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Model za analizo in optimiranje vpenjalnih priprav

A Model for Analysing and Optimazing Fixtures

Uroš Župerl - Franci Čuš

V prispevku je predstavljen nevronsko-analitični model za analizo in racionalizacijo vpenjalnih priprav, primernih za vpenjanje tankostenih izdelkov, pri katerih obstaja med obdelavo velika verjetnost deformacije zaradi vpenjalnih in rezalnih sil. Izdelan je program FIXAN, ki ovrednoti vpenjalno shemo in izračuna optimalne vrednosti in položaje vpenjalnih ter podpornih sil, ki so potrebne, da je obdelovanec varno vpet med obdelavo. Model je primeren za analizo vpenjalnih priprav, namenjenih za vpenjanje prizmatičnih in rotacijsko simetričnih izdelkov.

Model upošteva trenje, ki se pojavi med obdelovancem in elementi vpenjalne priprave. Hitrost izračuna je zaradi uporabe umetnih nevronskih mrež (UNM) zelo velika, zato je postopek mogoče izvesti v realnem času.

Z opisanim postopkom zmanjšamo čas snovanja vpenjalne priprave in preprečimo napake in deformacije med postopkom obdelave.

(Ključne besede: naprave vpenjalne, frezanje, optimiranje, mreže nevronalne)

This paper is about a neural–analytical model for the analysis and rationalization of fixtures that are suitable for clamping thin-wall products likely to undergo deformation due to the clamping and cutting forces that occur during machining. A program called FIXAN was used for the evaluation of the fixturing scheme and for the calculation of the optimum magnitude and positioning of the clamping forces required to enable the workpiece to be safely clamped during machining. The model is suitable for the analysis of fixtures intended for the fixing of prismatic and rotational products.

The model takes into consideration the friction occurring between the workpiece and the fixture components. Because of the use of an artificial neural network (ANN) the time needed for the calculation is very short, therefore, the procedure can be carried out in real time.

The described procedure ensures a reduction of the fixture-planning time and the prevention of defects and deformations during the machining process.

(Keywords: fixture analysis, milling, optimization, neural networks)

0 UVOD

Snovanje vpenjalnih priprav je zapleten in domiselen postopek, ki zahteva izkušenega tehnologa. Za vsak izdelek obstaja več mogočih izvedb vpenjalnih priprav, zato je obseg mogočih rešitev velik.

Razvoj umetne inteligence je prispeval k omejevanju obsega mogočih rešitev in s tem k doseganju boljših izvedb. Umetna inteligenca ponuja različne tehnike za rešitev problema snovanja vpenjalnih naprav. Najpomembnejši sta prigodno razsojanje (case–based reasoning) in ekspertni sistemi. Vendar ti dve tehniki ne zagotovita vedno optimalne rešitve. Bolj uspešni so sistemi, ki

0 INTRODUCTION

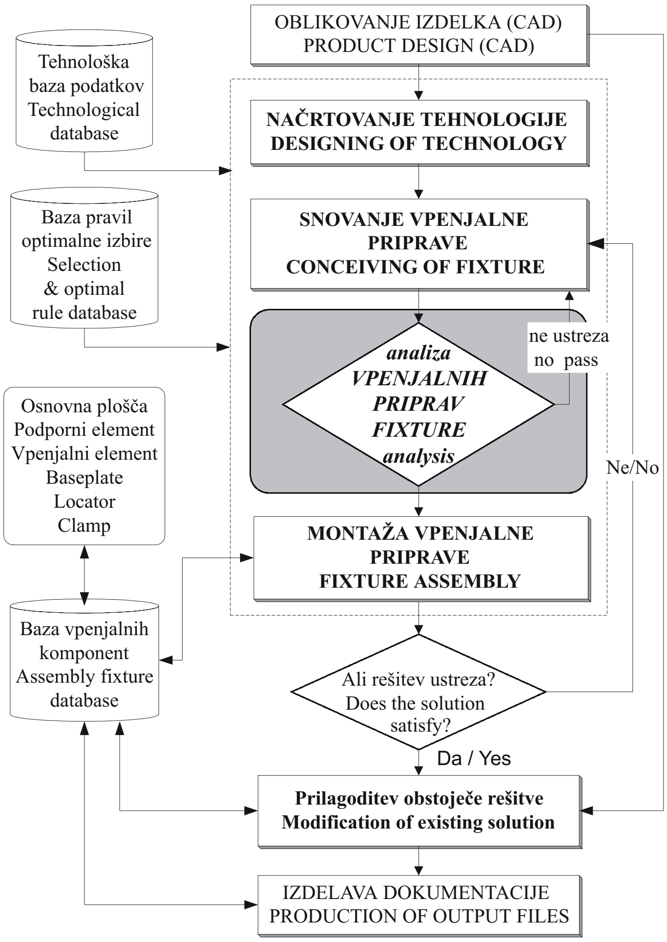
The designing of fixtures is a complex and intuitive process for which an experienced technologist is required. For each workpiece there are several possible solutions of the design for modular fixtures, therefore, the number of possible solutions is large.

The development of artificial intelligence has contributed to limiting the number of possible solutions and, consequently, to achieving better designs. Artificial intelligence offers various methods for solving the problem of fixtures' design. The most important methods are the case-based reasoning and the expert systems. However, these two methods do not always provide the best fixture solutions. The systems that use a uporabljajo kombinacijo več tehnik, npr. genetski algoritmi in nevronske mreže. Naloga računalniško podprtega sistema za snovanje vpenjalnih naprav [8] je izbrati pravilno kombinacijo osnovnih modularnih vpenjalnih elementov, jih postaviti in sestaviti na ustrezno mesto, tako da bo obdelovanec pri obdelavi varno vpet.

Opisan sistem (sl. 1) vsebuje modul za analizo vpenjalne priprave. Zmogljivejši moduli ponujajo tudi možnost racionalizacije in optimizacije dobljene rešitve. Po navadi izračun temelji na metodi analize sil, opremljeni z optimizacijskim postopkom.

combination of several methods, such as genetic algorithms and neural networks, are more successful. The task of the computer-supported system [8] for designing the fixtures is to select the correct combination of basic modular fixtures and to locate and assemble them in an appropriate place so that the workpiece will be safely fixed during machining.

Such a system (Figure 1) contains a module for the analysis of the fixture. These highly capable modules also offer the possibility to rationalize and optimize the obtained fixture solution. Usually, the calculation is based on the force analysis method provided with the optimization process.



Sl. 1. *Zgradba avtomatiziranega sistema za izbiro, analizo in montažo vpenjalnih priprav*
Fig. 1. *Structure of the automated system for the selection, analysis and assembly of fixtures*

1 DOSEDANJE RAZISKAVE IN UGOTOVITVE

Poleg iskanja matematičnih rešitev za pozicioniranje in vpenjanje obdelovancev, poteka razvoj v smeri iskanja rešitve z uporabo računalniške rutine ([4] in [5]). Raziskovalci so nedavno predlagali model “obdelovanec-vpenjalna priprava”, ki temelji na osnovi “screw theory” in uporabili metodo linearnega programiranja za določitev vpenjalnih sil [3]. Mittal predlaga dinamični model “vpenjalna priprava-

1 CURRENT RESEARCH AND FINDINGS

In addition to searching for a mathematical solution for the positioning and clamping of workpieces the development is oriented towards searching for solutions by means of a computer routine ([4] and [5]). Recently, researchers [3] proposed a “workpiece-fixture” model based on the screw theory and used the linear programming method for a determination of the clamping forces. Mittal proposed the dynamic “fixture-workpiece” model to determine obdelovanec” za določitev potrebnih vpenjalnih sil, ki so potrebne, da je obdelovanec med obdelavo v ravnotežju [1]. Vse naštete metode uporabljajo poenostavljene modele, ki ne upoštevajo trenja pri svojih izračunih. Rezultati so le približni.

the required clamping forces needed for equilibrium of the workpiece during machining [1]. All the above-mentioned methods use simplified models that do not take friction into account in their calculations. The results are only approximate.

2 TEORETIČNA IZHODIŠČA PRI IZDELAVI MODELA

2 A THEORETICAL ASSUMPTION USED IN MAKING THE MODEL

Pri izdelavi modela je bilo predpostavljeno, da bo obdelovanec vpet s prilagodljivo modularno vpenjalno pripravo, ki omogoča vpenjanje obdelovancev različnih oblik. Predpostavljeno je, da sta obdelovanec in vpenjalna priprava togi telesi.

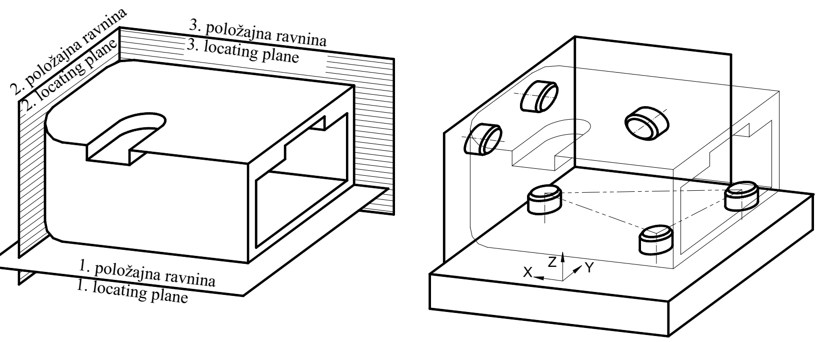
When making the model it was assumed that the workpiece would be fixed by a flexible modular fixture to ensure that workpieces with different shapes could be clamped. The fixture and the workpiece are assumed to be rigid bodies.

2.1 Vpenjalno načelo

2.1 Clamping principle

Pri izdelavi modela je bilo uporabljeno za vpenjanje vpenjalno načelo 3-2-1 (sl. 2), ki zahteva tri lokatorje na osnovni položajni ravnini, dva lokatorja na drugi položajni ravnini in en lokator na tretji položajni ravnini.

The clamping principle 3-2-1, which requires three locators on the first locating plane, two locators on the second locating plane and one locator on the third locating plane (Figure 2), was used for making the model.



Sl. 2. *Uporabljen vpenjalno načelo 3-2-1 za vpenjanje prizmatičnih obdelovancev*
Fig. 2. *The 3-2-1 clamping principle used for clamping the prismatic workpieces*

2.2 Vpliv vpenjalnih sil na shemo vpetja

2.2 The influence of clamping forces on the clamping scheme

Vpenjalna sila mora biti dovolj velika in ustrezno usmerjena, da se lega obdelovanca med obdelavo zaradi rezalnih sil ne spremeni. Vpenjalne sile na obdelovancu ne smejo ustvarjati notranjih napetosti in poškodovati oziroma deformirati površine obdelovanca. Dovoljene deformacije smejo biti takšne, da je izdelek po postopku obdelave znotraj predpisanih tolerančnih vrednosti. Vpenjalne sile delujejo vedno proti podporam, na katerih je podprt obdelovanec.

The clamping force must be large enough and suitably oriented so that the workpiece’s position does not change during machining due to the cutting forces. The clamping forces on the workpiece’s are not allowed to create internal stresses and to damage or deform the workpiece surface. The permissible deformation may be such that after machining the product is within the specified tolerance values. The clamping forces always act towards the locators on which the workpiece is supported.

2.3 Rezalne sile

2.3 Cutting forces

Izračun rezalnih sil je izveden po nevronskem modelu za simuliranje rezalnih sil [7]. Analitično modeliranje rezalnih sil [2] je težavno zaradi velikega števila medsebojno odvisnih obdelovalnih parametrov. Namesto poskusov iskanja analitičnih povezav med obdelovalnimi

The calculations of the cutting forces are made according to the neural network model for the simulation of cutting forces [7]. Analytical cutting-force modelling [2] is difficult due to the large number of interrelated machining parameters. Instead of attempting to find analytical relationships between parametri s statistiko, je uporabljeno strojno učenje.

Izdelava modela temelji na izvedenih eksperimentalnih meritvah rezalnih sil pri frezanju.

Za modeliranje rezalnih sil so bile uporabljene usmerjene nevronske mreže (UNM) s tremi nivoji. Vsebovale so 11 nevronov v vhodni ravni in 3 nevrone v izhodni ravni. Pri preskusih se je število nevronov v skritem nivoju spreminjalo.

Učenje UNM je bilo izvedeno z naslednjimi parametri: material obdelovanca, trdota obdelovanca, premer orodja, tip ploščice, rezalna hitrost, podajanje, prečna in vzdolžna globina rezanja, obraba orodja, komponente rezalne sile. Med postopkom učenja so bili UNM posredovani tudi želeni izhodi (tri komponente rezalne sile). Učenje UNM je bilo izvedeno z neobdelanimi eksperimentalnimi podatki, pri čemer je bilo uporabljenih 3500 popolnih učnih primerov.

3 MODEL ZA ANALIZO IN OPTIMIRANJE VPENJALNIH PRIPRAV

Razvit model je uporaben pri snovanju vpenjalnih priprav, saj lahko v kratkem času rutinsko določi optimalne velikosti, smeri in prijemališča vpenjalnih in podpornih sil za različne vpetostne primere. Naloga modela je, da preveri (analizira) dobljeno rešitev (konfiguracijo vpenjalne priprave), jo potrdi oziroma zavrne, če niso izpolnjeni vsi zastavljeni pogoji.

Namen modela je izboljšati izvedbo vpenjalne priprave in s tem povečati geometrijsko natančnost izdelanega tankostenega izdelka. Pomembno je upoštevati rezalne sile in vpenjalne sile ter izmere in razpoložljivost vpenjal, kakor tudi delovni prostor na stroju, ki omejuje možnosti vpetja.

Pri izdelavi programa FIXAN je bilo znanje izbrano iz literature (proizvajalci vpenjal) in od izvedencev iz prakse v proizvodnji. Pomemben vir znanja so že izdelani in preverjeni tehnološki postopki.

Stroški za načrtovanje in izdelavo vpenjalne priprave znašajo tudi do 15% celotnih proizvodnih stroškov [6]. Nadalje, če se pozicioniranje in fiksiranje izdelka ne da izvesti z zmernimi stroški, ali ne zadostimo zahtevam postopka, potem postopek obdelave ni upravičen. Zmanjševanje stroškov in časa za načrtovanje postopka vpenjanja je največje gonilo za sistematično načrtovanje vpenjalnih priprav.

Program FIXAN določi (sl. 3):
- minimalno število in položaj podpornih in vpenjalnih elementov,
- gibanje, ki ga dovoljujejo podporni elementi,
- reakcije na mestih stika "obdelovanec-vpenjalna priprava" (podporne sile),
- minimalne vpenjalne sile, potrebne za uravnoteženje rezalnih sil.

the machining parameters using statistics, machine learning is used.

The development of the model is based on the measurements of cutting forces during milling.

For modeling the cutting forces, three-layer feed-forward artificial neural networks (ANNs) were used. They contained 11 neurons in the input layer, and 3 in the output layer. The number of neurons in the hidden layer was varied in the experiments.

The ANNs were trained with the following parameters: type of machined material, hardness of the machined material, cutting tool diameter, type of insert, cutting speed, feed, radial and axial depth of cutting, tool wear, and components of cutting force. The desired outputs (the three cutting-force components) of the network also being supplied during training. Training of the ANN was made with raw experimental data from 3500 full training examples.

3 PRESENTATION OF THE MODEL FOR THE ANALYSIS AND OPTIMIZATION OF FIXTURES

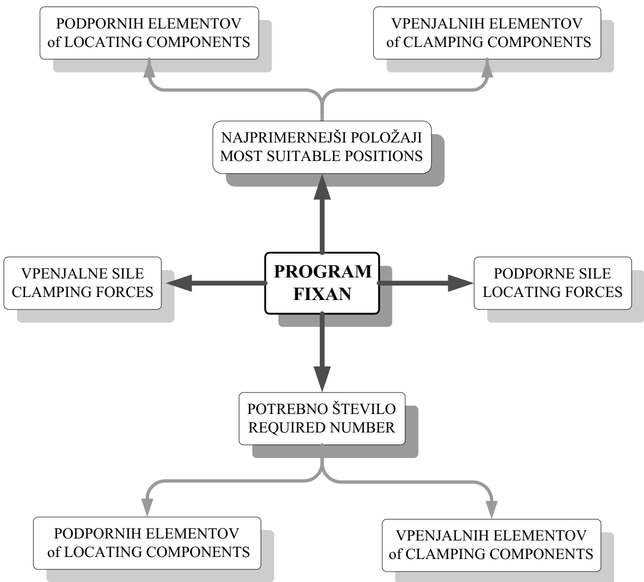
The developed model is useful for designing fixtures since it can routinely determine, within a short time, the optimum sizes, the direction and the application points of clamping and locating forces for different cases of clamping. The model is aimed at verifying (analysing) the obtained solution (configuration of the fixture), confirming or rejecting it, if all the set conditions are not fulfilled.

The purpose of the model is to improve the design of the fixture and thus to increase the geometrical accuracy of the thin-wall product. It is important to consider the cutting forces, the clamping forces and the dimensions and availability of fixtures as well as the space on the machine, which limits the possibility of clamping.

For working out the programme FIXAN, information was collected from the literature (makers of modular fixtures) and from experts in production practice. The technological procedures already worked out and verified are an important source of information.

The designing and manufacturing costs of the fixture amount to as much as 15% of the total production costs [6]. Further more, if the positioning and fixing of the product cannot be carried out with moderate costs or if the requirements of the process are not satisfied, the machining process is not justified. The reduction of the costs and the time to design the fixing process is the greatest motivating force for the systematic design of fixtures.

The FIXAN program determines (Figure3):
- the minimum number and position of the locating and clamping elements,
- the motion allowed by the locating elements,
- the reactions at the places of the "workpiece-fixture" contact (locating forces),
- the minimum clamping forces required for balancing the cutting forces.



Sl. 3. *Shematski prikaz nalog v programu FIXAN*
Fig. 3. *Representation of the tasks in the FIXAN program*

3.1 Teoretična zasnova modela za analizo in optimiranje vpenjalnih priprav

Stvari postanejo močno zapletene, kadar upoštevamo sile trenja med obdelovancem in elementi vpenjalne priprave.

Obdelovanec je podprt na šestih točkah P_1-P_6 in vpet s tremi vpenjalnimi silami Fvp_1, Fvp_2, Fvp_3 v točkah P_7, P_8, P_9 (sl. 4).

Kjer so:

$F_1,...,F_6$ - reakcije, ki delujejo na podporne elemente (N),
Fvp_1, Fvp_2, Fvp_3 -vpenjalne sile, ki delujejo v smeri normale na pozicionirne ravnine(N),
F_t, F_a, F_f - komponente rezalne sile F_c (N),
M_x, M_y, M_z - komponente rezalnega momenta M_c (Nm),
f_i (i=1...9) - rezultirajoče sile trenja v stičnih točkah (N),
F_g - sila teže obdelovanca (N),
μ - koeficient trenja.

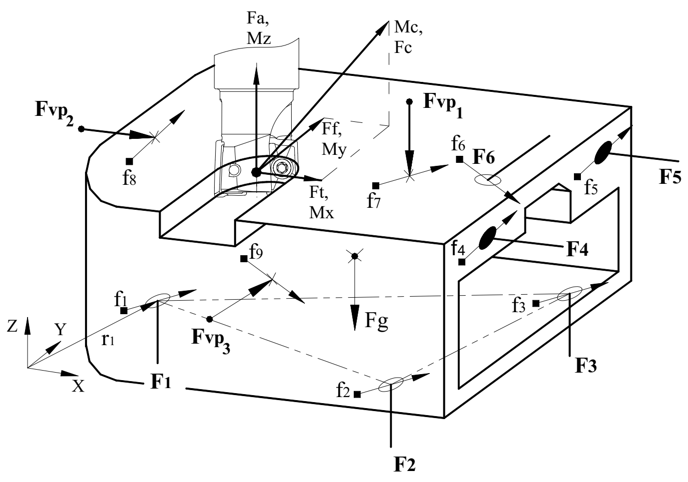
3.1. Theoretical concept of the model for the analysis and the optimization of fixtures

The scene is much more complex when frictional forces between the workpiece and fixture elements are taken into account.

The workpiece is located on the six points P_1-P_6 and is held by three clamping forces Fvp_1, Fvp_2, Fvp_3 at points P_7, P_8, P_9 (Figure 4).

Where:

$F_1,...,F_6$ - reactions acting on locating elements (N),
Fvp_1, Fvp_2, Fvp_3 - clamping forces acting in the direction of the normal on to positioning planes (N),
F_t, F_a, F_f - components of cutting force F_c (N),
M_x, M_y, M_z - components of cutting moment M_c (Nm),
f_i (i=1...9) - resulting frictional forces in contact points (N),
F_g - force of workpiece weight (N),
μ - friction coefficient.



Sl. 4. *Sile na obdelovancu med postopkom frezanja*
Fig. 4. *Forces on the workpiece during the milling process*

Rezultirajoča sila trenja f_i med lokatorjem in obdelovancem je $\mu \cdot F_i$ in med vpenjalnim elementom in obdelovancem $\mu \cdot F_{vp\,j}$, (j = 1...3). Reakcije na podpornih elementih morajo biti pozitivne, ker se v nasprotnem primeru izgubi stik med obdelovancem in elementi vpenjalne priprave.

The resulting force of the friction f_i between the locator and workpiece is $\mu \cdot F_i$ and between the fixing element and the workpiece it is $\mu \cdot F_{vp\,j}$, (j = 1...3). The reactions on the locating elements must be positive, because otherwise the contact between the workpiece and the fixture is lost.

3.2 Ravnotežne enačbe

Za dosego statičnega ravnotežja in dimenzijske natančnosti pri obdelavi morata biti rezultirajoča sila in moment na obdelovancu enaka nič. Ravnotežne enačbe so:

3.2 Equations of equilibrium

To achieve static equilibrium and dimensional accuracy during machining the resulting force and moment on the workpiece must be zero. The equations of equilibrium are:

$$\left(\sum_{i=1}^{6} F_i\right)_x - R_x = \left(\sum_{i=1}^{6} F_i\right)_y - R_y = \left(\sum_{i=1}^{6} F_i\right)_z - R_z = 0 \qquad (1)$$

$$\left(\sum_{i=1}^{6} (F_i \times r_i)\right)_x - M_x = \left(\sum_{i=1}^{6} (F_i \times r_i)\right)_y - M_y = \left(\sum_{i=1}^{6} (F_i \times r_i)\right)_z - M_z = 0 \qquad (2)$$

kjer so:
r_i - vektorji, ki definirajo podporne točke,
R_x, R_y, R_z - komponente rezultirajoče rezalne sile F_c.

where:
r_i - the vectors defining the locating points
R_x, R_y, R_z - components of the resulting cutting force F_c

3.3 Matrične ravnotežne enačbe za izračun podpornih sil

Zaradi numeričnega reševanja problema so ravnotežne enačbe zapisane v matrični obliki:

3.3 Matrix equilibrium equations for the calculation of locating forces

Because the problem is solved numerically the equilibrium equations are written in the matrix form:

$$[A]_{lok} \cdot [F]_{lok} + [w_e] = 0 \qquad (3)$$

Geometrijska matrika $[A]_{lok}$ je enaka:

The geometrical matrix $[A]_{lok}$ is as follows:

$$[A]_{lok} = \left[\begin{array}{cccccc} f_{1x} & f_{2x} & f_{3x} & -1 & -1 & f_{6x} \\ f_{1y} & f_{2y} & f_{3y} & f_{4y} & f_{5y} & -1 \\ 1 & 1 & 1 & -f_{4z} & -f_{5z} & -f_{6z} \\ \hdashline r_{1y} & r_{2y} & r_{3y} & \begin{pmatrix} -f_{4y} \cdot r_{4z} - \\ -f_{4y} \cdot r_{4y} \end{pmatrix} & \begin{pmatrix} -f_{5y} \cdot r_{5z} - \\ -f_{5z} \cdot r_{5y} \end{pmatrix} & \begin{pmatrix} -f_{6z} \cdot r_{6y} + \\ +r_{6z} \end{pmatrix} \\ -r_{1x} & -r_{2x} & -r_{3x} & \begin{pmatrix} -r_{4z} + \\ +f_{4z} \cdot r_{4x} \end{pmatrix} & \begin{pmatrix} -r_{5z} + \\ +f_{5z} \cdot r_{5x} \end{pmatrix} & \begin{pmatrix} f_{6x} \cdot r_{6z} + \\ +f_{6z} \cdot r_{6x} \end{pmatrix} \\ \begin{pmatrix} -f_{1x} \cdot r_{1y} + \\ +f_{1y} \cdot r_{1x} \end{pmatrix} & \begin{pmatrix} -f_{2x} \cdot r_{2y} + \\ +f_{2y} \cdot r_{2x} \end{pmatrix} & \begin{pmatrix} -f_{3x} \cdot r_{3y} + \\ +f_{3y} \cdot r_{3x} \end{pmatrix} & \begin{pmatrix} r_{4y} + \\ +f_{4y} \cdot r_{4x} \end{pmatrix} & \begin{pmatrix} r_{5y} + \\ +f_{5y} \cdot r_{5x} \end{pmatrix} & \begin{pmatrix} -r_{6x} - \\ -f_{6x} \cdot r_{6y} \end{pmatrix} \end{array}\right] \qquad (4)$$

Vektor podpornih sil $[F]_{lok}^{T}$:

The vector of supporting forces $[F]_{lok}^{T}$:

$$[F]_{lok}^{T} = [F_1 \quad F_2 \quad F_3 \quad F_4 \quad F_5 \quad F_6] \qquad (5)$$

Vektor zunanjih sil $[w_e]$:

The vector of external forces $[w_e]$:

$$[w_e] = \begin{bmatrix} f_{7x} + f_{9x} + F_{vp_2} + R_x \\ f_{7y} + f_{8y} + F_{vp_3} + R_y \\ -f_{8z} - f_{9z} - F_g + R_z \\ -f_{7y} \cdot r_{7z} - f_{8y} \cdot r_{8z} - f_{8z} \cdot r_{8y} - f_{9z} \cdot r_{9y} - F_{vp_1} \cdot r_{7y} - F_{vp_3} \cdot r_{9z} - F_g \cdot r_{gy} + M_x \\ f_{7x} \cdot r_{7z} + f_{8z} \cdot r_{8x} + f_{9x} \cdot r_{9z} + f_{9z} \cdot r_{9x} + F_{vp_1} \cdot r_{7x} + F_{vp_2} \cdot r_{8z} + F_g \cdot r_{gx} + M_y \\ -f_{7x} \cdot r_{7y} + f_{7y} \cdot r_{7x} + f_{8y} \cdot r_{8x} - f_{9x} \cdot r_{9y} - F_{vp_2} \cdot r_{8y} + F_{vp_3} \cdot r_{9x} + M_z \end{bmatrix} \qquad (6)$$

Po vstavitvi geometrijske matrike $[A]_{lok}$ in vektorja zunanjih sil $[w_e]$ v enačbo (3) sledi:

After entering the geometrical matrix $[A]_{lok}$ and the vector of external forces $[w_e]$ into equation (3) the following is obtained:

$$[F]_{lok}=-\left[\begin{array}{cccccc} f_{1x} & f_{2x} & f_{3x} & -1 & -1 & f_{6x} \\ f_{1y} & f_{2y} & f_{3y} & f_{4y} & f_{5y} & -1 \\ 1 & 1 & 1 & -f_{4z} & -f_{5z} & -f_{6z} \\ \hline r_{1y} & r_{2y} & r_{3y} & \begin{pmatrix}-f_{4y}\cdot r_{4z}- \\ -f_{4y}\cdot r_{4y}\end{pmatrix} & \begin{pmatrix}-f_{5y}\cdot r_{5z}- \\ -f_{5z}\cdot r_{5y}\end{pmatrix} & \begin{pmatrix}-f_{6z}\cdot r_{6y}+ \\ +r_{6z}\end{pmatrix} \\ -r_{1x} & -r_{2x} & -r_{3x} & \begin{pmatrix}-r_{4z}+ \\ +f_{4z}\cdot r_{4x}\end{pmatrix} & \begin{pmatrix}-r_{5z}+ \\ +f_{5z}\cdot r_{5x}\end{pmatrix} & \begin{pmatrix}f_{6x}\cdot r_{6z}+ \\ +f_{6z}\cdot r_{6x}\end{pmatrix} \\ \begin{pmatrix}-f_{1x}\cdot r_{1y}+ \\ +f_{1y}\cdot r_{1x}\end{pmatrix} & \begin{pmatrix}-f_{2x}\cdot r_{2y}+ \\ +f_{2y}\cdot r_{2x}\end{pmatrix} & \begin{pmatrix}-f_{3x}\cdot r_{3y}+ \\ +f_{3y}\cdot r_{3x}\end{pmatrix} & \begin{pmatrix}r_{4y}+ \\ +f_{4y}\cdot r_{4x}\end{pmatrix} & \begin{pmatrix}r_{5y}+ \\ +f_{5y}\cdot r_{5x}\end{pmatrix} & \begin{pmatrix}-r_{6x}- \\ -f_{6x}\cdot r_{6y}\end{pmatrix} \end{array}\right]^{-1}\cdot \qquad (7)$$

$$\cdot\begin{bmatrix} f_{7x}+f_{9x}+F_{vp2}+R_x \\ f_{7y}+f_{8y}+F_{vp3}+R_y \\ -f_{8z}-f_{9z}-F_g+R_z \\ -f_{7y}\cdot r_{7z}-f_{8y}\cdot r_{8z}-f_{8z}\cdot r_{8y}-f_{9z}\cdot r_{9y}-F_{vp1}\cdot r_{7y}-F_{vp3}\cdot r_{9z}-F_g\cdot r_{gy}+M_x \\ f_{7x}\cdot r_{7z}+f_{8z}\cdot r_{8x}+f_{9x}\cdot r_{9z}+f_{9z}\cdot r_{9x}+F_{vp1}\cdot r_{7x}+F_{vp2}\cdot r_{8z}+F_g\cdot r_{gx}+M_y \\ -f_{7x}\cdot r_{7y}+f_{7y}\cdot r_{7x}+f_{8y}\cdot r_{8x}-f_{9x}\cdot r_{9y}-F_{vp2}\cdot r_{8y}+F_{vp3}\cdot r_{9x}+M_z \end{bmatrix}$$

Kadar je koeficient trenja med obdelovancem in vpenjalnimi elementi enak nič, se zgornja enačba poenostavi in dobi naslednjo obliko:

When the coefficient of friction between the workpiece and the clamping elements is equal to zero, the above equation is simplified and assumes the following form:

$$[F]_{lok}=\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \end{bmatrix}=-\left[\begin{array}{cccccc} 0 & 0 & 0 & -1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ \hline r_{1y} & r_{2y} & y_{3y} & 0 & 0 & +r_{6y} \\ -r_{1x} & -r_{2x} & -r_{3x} & -r_{4z} & -r_{5z} & 0 \\ 0 & 0 & 0 & r_{4y} & r_{5y} & -r_{6x} \end{array}\right]^{-1}\cdot\begin{bmatrix} F_{vp2}+R_x \\ F_{vp3}+R_y \\ F_g+R_z \\ -F_{vp1}\cdot r_{7y}-F_{vp3}\cdot r_{9z}-F_g\cdot r_{gy}+M_x \\ F_{vp1}\cdot r_{7x}+F_{vp2}\cdot r_{8z}+F_g\cdot r_{gx}+M_y \\ F_{vp2}\cdot r_{8y}+F_{vp3}\cdot r_{9x}+M_z \end{bmatrix} \qquad (8)$$

3.4 Iskanje ustrezne vpenjalne razporeditve in vpenjalnih sil

Zaradi sil trenja je število neznank v sistemu večje od števila ravnotežnih enačb, zato sistem ni vedno rešljiv. Sistem ima netrivialno rešitev takrat, ko je determinanta matrike različna od nič. Postopek izračuna vpenjalnih sil se poenostavi z iteracijskim načinom reševanja matrične enačbe. Z iteracijsko metodo rešimo enačbo (3), s čimer izračunamo minimalne potrebne vpenjalne sile. Iteracija se začne z začetno vrednostjo vpenjalnih sil $F_{vpj}=0; j=1, 2, 3$, potem se ta vrednost postopoma koračno veča, dokler vse sile F_i niso pozitivne. Na tak način pridemo do osnovne rešitve problema. Osnovno rešitev je mogoče optimirati takole:

Prvi vpenjalni sili se priredi vrednost osnovne rešitve, preostalim pa se postopoma koračno zvišuje

3.4 Searching for the appropriate fixing configuration and clamping forces

Because of frictional forces the number of unknown variables in the system is far larger than the number of equilibrium equations, therefore, the system is not always solvable. The system has a non-trivial solution when the determinant of the system is other than zero. The procedure for calculating the clamping forces is simplified by the iteration method of solving the matrix equation. By using the iteration method equation (3) is solved and the minimum required clamping forces are calculated. The iteration starts with the initial value of the clamping force $F_{vpj}=0; j=1, 2, 3$, afterwards, this value gradually increases incrementally until all the forces F_i are positive. In this way we reach the basic-fundamental solution of the problem. The basic solution can be optimised in this following way:

The value of the basic solution is adapted to the first clamping force whereas the values of the vrednost, dokler vse izračunane podporne sile niso pozitivne. Nato se postopek ponovi za vsako vpenjalno silo.

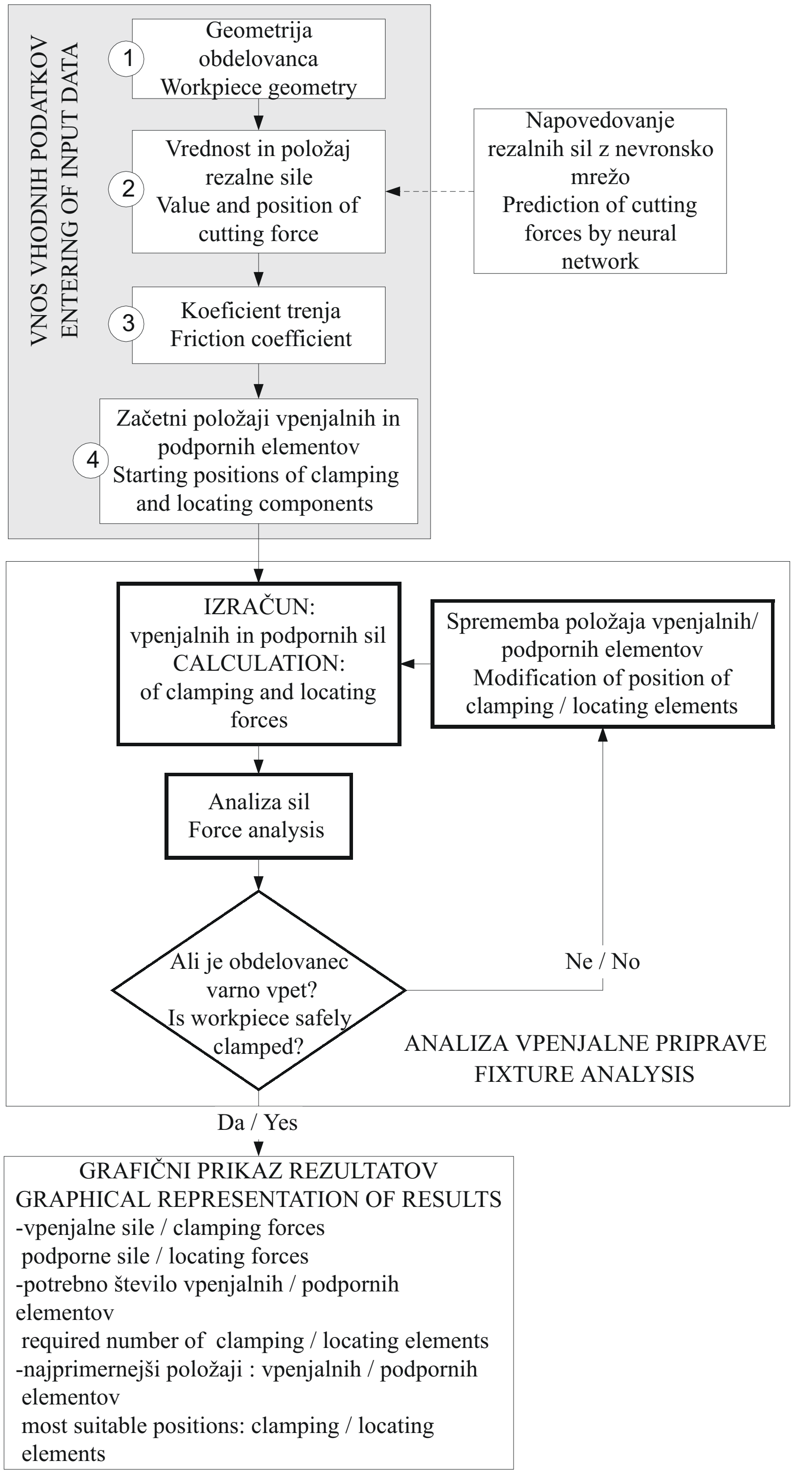
3.5 Grafični prikaz poteka dela v programu FIXAN

Slika 5 prikazuje zaporedje korakov, ki jih je treba izvesti pri iskanju optimalne vpenjalne sheme.

others are gradually increased incrementally until all the calculated locating forces are positive. The procedure is then repeated for each clamping force.

3.5 The graphical representation of the process of work in the FIXAN program

Figure 5 shows the sequence of steps to be taken when searching for the optimum clamping scheme.



Sl. 5. *Definicija programskih korakov v programu FIXAN*
Fig. 5. *The definition of the program steps in the FIXAN program*

Program zahteva v korakih (1 do 4) ročen vnos začetnih (želenih) položajev vpenjalnih/podpornih elementov ter vrednosti rezalnih sil, koeficienta trenja in teže obdelovanca. Začetne položaje komponent priprave določi operater glede na izkušnje, geometrijo obdelovanca in operacijo obdelave.

V primeru nerodne izbire položajev komponent vpenjalne priprave, ko program z variiranjem vrednosti vpenjalnih sil ni zmožen zagotoviti učinkovite vpenjalne sheme, avtomatično spremeni koordinate posameznim vpenjalnim ali podpornim elementom.

Elemente priprave razporedi okrog obdelovanca tako, da je ta varno vpet z minimalnimi potrebnimi vpenjalnimi silami.

In steps (1 to 4) the programme requires manual entering of the starting (desired) positions of the clamping/locating elements and the values of the cutting forces, the friction coefficient and the workpiece's weight. The starting position of the fixture components are determined by the operator on the basis of experience, workpiece geometry and machining operation.

In the case of inappropriate selection of the fixture components, when the program is not capable of ensuring an efficient clamping scheme by varying the values of the clamping forces, it automatically changes the coordinates of the individual clamping or locating elements.

It arranges the clamping components around the workpiece so that the latter is safely clamped by the minimum required clamping forces.

4 PRIMER ANALIZE IN OPTIMIRANJA VPENJALNE SHEME

Na številsko krmiljenem frezalnem stroju je treba izdelati utor, prikazan na sliki 6. Uporabimo frezalo s premerom 16 mm z dvema rezalnima ploščicama (R-216-16 03 M-M) pri naslednjih rezalnih pogojih: rezalna hitrost (v = 25 m/min), podajanje na zob (f_z = 0,01 mm/zob), globina rezanja (a = 4 mm). Material obdelovanca je jeklo z oznako Ck-45. Na podlagi formul, podanih v literaturi [7], so izračunane komponente rezalnih sil pri podanih rezalnih parametrih. Vrednosti komponent rezalnih sil (F_a = 450 N, F_f = 315 N, F_t = 810 N), položaj orodja, začetne položaje vpenjalnih/podpornih elementov, koeficient trenja (η = 0,4), in težo obdelovanca (F_g = 47 N) vstavimo v okno za vnos vhodnih podatkov.

4.1 Določitev vpenjalnih sil z iteracijo

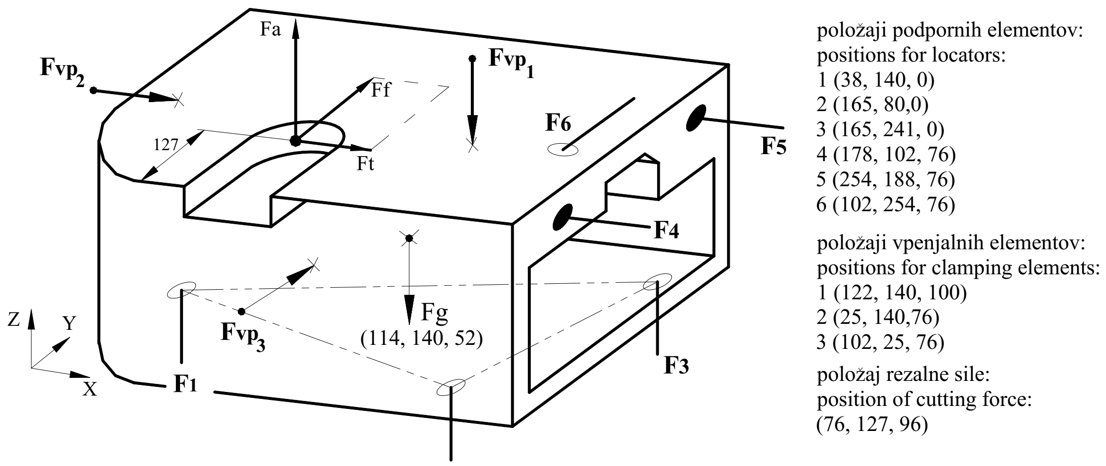
Vpetje izvedemo s tremi vpenjalnimi elementi. Z zgornjim vpenjalnim elementom je vpet

4 EXAMPLE OF AN ANALYSIS AND OPTIMIZATION OF THE CLAMPING SCHEME

On a NC milling machine it is necessary to make the slot shown in Figure 6. To this end we use a milling cutter of 16-mm diameter with two cutting inserts (R-216-16 03 M-M) and the following cutting conditions: cutting speed (v = 25 m/min), feedrate (f_z = 0,01 mm/tooth), cutting depth (a = 4 mm). The workpiece material is the steel Ck-45. The components of the cutting forces with the cutting parameters defined above are calculated on the basis of equations given in literature [7]. The values of the components of the cutting forces (F_a = 450 N, F_f = 315 N, F_t = 810 N), the tool position, the starting positions of the clamping/locating elements, the friction coefficient (η = 0.4) and the workpiece's weight (F_g = 47 N) are entered into the window for the input data.

4.1 Determination of clamping forces by iteration

Clamping is effected by the three clamping elements. With the upper clamping element the



Sl. 6. *Vpenjalna in podporna shema za izdelavo utora na prizmatičnem obdelovancu*
Fig.6. *Clamping and locating scheme for machining the slot on a prismatic workpiece*

obdelovanec v smeri osi Z, s stranskima pa je pritisnjen ob navpični pozicionirni ravnini. Enačba (3) dobi naslednjo obliko:

workpiece is clamped in the direction of the Z axis and with the two side elements it is pressed along the vertical locating plane. Equation (3) assumes the following form:

$$\begin{bmatrix} 0,373 & 0,373 & 0,373 & -1 & -1 & 0,194 \\ 0,145 & 0,145 & 0,145 & 0,229 & 0,229 & -1 \\ 1 & 1 & 1 & -0,328 & -0,328 & -0,35 \\ 5,512 & 1,496 & 9,488 & -2,002 & -3,112 & -0,505 \\ -1496 & -6,496 & -0,696 & -0,696 & 0,385 & 1,985 \\ -1,838 & 0,384 & -2,595 & 5.623 & 9,695 & -5,958 \end{bmatrix} \cdot \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \\ F_6 \end{bmatrix} =$$

$$= -\begin{bmatrix} 0,373 \cdot F_{vp_1} + F_{vp_2} + 0,194 \cdot F_{vp_3} + 810 \\ 0,145 \cdot F_{vp_1} + 0,328 \cdot F_{vp_2} + F_{vp_3} + 315 \\ -0,459 \cdot F_{vp_2} - F_{vp_1} - 450 + 80 \\ -6.38 \cdot F_{vp_1} - 2,245 \cdot F_{vp_2} - 3,336 \cdot F_{vp_3} - 440,95 + 4501,57 \\ 7,034 \cdot F_{vp_1} + 3,218 \cdot F_{vp_2} + 1,985 \cdot F_{vp_3} + 6361,4 + 359,05 \\ -1,359 \cdot F_{vp_1} - 5,321 \cdot F_{vp_2} + 3,825 \cdot F_{vp_3} - 2910,63 \end{bmatrix} \quad (9)$$

Mogoče rešitve za Fvp_i so tiste, ki vodijo do pozitivnih vrednosti F_i; z drugimi besedami, obdelovanec bo ostal med obdelavo v stiku s podpornimi elementi. Determinanta F_{loc} je negativna, zato obstaja netrivialna rešitev problema. Obstoj netrivialne rešitve pomeni, da je konfiguracija vpenjalne priprave sprejemljiva. Za rešitev šestih simultanih linearnih ravnotežnih enačb z devetimi neznankami predpostavimo, da imajo Fvp_1, Fvp_2, in Fvp_3 enake vrednosti. Vrednosti teh treh spremenljivk so na začetku enake 0, nato se z nespremenljivim korakom v vsaki iteraciji stopnjujejo do vrednosti, pri katerih so vse sile F_i pozitivne.

Dobljene vrednosti sil Fvp_1, Fvp_2 in Fvp_3, ki so enake 440N, bodo prvi niz sprejemljivih rešitev, ki so navedene kot primer (1) v preglednici 1.

The possible solutions for Fvp_is are those that result in positive values of F_is; in other words, the workpiece will remain in contact with the locators during the entire cutting process. The determinant of F_{loc} is other than zero, therefore, a non-trivial solution exists. The existence of the non-trivial solution implies that the clamping fixture configuration is acceptable. To solve these six linear simultaneous equilibrium equations with nine unknowns, we assume that Fvp_1, Fvp_2 and Fvp_3 have the same magnitude. Their values start from zero and are incremented by a constant value in each iteration until positive values of all F_is are achieved.

The obtained values of Fvp_1, Fvp_2 and Fvp_3, which are equal to 440N, will be the first set of possible solutions, which are listed as case (1) in Table 1.

Preglednica1. *Reakcije na podpornih elementih, ki so posledica različnih načinov vpetja obdelovanca*
Table 1. *Reaction on the locating elements which results from different methods of workpiece clamping*

Sile N Forces N	(1) primer / case	(2)	(3)	(4)	(5)
Fvp_1	440	430	440	410	0
Fvp_2	440	440	440	220	320
Fvp_3	440	440	0	0	0
F_1	2,14	0,967	125,57	7,808	0,44
F_2	475,9	472,12	432,77	249,644	396,842
F_3	693,7	688,765	613,25	419,354	643,647
F_4	826,0	823,769	652,30	539,109	618,558
F_5	673,5	672,009	761,73	590,891	564,291
F_6	962,9	961,526	522,97	419,862	446,534

4.2 Racionalizacija zasnove vpenjalne priprave

Preglednica 1 prikazuje vrednosti reakcij F_i (i = 1 do 6) na podpornih elementih in mogoče rešitve za Fvp_i pri različnih primerih vpetja. Primer (1) prikazuje prvo sprejemljivo rešitev, pri kateri so vse vpenjalne sile enake (440 N). Pri drugih primerih (2 in 3) priredimo dvema vpenjalnima silama vrednost 440 N, medtem ko vrednost tretje vpenjalne sile postopoma večamo, dokler ne postanejo vsi F_i pozitivni.

S takim postopkom zmanjšamo vrednost potrebnih vpenjalnih sil, pri čemer pa ostane obdelovanec vseskozi v stiku z elementi vpenjalne priprave. Vrednosti vpenjalnih sil, ki jih dobimo v primeru (5), so boljše kakor v primeru (1). V primeru (3) vpenjalni element 3 ni potreben, saj je sila na ta element enaka 0 (Fvp_3 = 0). Program vedno predlaga dve optimalni rešitvi konfiguracije vpenjanja (primer 4 in 5), med katerima lahko uporabnik izbira.

Vpliv vpenjalnih sil Fvp_1, Fvp_2 in Fvp_3 na vrednosti reakcij podpornih elementov med frezanjem prikazuje slika 7. Z večanjem vpenjalne sile, po pričakovanjih, se večajo tudi vrednosti reakcij na podpornih elementih. Kritično mesto vpenjalne priprave je pri podpornem elementu 1. Pri obdelavi bo obdelovanec najprej zgubil stik z vpenjalno pripravo prav na tem mestu (P_1).

Razpored vpenjalne priprave je mogoče izboljšati:

- s postavitvijo dodatnega vpenjalnega elementa nad kritični podporni element 1,
- povečati velikost vpenjalne sile Fvp_3, ali spremeniti položaj vpenjalnega elementa 7.

4.2 Rationalization of fixture design

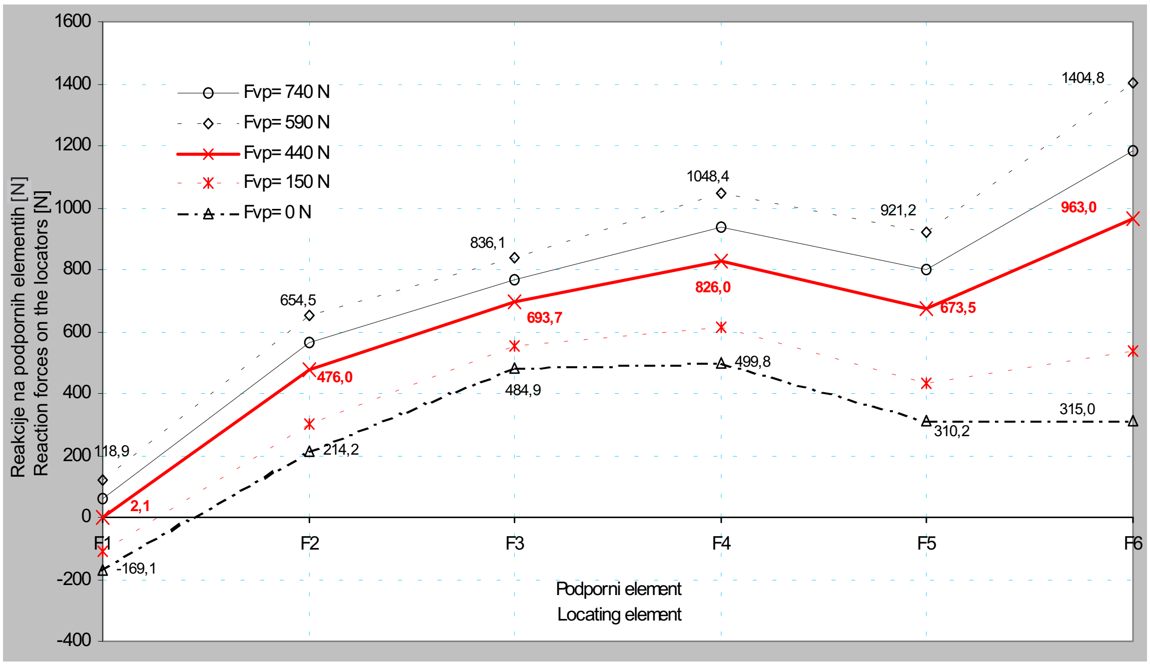
Table 1 lists the reaction forces F_i (i = 1 to 6) on the six locators and the possible solutions for Fvp_is under different clamping conditions. The case (1) shows the first acceptable solution where all the clamping forces are equal (440 N). For the other cases (case 2 and 3) two of the clamping forces are set to a value of 440N, while the value of the third clamping force is gradually increased until all F_is are positive.

With such a procedure the value of the required clamping forces is reduced, while the workpiece remains in contact with the fixture components at all times. The values of the clamping forces obtained in case (5) are more adequate than in case (1). In case (3) the clamping element 3 is not necessary, since the force acting on that element is equal to 0 (Fvp_3 = 0). The program proposes the optimum solutions of the clamping configuration (case 4 and 5) from which the user can choose.

The influence of the clamping forces Fvp_1, Fvp_2, Fvp_3 on the values of the reactions of the locating elements during milling is shown in Figure 7. If the clamping forces are increased, the values of the reactions on the locating elements are also expected to increase. The critical point of the fixture is on the locating element 1. During machining the workpiece will first lose contact with the clamping device just at that point (P_1).

The fixture configuration can be improved by:

- placing on additional clamping element above the critical locating element 1,
- increasing the value of the clamping force Fvp_1 or changing the position of the clamping element 7.



Sl. 7. *Prikaz reakcij na lokatorjih v različnih razmerah vpenjanja*

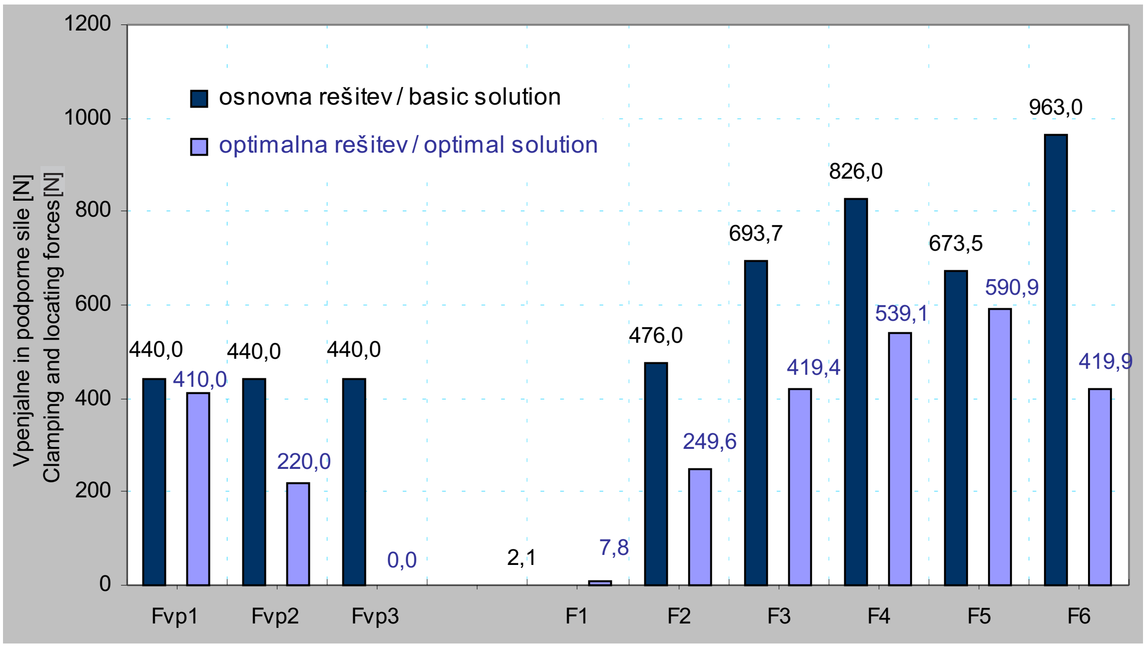
Fig. 7. *Representation of the reactions of locators under different clamping conditions*

Pri vpenjalni sili *Fvp* =0N do *Fvp* =440N konfiguracija vpenjalne priprave v danih razmerah obdelave ni primerna za vpenjanje obdelovanca. Obdelovanec bo varno vpet med obdelavo takrat, ko bo vpenjalna sila večja ali enaka 440N (odebeljena črta na sliki 7). Največja obremenitev vpenjalne naprave je na mestu podpornega elementa 6. Ta prevzame med obdelavo v položajni ravnini *XZ* vse obremenitve, ki delujejo v smeri osi *Y*.

Predlagane in analizirane vpenjalne primere (1 in 4) prikazuje slika 8.

With clamping force *Fvp*=0N up to *Fvp*=440N the clamping fixture configuration is not suitable for clamping the workpiece in the given conditions of machining. The workpiece will be safely clamped during machining, when the clamping force is higher than, or equal to, 440N (thickened line in Figure 7). The maximum loading of the clamping fixture occurs at the point of the locating element 6, which, during machining in the locating plane *XZ*, takes all loadings acting in the direction of the *Y* axis.

The proposed and analysed clamping cases (1 and 4) are shown in Figure 8.



Sl. 8. *Primerjava vpenjalnih primerov*
Fig. 8. Comparison of clamping cases

S programom FIXAN je mogoče s primerno izbiro in postavitvijo vpenjalnih elementov izboljšati razpored vpenjalne priprave.

By using the FIXAN program it is possible to improve the clamping fixture configuration by rational selection and by the placing of the clamping elements.

5 ANALIZA REZULTATOV MODELA

S testiranjem je bila potrjena pravilnost rezultatov modela. Odstopanje napovedanih sil od dejanskih je nekoliko večje le pri zelo majhnem koeficientu trenja ($0{,}01 \le \mu \le 0{,}2$) med obdelovancem in vpenjalno pripravo. Odstopanje napovedanih rezultatov smo poskušali kompenzirati v samem matematičnem modelu, vendar izvedeni popravki niso pomembno izboljšali vrednosti napovedanih sil. Potreben popravek je bil zato izveden z vpeljavo nevronske mreže v model (sl. 9). Z uporabo UNM zajamemo vse vplivne faktorje, ki niso upoštevani v ravnotežni matrični enačbi.

Postopek izračuna, ki je prikazan na sliki 9, je naslednji:

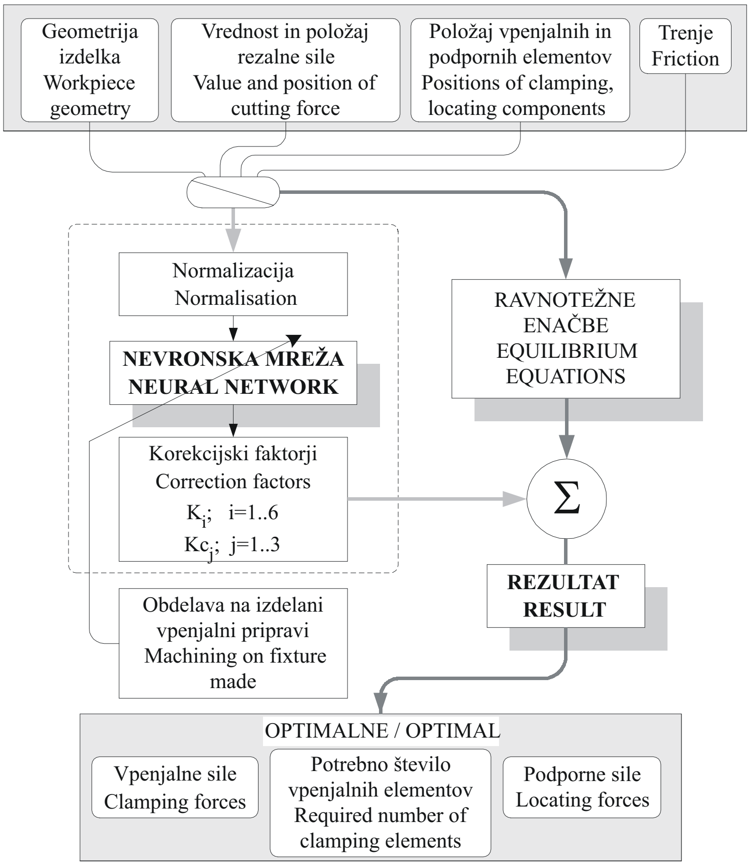
5 ANALYSIS OF RESULTS OBTAINED BY THE MODEL

The tests confirmed the correctness of the results of the model. The deviation of the predicted forces from the actual forces is slightly greater only in the case of a very small coefficient of friction ($0.01 \le \mu \le 0.2$) between the workpiece and the fixture. We tried to compensate for the deviation of the predicted results in the mathematical model, but the corrections did not significantly improve the values of the predicted forces. Therefore the required correction was made by introducing the ANN into the model (Figure 9). By using the ANN all the influencing factors, not taken into account in the equilibrium matrix equation, are included.

The process of the calculation shown in Figure 9 is as follows:

Najprej po matrični enačbi (7) določimo približne vrednosti vpenjalnih /podpornih sil. Te vrednosti nato popravimo s korekcijskimi parametri K_i, Kc_j, ki jih posreduje predhodno naučena nevronska mreža.

First, the approximate values of the clamping/locating forces are determined according to equation (7). These values are then corrected by the correction parameters K_i, Kc_j, specified by the previously trained neural network.



Sl. 9. *Shematski prikaz delovanja opisanega modela*
Fig. 9. *Schematic representation of functioning of the described model*

Uporabljena je usmerjena nevronska mreža s petimi nivoji. Vsebuje 18 nevronov v vhodnem nivoju in 9 nevronov v izhodnem nivoju. Vhodni vektor sestoji iz: komponent rezalnih sil, koordinat mesta obdelave, koordinat položaja vpenjalnih in podpornih elementov, teže obdelovanca in koeficienta trenja. Izhodni vektor vsebuje 9 korekcijskih faktorjev, s katerimi so pomnožene vrednosti izračunanih sil.

Želeni izhodi (devet vpenjalnih/podpornih sil) so bili tudi posredovani UNM med postopkom učenja. Učenje UNM je bilo izvedeno z eksperimentalnimi podatki, pri čemer je bilo uporabljenih 80 učnih primerov. Za testiranje naučene mreže je bilo uporabljenih še dodatnih 40 testnih primerov. Podatki za testiranje in učenje so pridobljeni z eksperimentalnimi meritvami na že izdelanih vpenjalnih pripravah.

Z uvedbo UNM se je natančnost napovedanih sil izboljšala za 32% pri $\mu \leq 0,3$ in za 2% pri $\mu > 0,3$. Povprečna napaka napovedi je

A five-layer feed-forward neural network was used. It contains 18 neurons in the input layer, and 9 in the output layer. The input vector consists of: components of the cutting forces, the coordinates of the point of machining, the coordinates of the position of the clamping and supporting parts, the workpiece's weight and the friction coefficient. The output vector contains nine corrections factors by which the values of the calculated forces are multiplied.

The desired outputs (the nine clamping/locating forces) of the ANN are also supplied during training. Training of the ANN was made with the experimental data of 80 training examples. An additional 40 examples were used to test the trained network. The data for training and testing are obtained from the experimental measurements on the fixtures already made.

Due to the introduction of the ANN the accuracy of the predicted forces was improved by 32% in the case of $\mu \leq 0.3$ and by 2% in the case of $\mu > 0.3$. The average estimation error is about 7.4%, približno 7,4%, kar je malo v primerjavi z 12,7-odstotno napako pri analitičnem modelu. Opisan postopek z uporabo UNM je hiter, preprost in učinkovit.

which is low compared to the 12,7% estimation error of the analytical model. The described procedure with the use of an ANN is fast, simple and efficient.

6 SKLEP

Z razvitim modelom smo pomembno skrajšali čas snovanja priprav (15%) ter dosegli večjo izdelovalno natančnost. Z opisanim sistemom je mogoče napovedati in preprečiti napake na obdelovancu med postopkom vpenjanja in obdelave. V raziskavi je ugotovljeno, da se z upoštevanjem trenja močno zmanjša vrednost potrebne vpenjalne sile kakor tudi število potrebnih vpenjalnih elementov. Razvit program FIXAN skrajša čas načrtovanja postopka obdelave. Omogoča izdelavo kakovostnih načrtov vpenjanja tudi manj izkušenim operaterjem.

6 CONCLUSION

With the developed model we have significantly reduced the time of producing the fixture (15%) and we have reached a greater manufacturing accuracy. With the described system it is possible to anticipate and prevent any defects on the workpiece during the clamping and machining process. During the research we found that by taking the friction into account the value of the required clamping force as well as the number of the required clamping elements decreased significantly. The FIXAN program reduces the planning time for the machining process; it even allows inexperienced operators to prepare high-quality clamping drawings.

7 LITERATURA
7 REFERENCES

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Naslov avtorjev: Uroš Župerl
Prof. dr. Franci Čuš
Univerza v Mariboru
Fakulteta za strojništvo
Smetanova 17
2000 Maribor
uros.zuperl@uni-mb.si
franc.cus@uni-mb.si

Authors' address: Uroš Župerl
Prof. Dr. Franci Čuš
University of Maribor
Faculty of Mechanical Eng.
Smetanova 17
2000 Maribor, Slovenia
uros.zuperl@uni-mb.si
franc.cus@uni-mb.si

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