$n_{acc} = i \cdot \mathrm{v}/p \tag{6}$$

The maximum engine speed ($n_{max\,M}$) is chosen such as:

$$n_{max\,M} \geq n_{acc} \tag{7}$$

In order to analyze the dynamics of advanced kinematic chain we need to start from the equation of rotational motion acceleration time. Thus we have to take into account:

- the moment at acceleration (M_a);
- the moment of inertia reduced to the axis of rotation (J_{red});
- angular motion ($\varepsilon = \mathrm{d}^2\varphi_M/\mathrm{dt}^2$);
- motor angular velocity($\omega_M = \mathrm{d}\varphi_M/\mathrm{dt}$);
- screw angular velocity ($\omega_s = \mathrm{d}\varphi_s/\mathrm{dt}$)
- the speed shelf linear sled that is equal to the speed for the screw-nut mechanism ($v = n_s \cdot p$). On these basis we obtain the following equations:

$$M_a = J_{red} \cdot \varepsilon = J_{red} \cdot d^2\varphi_M / dt^2 \tag{8}$$

$$i = \omega_M/\omega_s = d\varphi_M/dt / d\varphi_s/dt \tag{9}$$

$$d\varphi_M/dt = i \cdot d\varphi_s/dt \tag{10}$$

The equation for the linear motion of the plate (x) is:

$$x = v \cdot t \tag{11}$$

The equation for the angular motion of the screw (φ_s)

$$\varphi_s = \omega_s \cdot t \tag{12}$$

Dividing (11) to (12), it yield:

$$x/\varphi_s = v \cdot t/ \omega_s \cdot t \tag{13}$$

$$J_{Rs} + J_S + m \cdot p^2/4\,\pi^2 - (J_M + J_{RM}) \cdot i^2 = 0 \text{ or} \tag{14}$$

$$d^2\varphi_s / dt^2 = d^2x / dt^2 \cdot 2\,\pi / p \tag{15}$$

Based on relations (8), (9) and (10) one obtains the acceleration (M_a):

$$M_a = J_{red} \cdot i \cdot \varphi_S = J_{red} \cdot i \cdot d^2x /dt^2 \cdot 2\,\pi / p \tag{16}$$

Hence the acceleration for the linear motion ($a = d^2x/dt^2$) of the plateau is:

$$d^2x / dt^2 = p/2\,\pi \cdot 1/i \cdot M_a/ J_{red} \tag{17}$$

If we consider that the plateau sled has a mass m and it moves with a linear velocity v ($v=n \cdot p$) and if the screw feed mechanism has the angular velocity ω_s , ($\omega_s=2\,\pi \cdot n$) by equalizing the translational kinetic energy to the rotational kinetic energy then it results (J_{Tred}) the rotational moment of inertia reduced to the screw axis :

$$m \cdot v^2/2 = J_{Tred} \cdot \omega_s^2/2 \tag{18}$$

$$J_{Tred} = m \cdot (p/2\,\pi)^2 \tag{19}$$

The total moment of inertia at the center screw (J_{TS}) is determined as the sum of the moment of inertia of the wheel axle feed screw (J_{RS}), the moment of inertia of feed screw (J_S) and J_{Tred}:

$$J_{TS} = J_{Rs} + J_S + J_{Tred} \tag{20}$$

By considering $i = \omega_M/ \omega_s$, and by equalizing the kinetic energy of the resulting moment of inertia reduced to motor shaft (J_{Mred}) then it results:

$$J_{TS} \cdot \omega_s^2/2 = (J_{Mred} \cdot \omega_M^2)/2 \tag{21}$$

$$J_{M\,red} = J_{TS} \cdot 1/i^2 \tag{22}$$

The total moment of inertia of the motor shaft (J_{TM}) is obtained as a sum of the moment of inertia of the axle motor (J_M) and the moment of inertia of the wheel from the axle motor (J_{RM}):

$$J_{TM} = J_M + J_{RM} \tag{23}$$

The total moment of inertia reduced to motor shaft J_{TredM} is obtained as a sum of the total moment of inertia of the motor shaft J_{TM} and the moment of inertia reduced to motor shaft J_{Mred}:

$$J_{TredM} = J_{TM} + J_{M\,red} \tag{24}$$

$$J_{TredM} = J_M + J_{RM} + J_{TS} \cdot 1/i^2 \tag{25}$$

Starting from the equation of the total rotational momentum during acceleration (M_{acc}) it results:

$$M_{acc} = J_{TredM} \cdot \varepsilon = J_{TredM} \cdot d^2\varphi_M/dt^2 \tag{26}$$

$$i = \omega_M/ \omega_s = d^2\varphi_M/dt^2/ d^2\varphi_s/dt^2 \tag{27}$$

$$i \cdot d^2\varphi_s / dt^2 = d^2\varphi_M/dt^2 \tag{28}$$

As $d^2\varphi_s / dt^2 = d^2x / dt^2 \cdot 2\,\pi / p$ it results that:

$$d^2\varphi_M/dt^2 = i \cdot d^2x / dt^2 \cdot 2\,\pi\,p\,. \tag{29}$$

If we insert the relation (28) within relation (25) then it results:

$$M_{acc} = J_{TredM} \cdot i \cdot d^2x / dt^2 \cdot 2\,\pi / p \tag{30}$$

Based on that relation it follows that:

$$d^2x / dt^2 = p/2\,\pi \cdot 1/ i \cdot M_{acc} / J_{TredM} \tag{31}$$

If within equation (30) it is considered that $M_{acc} = M_M$ then by replacing J_{TredM} , J_{TM} , J_{TS} it results the following equation for acceleration:

$$d^2x / dt^2 = M_M/2\,\pi \cdot i \cdot p/ [(J_M + J_{RM}) \cdot i^2 + J_{Rs} + J_S + m \cdot p^2/4\,\pi^2] \tag{32}$$

In order to reach the maximum acceleration, the derivatives of acceleration with respect to *i,* respectively to *p* needs to be equal to zero:

$$J_{Rs} + J_S + m \cdot p^2/4\,\pi^2 - (J_M + J_{RM}) \cdot i^2 = 0 \tag{33}$$

$$(J_M + J_{RM}) \cdot i^2 + J_{Rs} + J_S - m \cdot p^2/4\,\pi^2 = 0 \tag{34}$$

It follows that:

$$i_{opt\,acc} = \sqrt{\frac{J_{Rs} + J_S + \frac{m \cdot p^2}{4 \cdot \pi^2}}{J_M + J_{RM}}} \tag{35}$$

$$p_{opt\,acc} = \sqrt{\frac{\left[J_{Rs} + J_S + \left(J_M + J_{RM}\right) \cdot i^2\right]}{\frac{m}{4\pi^2}}} \tag{36}$$

4. Application for SAN 500x250

The *SAN* 500x250 case may be taken into account in the analysis. The following data is considered: m_T = 890 kg; $J_M = 168 \cdot 10^{-4}$ kg·m^2; M_M = 38 N·m; $l_s = 995 \cdot 10^{-3}$m; $l_{TS} = 1185 \cdot 10^{-3}$m; $d_s = 50 \cdot 10^{-3}$m; *i* – the transmission ratio has variable values; *p* –variable values; $D_{RM} = 88{,}92 \cdot 10^{-3}$m; $d_{i\ RM} = 38 \cdot 10^{-3}$m; $l_{RM} = 65 \cdot 10^{-3}$m; $D_{RS} = 177{,}87 \cdot 10^{-3}$m; $d_{i\ RS} = 32 \cdot 10^{-3}$m; $l_{RS} = 59 \cdot 10^{-3}$m. Based on this data, the kinematic chain advance for *SAN* 500x250 can be analyzed in terms of tracking how the acceleration is affected by the constructive parameters of the advance sled. If it is inserted into the acceleration equation with *p* constant and *i* variable respectively *i* constant and *p* variable then two families of curves are obtained. These curves (presented in fig. 2 and fig. 3) illustrate how acceleration varies with respect to the the two parameters. Considering this data the acceleration equation:

$$a = 50/2\pi \cdot i \cdot p/(0{,}0193 \cdot i^2 + 22{,}57 \cdot p^2 + 0{,}041) \tag{37}$$

For each pair of parameters (*p* constant and *i* variable) taking one value for *p* it results a curve for each of them. This curve has a maximum point ($i_{opt\ acc}$) meaning there is a value of *i* for which the acceleration is maximum. Similarly for each pair of parameters (*p* variable and *i constant*) taking a value for *i* it results a curve which has a maximum $p_{opt\ acc}$. This means there is a value for i for which the acceleration is maximum.

If this is solved with respect to p then one obtain the following equation:

$$p_{1,2} = \frac{i \pm \sqrt{i^2 - a^2 \cdot (0{,}022 \cdot i^2 + 0{,}056)}}{5{,}6 \cdot a}. \quad (38)$$

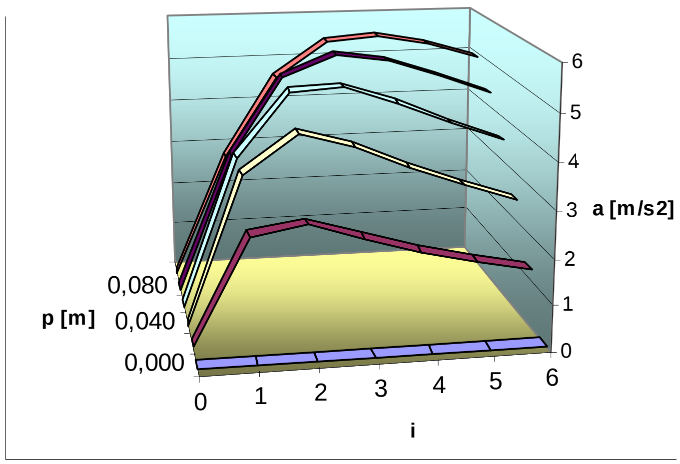


Fig.2. Variation of the acceleration with p_{const} i_{var}

If one solves it with respect to i, then one obtains the following equation:

$$i_{1,2} = \frac{p \pm \sqrt{p^2 - a^2 \cdot (0{,}022 \cdot p^2 + 0{,}00004)}}{0{,}0004 \cdot a} \quad (39)$$

$p_{opt\ acc}$; $i_{opt\ acc}$ are expressed as:

$$i_{opt\ acc} = \sqrt{\frac{22{,}57 \cdot p^2 + 0{,}041}{0{,}0193}} \quad (40)$$

$$p_{opt\ acc} = \sqrt{\frac{0{,}0193 \cdot i^2 + 0{,}041}{22{,}57}} \quad (41)$$

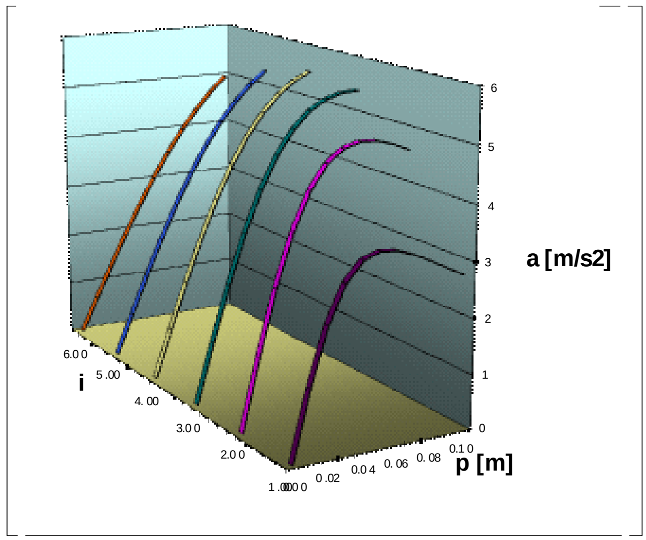


Fig.3. Variation of the acceleration with i_{cunst} p_{var}

In some practical situations, when one of the parameters *i* or *p* is constructively adopted, one can determine the optimum value of the other

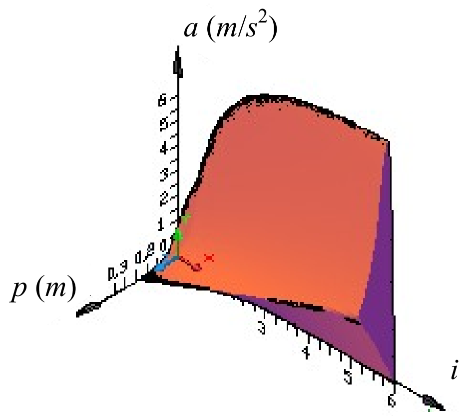


Fig.4. Acceleration represented as the outer surface of a solid

parameter that maximizes (optimizes) the acceleration.A plot of the equation that defines the acceleration as the outer surface is shown in Fig.4.

If sections are parallel to the base plane with different values of acceleration the plot from Fig.5 is obtained.

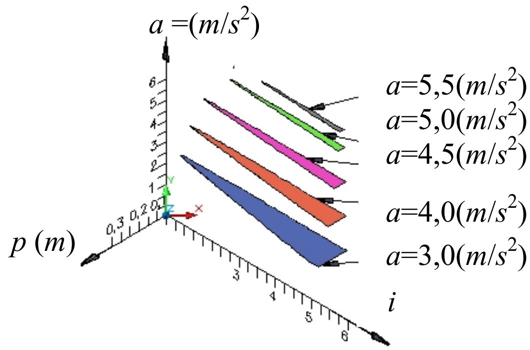


Fig.5. Sections through the outer surface of the solid which represents the acceleration

If we focus on the outer surface of the solid, the curves that are generated in Fig.6 are obtained.

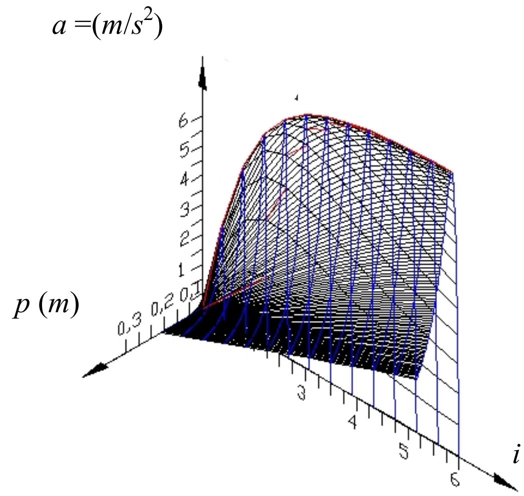


Fig.6. Curves generating the outside surface representing the acceleration

From the analysis of the graphs we can observe that the surface representing the acceleration presents a maximum, which is found where the derivatives of the acceleration with respect to i and p are canceled.

For the constructive solution taken into the analysis, at the screw pitch taken constructively equal to 10 mm, $i_{opt} = 2$ and $a_{max} = 1.3$ m/sec^2.

5. The finite element method used for the evaluation of some constructive variants

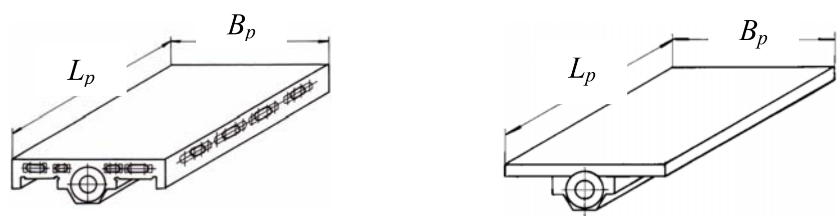
For the utilization of optimization techniques in design one should have enough time for elaboration of alternative constructive variants. In this case, we highlight the use of finite element method for the evaluation of two constructive variants of structure element plate type, in the work unit frame, type feed and/or positioning slide designed by the author of the paper, for a special machine-tool with ring rotary table and central column, for machining the bearing lid group, cylinder carter, for an automobile plant.

These two analysed constructive variants are:

- variant 1: cast construction, used in feed slide SAN 500 x 250 frame (Fig. 7.a);
- variant 2: plate type (Fig. 7.b)

To load the working unit we took into consideration the fact that the machining of drilling was done with a drill $\Phi 20 \cdot 10^{-3}$m with feed of $0.16 \cdot 10^{-3}$m /rot of a member of grey cast iron with $\sigma_r = 2000 \cdot 10^6$ N/m^2, resulting in a feed force of 2500 N.

It was considered that the feed force acts in the feed slide tableaxis at a height of $250 \cdot 10^{-3}$m from the table surface. To determine the behaviour of these two variants we used an adequate computer programme and the finite element method.



a) b)

Fig.7. Constructive variants of table of feed slide (a- cast construction table variant , b- table variant type plate)

The steps were:

- to design in AutoCAD these two constructive variants (fig. 8- the casted piece);
- to highlight the loads and the constraints on the member for each constructive variant;
- to determine the stress and strains that occur in the structure for each constructive variants, as a result of external loads.

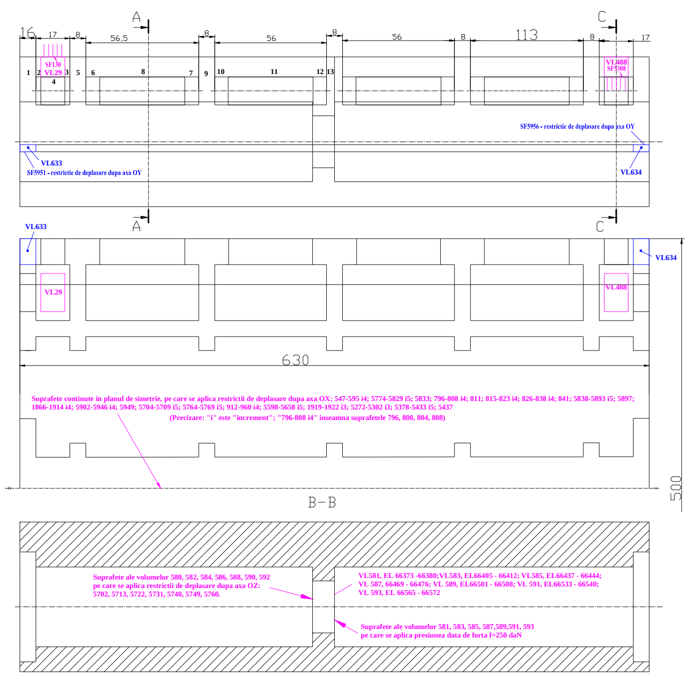


Fig.8. Plateau representation of the casted piece in ACAD

Using colours for each constructive variant the post procesor of the used programme used highlights the structure representation underlining stress (for the piece represented without and with deformations) and the structure stresses deformation (for the piece represented without and with deformations).

The research allows choosing an adequate constructive variant, as a function of the dimension of the external solicitation and of the efforts allowed by the analysed member. Fig. 9 and fig. 10 present in parallel the tension state and the deformation state for these two constructive variants. To reduce the work volume on the computer, and taking into consideration the symmetry of the member and the symmetry of the charge, the analysis is performed on half of the longitudinal member-section. The research allowed choosing a fit constructive variant, as a function of the dimension of the external solicitation and respectively by the allowable stress of the analyzed piece.

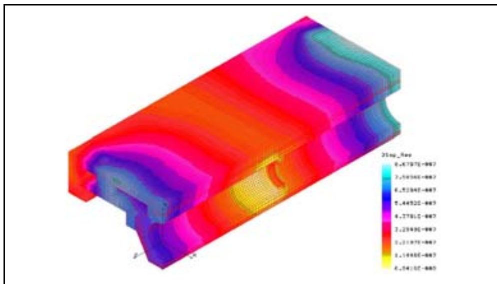
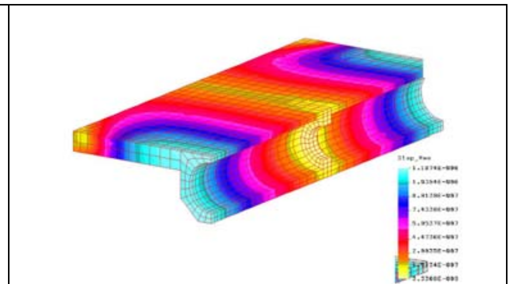
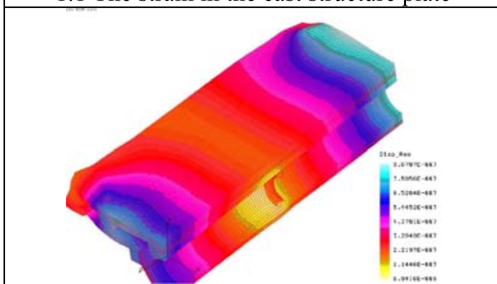
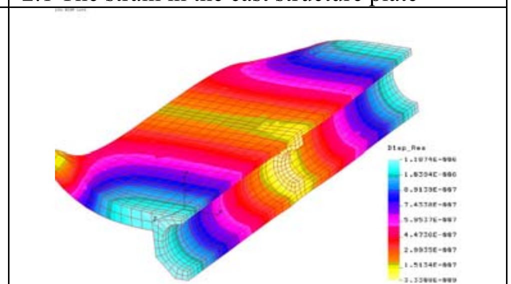
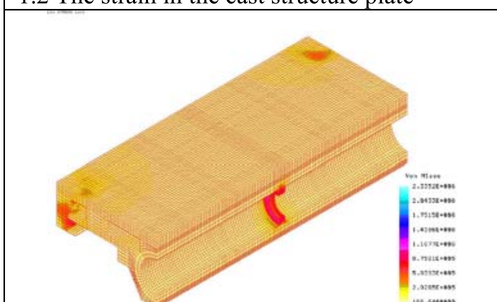
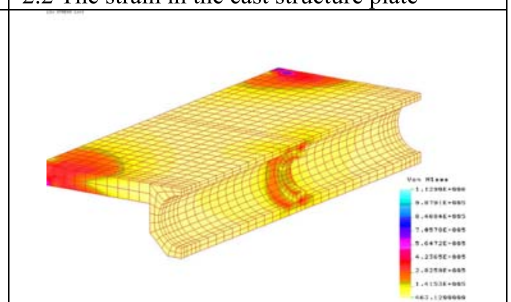
	
1.1 The strain in the cast structure plate	2.1 The strain in the cast structure plate
	
1.2 The strain in the cast structure plate	2.2 The strain in the cast structure plate
	
1.3 The stress in the cast structure	2.3 The stress in the plate type plate

Fig. 9. The stress and strain states for two plate types with the same dimension and load

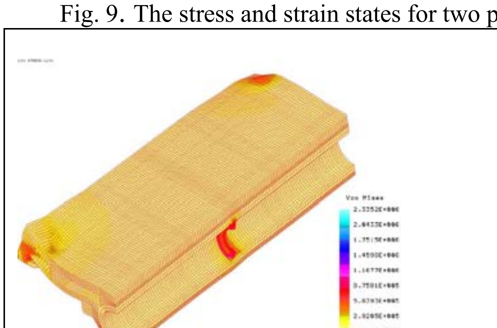
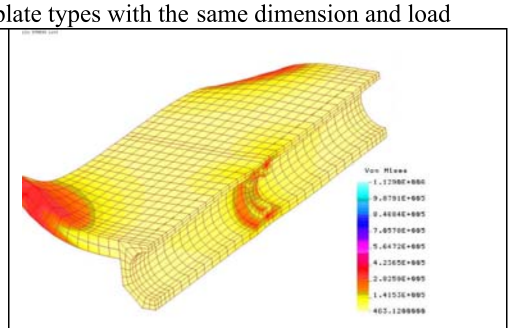
	
1.4 The stress in the cast structure	2.4 The stress in the plate type plate

Fig. 10. The representation of deformation state and stress state for two plate types with the same dimension and load

6. Examples of constructive performance solutions for achievingmovement of advance and / or positioning

Work units with radial module, with numerical control are usualy composed of an advance sledge on the principal axis Z and a main shaft with numerical control for the secondary axis U.Between the numerical controled advance sledge and the module for radial feed there are obvious constructive and functional similarities .

The module for radial feed (the plate designed by the author, for numerical control , is composed of efficient constructive elements with high loading capacities with small dimensions (optimized constructive solutions as compared to classical solution). Radial feed module is used in a machine for processing multifactor valve body (Fig. 11).

Fig.11**.** Processing machine for valve body multifactor

The module for radial feed turning (the plate Φ125, stroke work C=3 mm) designed by the author, is mounted on the front side of the spindles and transforms the movement after spindle axis direction of the element from the driving mechanism, into movement after radial direction, orthogonal on spindle axis of the plate (slideway) of turning module and through that on the tool-support and turning cutter point. The stroke of the turning mode plate is 3mm. The guideway of turning module plate with radial feed is done with linear guideway with balls SGL 15 F. Radial feed module is used in a machine for boring assembled branch rod (Fig. 12).

Fig.12. Special machine for boring asambled branch rod

The driving mechanism of turning module with radial feed is mounted on rear side of the spindle and ensures the axial movement, which in turning module with radial feed, is transformed in radial movement of turning module plate.The feed mechanism is the ball screw-nut type, with rotary nut, with bearings type 7011 ATA P4 DB-UM and screw fixed on a guide support on a linear ball guideway, preloaded, STAR 15.

The connection between the mechanism that transforms the axial movement into radial movement and driven mechanism of turning mode is done with one rod and one bearings set type 7206-BDB-UM-P5.

7. Conclusions

In conclusion, the paper highlights several original elements for optimizing working units to carry out advance movement or positioning with numerical command. The paper focus on the importance of analyzing the advance kinematic chain, by using specific software programmes. In order to choose the constructive variant of some structure elements (as for example the plateau type of the advance sledge) the finite element method was used.

The paper disseminates only some of the results obtained during the research and design activity included in the programme dedicated to the author's PhD dissertation paper. Based on the research and design activity some examples of constructive performance solutions for achieving movement of advance and/or positioning and present machine tools that use these modules one describe in chapter 6.The constructive solutions presented are original and had been designed by the author. My results applied for some customers in Romania prove the utility of the solutions presented. The solutions had been considered helpful by the customers that had requested them. The modules and working units are functioning with efficient results that are well appreciated by customers on the national economy level. The constructive solutions have a novelty character at least at the national level and they might be patentable as other of the previous research of the author [9] [10]. They are in line with the current state of knowledge on the national level regarding the design of modules and working units for achieving the advance movement and/or positioning. In the future, the author will focus more for developing a range of standard modules work.

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