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Vsebina
Contents

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Razprave

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Določevanje značilnih tehnoloških in gospodarskih parametrov med postopkom odrezovanja

A Determination of the Characteristic Technological and Economic Parameters during Metal Cutting

Uroš Župerl - Franci Čuš

V prispevku je predlagan nov nedeterministični optimizacijski postopek za zahtevno optimizacijo rezalnih parametrov pri odrezovanju. Ta postopek uporablja umetne nevronske mreže (ANN) za reševanje problema optimiranja rezalnih pogojev. Predlagan postopek temelji na kriteriju največje stopnje proizvodnje in vključuje štiri tehnološke omejitve. Z izbiro optimalnih rezalnih parametrov je mogoče doseči ugodno razmerje med nizkimi obdelovalnimi stroški in visoko produktivnostjo ob upoštevanju podanih omejitev postopka rezanja. Eksperimentalni rezultati kažejo, da je predlagani algoritem pri reševanju nelinearnih optimizacijskih problemov s postavljenimi omejitvami učinkovit in ga je mogoče vključiti v inteligentne obdelovalne sisteme. Najprej je oblikovan problem določitve optimalnih parametrov odrezovanja, kot večciljni optimizacijski problem. Nato so predlagane nevronske mreže za predstavitev proizvajalčevih prednostnih struktur. Za demonstracijo zmogljivosti predlaganega postopka je nadrobno obravnavan nazoren primer.

(Ključne besede: odrezovanje, pogoji rezanja, struženje, optimiranje, postopki nedeterministični)

A new non-deterministic optimization approach to the complex optimization of cutting parameters during machining is proposed. It uses artificial neural networks to solve the cutting-conditions optimization problem. The developed approach is based on the "maximum production rate criterion" and incorporates four technological constraints. By selecting the optimum cutting conditions it is possible to reach a favourable ratio between low machining costs and high productivity, taking into account the given limitation of the cutting process. First, the problem of determining the optimum machining parameters is formulated as a multiple-objective optimization problem. Then, neural networks are proposed to represent manufacturers' preference structures. The experimental results show that the proposed algorithm for solving the non-linear-constrained optimization problems is efficient and can be integrated into intelligent manufacturing systems. To demonstrate the performance of the proposed approach, an illustrative example is discussed in detail.

(Keywords: machining, cutting parameters, turning, nondeterministic optimization)

0 UVOD

Inteligentna proizvodnja dosega znatne denarne in časovne prihranke, če vključuje učinkovito avtomatično načrtovanje postopka. Načrtovanje postopka obsega določitev primernih strojev, odrezovalnih orodij in odrezovalnih parametrov pri določenih pogojih rezanja za vsako opravilo na danem obdelovancu. Optimalna izbira rezalnih pogojev pomembno prispeva k povečanju produktivnosti in zmanjšanju stroškov, zato je največji del pozornosti v tem prispevku posvečen prav temu problemu. Problem gospodarnosti

0 INTRODUCTION

Intelligent manufacturing achieves substantial savings in terms of money and time if it integrates an efficient automated process-planning. Process planning involves a determination of the appropriate machines, the tools for machining parts and the machining parameters under certain cutting conditions for each operation of a given machined part. The optimum selection of the cutting conditions contributes significantly to an increase in productivity and a reduction of costs. For this reason a lot of attention is paid to this problem in this contribution. The machining-economics problem obdelave vključuje določitev karakterističnih parametrov postopka, in sicer običajno hitrosti rezanja, stopnje podajanja in globine rezanja, z namenom optimirati ciljno funkcijo. Vključene ciljne funkcije, s katerimi merimo optimalnost rezalnih pogojev, so: (1) najmanjši stroški na enoto, (2) največja stopnja proizvodnje, (3) utežna kombinacija večciljnih funkcij. Rezalne omejitve, ki bi jih morali upoštevati pri gospodarnosti obdelave vključujejo: omejitev obstojnosti, rezalne sile, moči, temperature odrezka in omejitev hrapavosti površine.

Običajno so problem gospodarnosti obdelave reševali z uporabo optimizacijskih algoritmov, ki vsebujejo geometrično in stohastično programiranje [1], diferencialni račun [2], linearno programiranje [2] in računalniške simulacije [3]. Ti algoritmi so bili razviti ob upoštevanju samo enega cilja, to je npr. zmanjševanje stroškov, povečanje dobička, itn.

Medtem ko večina dosedanjih raziskav temelji na enovariantni optimizaciji, obstaja nekaj uspelih poskusov tudi pri večvariantni optimizaciji. Philipson in Ravidran [2] uporabita ciljno programiranje za optimiranje postopka obdelave, Ghiassi [4] uporabi več ciljne tehnike linearnega programiranja in interaktivne tehnike. Raznolikost izdelkov in negotovost na tržišču povzročata, da so interaktivne metode načrtovanja postopka obdelave neučinkovite zaradi močnih in pogostih interakcij z izdelovalci pri načrtovanju postopkov obdelave. Bolj zaželena je metoda na podlagi prednostnega modela, npr. večatributna vrednostna funkcija, ki predstavlja izdelovalčevo celovito prednost.

Optimiranje rezalnih parametrov je nelinearna optimizacija z omejitvami, zato je težko rešiti ta problem z nedeterminističnimi algoritmi. Zato so bile nedavno uporabljene nedeterministične tehnike reševanja različnih tipov optimizacijskih problemov pri odrezovanju. Lokalne iskalne tehnike vključujejo simulacijsko ohlajanje (SA) [5], genetske algoritme (GA) [6], algoritma UNM in PSO [7].

Nov postopek, ki omogoča učinkovito in hitro izbiro optimalnih rezalnih pogojev brez kršenja postavljenih rezalnih omejitev so umetne nevronske mreže (UNM - ANN). Algoritem deluje na podlagi usmerjenih in žarkovnih mrež ob hkratni uporabi novih sodobnih algoritmov učenja, ki se avtomatično prilagajajo trenutnim razmeram med postopkom učenja.

Cilj raziskave je prikazati potencial nevronskih mrež pri optimiranju postopka odrezovanja. Gibalo študije je tudi predstaviti proizvajalčeve prednostne strukture z uporabo UNM. Glavni cilj prispevka je določiti takšne optimalne rezalne pogoje (rezalno hitrost, podajanje in globino reza), ki čim bolj povečajo obseg proizvodnje, zmanjšajo obdelovalne stroške in izboljšajo kakovost izdelka.

consists of determining the characteristic process parameters, usually the cutting speed, the feed rate and the depth of cut, in order to optimize an objective function. The included objective functions for measuring the optimality of the machining conditions are: (1) minimum unit-production cost, (2) maximum production rate, (3) maximum production rate and (4) a weighted combination of several objective functions. The cutting constraints that should be considered in machining economics include the following: tool-life constraint, cutting-force constraint, power, chip-tool interface-temperature constraint, surface-finish constraint.

Usually, the machining-economics problem has been solved using optimization algorithms, which include geometric and stochastic programming [1], differential calculus [2], linear programming [2], and computer simulating [3]. These algorithms were developed by considering only a single objective, such as minimization of cost or maximization of profit, etc.

While most of the research undertaken so far has been based on single-objective optimization, there have been some successful attempts at multi-objective optimization. Philipson and Ravidran [2] apply goal-programming techniques for machining-process optimizations, Ghiassi [4] applies multi-objective linear-programming techniques and interactive techniques. The diversity of product mix and the uncertainty of market value make interactive approaches to machining-process planning inefficient owing to the extensive and frequent interactions with manufacturers for planning the machining process. A global approach based on a preference model, such as a multi-attribute value function that represents a manufacturer's overall preference, is more desirable.

The optimization of machining parameters is a non-linear optimization with constraints, so it is difficult for non-deterministic optimization algorithms to solve this problem. Consequently, non-deterministic techniques have recently been applied to solve various types of optimization problems in machining. Local search techniques include the simulated annealing (SA) algorithm [5], the genetic algorithm (GA) approach [6], the ANN approach and the PSO algorithm [7].

The new approach, which ensures efficient and fast selection of the optimum cutting conditions, without violating any imposed cutting constraints, is the artificial neural network (ANN). The algorithm works on the basis of feedforward and radial basis networks with the simultaneous use of a new, advanced learning algorithm, which automatically adapts to current conditions during the training process.

The purpose of this study is to demonstrate the potential of neural networks for machining-process optimization. The motivation of this study is also to represent the manufacturer's preference structures using ANNs. The main objective of the paper is to determine the optimal machining parameters (cutting speed, feedrate, depth of cut) that maximize the extent of production, reduce the manufacturing costs and improve the product quality.

Prispevek je oblikovan takole. V poglavju 1 je oblikovano opravilo struženja kot večciljni optimizacijski problem s tremi neprimerljivimi in nasprotujočimi si cilji. V poglavju 1 je predlagana nevronska mreža, da pridemo do izdelovalčeve posredne večatributne vrednostne funkcije. Nato je opisan nevronski algoritem za optimiranje rezalnih parametrov. V poglavju 4 so obravnavani rezultati izračunov, ki kažejo razlike med različnimi metodami.

The paper is organised as follows. In section 2, a turning operation is formulated as a constrained multi-objective optimisation problem with three non-commensurate and conflicting objectives. In Section 3, a neural network is proposed for accessing a manufacturer's implicit multi-attribute value function. Then a neural algorithm for cutting-parameter optimization is described. In Section 5, computational results are discussed to show the differences between the various approaches.

1 TEORETIČNI POSTOPEK K REŠEVANJA PROBLEMA OPTIMIRANJA

Naloga optimizacije je določiti takšen niz rezalnih pogojev v (rezalna hitrost), f (podajanje), a (globina rezanja), ki zadosti omejitvenim enačbam in uravnoteži nasprotujoče si ciljne dejavnike. Opravilo struženja je oblikovano kot večvariantni optimizacijski problem z omejitvenimi neenačbami ter s tremi nasprotujočimi si cilji (stopnja proizvodnje, stroški opravila, kakovost obdelave). Rezalni parametri morajo biti tako izbrani, da je stroj čim bolj izkoriščen in obstojnost orodja čim daljša. V splošnem izbira lažjih delovnih razmer ni gospodarsko upravičena. Z zmanjševanjem rezalne hitrosti, podajanja in globine rezanja se zmanjša delovni učinek in podaljša obstojnost orodja. Tako se sicer prihrani pri orodjih in zmanjša stroške za menjavo orodij, vendar se povečajo stroški delovnega mesta. Nasprotno tudi velja, da ni vedno namen izdelati čim več v najkrajšem mogočem času. Pri izbiri optimalnih rezalnih pogojev za dano strojno opravilo naredimo kompromis med največjo stopnjo odvzemanja materiala in najmanjšo obrabo orodja.

1 THEORETICAL APPROACH TO SOLVING THE OPTIMIZATION PROBLEM

The purpose of the optimization is to determine such a set of cutting conditions – v (cutting speed), f (feedrate), a (depth of cut) – that satisfies the limitation equations and balances the conflicting objectives. The operation of turning is defined as a multiple-objective optimization problem with limitation non-equations and with three conflicting objectives (production rate, operation cost, quality of machining). The cutting parameters must be selected so that the machine is utilised to the maximum possible extent and that the tool-life is as long as possible. In general, the selection of the easier operating conditions is not economically justified. If the cutting speed, feeding and cutting depth are decreased, the work efficiency is reduced and the tool resistance to is wear prolonged. In this way the tools are saved and the cost of the tool replacement is reduced, but the labor costs are increased. Conversely, it is not always our aim to produce as much as possible within the shortest possible time. When selecting the optimum cutting conditions for some machine operation we make a compromise between the extent of removal of the material and the minimum tool wear.

1.1 Izoblikovanje ciljnih funkcij

1. Stopnja proizvodnje
   Stopnjo proizvodnje običajno merimo s celotnim časom, ki je potreben za izdelavo enega izdelka (T_p). Je funkcija stopnje odvzemanja kovine (*SOK* - *MRR*) in obstojnosti orodja;

1.1 Formulation of objective functions

1. Production rate
   The production rate is usually measured as the entire time necessary for the manufacture of a product (T_p). It is a function of the metal removal rate (*MRR*) and the the tool-life;

$$T_p = T_s + V \times \frac{(1+\frac{T_c}{T})}{MRR} + T_i \qquad (1),$$

kjer so = T_s, T_c, T_i in V pripravljalni čas orodja, čas menjave orodja, čas ko orodje ne reže in prostornina odvzetega materiala. V določenih opravilih so T_s, T_c, T_i in V stalnice, od koder izhaja, da je T_p funkcija *SOK* in *T*.

- Stopnja odvzemanja kovin (*SOK*). *SOK* lahko z analitično izpeljavo izrazimo kot zmnožek rezalne hitrosti, podajanja in globine reza:

where T_s, T_c, T_i and V are the tool set-up time, the tool change time, the time during which the tool does not cut and the volume of the removed metal. In some operations the T_s, T_c, T_i and V are constants, so that T_p is a function of *MRR* and *T*.

- The metal removal rate (*MRR*). *MRR* can be expressed by analytical derivation as the product of the cutting speed, the feeding rate and the cutting depth:

$$MRR = 1000 \cdot v \cdot f \cdot a \qquad (2)$$

- Obstojnost orodja (T). Obstojnost orodja je merjena kot povprečen čas med menjavami ali ostrenjem orodja. Zveza med dobo trajanja orodja in parametri je podana z dobro znanim Taylorjevim obrazcem:

- Tool-life (T). The tool-life is measured as the average time between tool changes or tool sharpenings. The relation between the tool life and the parameters is expressed with the well-known Taylor's formula:

$$T = \frac{k_T}{v^{\alpha_1} \cdot f^{\alpha_2} \cdot a^{\alpha_3}} \quad (3),$$

kjer so k_T, α_1, α_2 *in* α_3, vedno pozitivni stalni parametri, določeni statistično [8].

where k_T, α_1, α_2 and α_3, which are always positive constant parameters, are determined statistically [8].

2. Stroški opravila
Stroške obdelave lahko izrazimo kot stroške na izdelek (C_p). Pri stroških opravila ločimo dve veličini, povezani z rezalnimi parametri (T, T_p) [5]:

2. Operation cost
The operation cost can be expressed as the cost per product (C_p). In the cost of the operation two values connected with the cutting parameters (T, T_p) [5] are distinguished:

$$C_p = T_p \cdot \left(\frac{C_t}{T} + C_l + C_0 \right) \quad (4),$$

kjer so C_t, C_l in C_0 orodni stroški, stroški dela in režijski stroški. V določenih operacijah so C_t, C_l *in* C_0 neodvisni od rezalnih parametrov.

where C_t, C_l and C_0 are the tool cost, the labour cost and the overhead cost respectively. In some operations C_t, C_l and C_0 are independent of the cutting parameters.

3. Kakovost obdelave
Najpomembnejše merilo za oceno kakovosti površine je hrapavost, izračunana po:

3. Cutting quality
The most important criterion for the assessment of the surface quality is roughness, which is calculated according to:

$$R_a = k \cdot v^{x_1} \cdot f^{x_2} \cdot a^{x_3} \quad (5),$$

kjer so x_1, x_2, x_3 in k stalnice, ki pripadajo specifični kombinaciji orodje – obdelovanec.

where x_1, x_2, x_3 and k are the constants relevant to a specific tool-workpiece combination.

Na sliki 1 je na temelju zgornje razprave prikazana hierarhična struktura ciljev, prilastkov in rezalnih parametrov.

Based on the above discussion, a hierarchical structure of the objectives, attributes and cutting parameters is depicted in Figure 1.

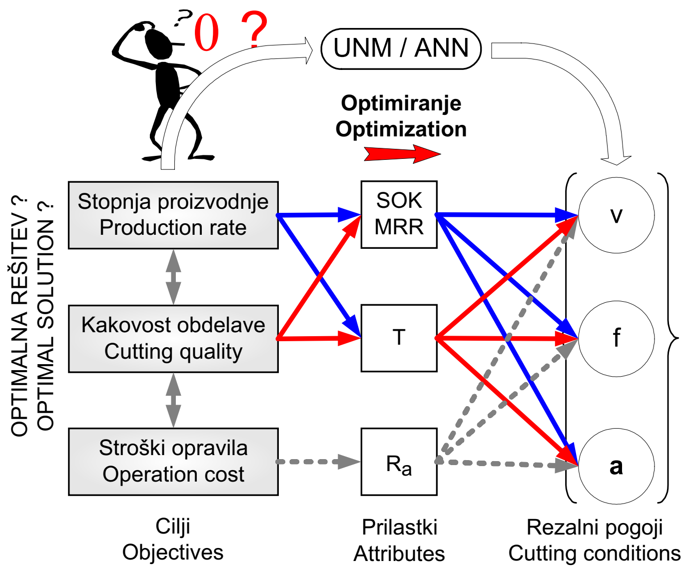
Da bi lahko ovrednotili medsebojne vplive in učinke med dejavniki ter dobili celostni pregled nad vrednostnim sistemom podjetja, je priporočljivo določiti večprilastno funkcijo proizvajalca (y) [5], ki pomeni zmožnost podjetja – proizvajalca. Večprilastna vrednostna funkcija je definirana kot funkcija z dejanskimi vrednostmi, ki priredi dejansko vrednost vsaki večprilastni alternativi, tako da je bolj zaželena alternativa povezana z večjo vrednostjo indeksa kakor manj zaželena alternativa. Izbrana je naslednja večprilastna vrednostna funkcija proizvajalca [5].

In order to ensure an evaluation of the mutual influences and the effects between the objectives, and to be able to obtain an overall survey of the manufacturer's value system it is recommendable to determine the multi-attribute function of the manufacturer (y) [5] representing the company's (or manufacturer's) overall preference. A multi-attribute value function is defined as a real-valued function that assigns a real value to each multi-attribute alternative, in such a way that a more preferable alternative is associated with a larger value index than a less preferable alternative. The following manufacturer's implicit value function [5] is selected:

$$y = 0,42 \cdot e^{(-0,22Tp)} + 0,36 \cdot e^{(-0,32Cp)} + 0,17 \cdot e^{(-0,26Ra)} + \frac{0,05}{\left(1 + 1,22 \cdot T_p \cdot C_p \cdot R_a\right)} \quad (6).$$

Celostni postopek določevanja najprimernejših rezalnih parametrov je postopek z največjo večprilastne posredne funkcije proizvajalca. Natančneje, zanima nas modeliranje večprilastnih vrednostnih funkcij z nevronskimi mrežami. Vsak proizvajalec ima svojo obliko funkcije (y); to pomeni, da ima tudi svoje drugačne optimalne rezalne pogoje.

One global approach to determining the most desirable cutting parameters is by maximising the manufacturer's implicit multi-atttribute function. Specifically, we are interested in modelling a manufacturer's implicit multi-attribute value functions by neural networks. Every manufacturer has its own form of the function (y); it means that it also has its own different optimum cutting conditions.



Sl. 1. *Prikaz hierarhične strukture dejavnikov, prialstkov in rezalnih parametrov*
Fig. 1. *A hierarchical structure of the objectives, attributes and cutting parameters*

1. 2 Določitev omejitev

Obstaja več dejavnikov, ki omejujejo rezalne parametre. Ti dejavniki običajno izvirajo iz tehnoloških in organizacijskih specifikacij. Upoštevane so naslednje omejitve:

1. Dovoljeno območje rezalnih pogojev
   Zaradi omejitev na stroju in rezalnem orodju ter varnosti pri obdelavi so rezalni parametri omejeni z spodnjo in zgornjo dopustno mejo:

1.2 Definition of constraints

There are several factors limiting the cutting parameters. Those factors usually originate from technical specifications and organisational considerations. The following constraints are taken into account:

1. Permissible range of cutting conditions.
Due to the limitations of the machine and the cutting tool and due to the safety of the machining the cutting parameters are limited by upper and lower limits:

$$v_{min} \leq v \leq v_{max}, f_{min} \leq f \leq f_{max}, a_{min} \leq a \leq a_{max} \quad (7).$$

2. Posredne omejitve, ki izhajajo iz karakteristik orodja in zmogljivosti stroja.
   Za izbrano orodje poda omejitve rezalnih pogojev proizvajalec orodja. Omejitev na stroju pa sta rezalna moč, rezalna sila. Podobno so s fizikalnimi lastnostmi določene obdelovalne karakteristike materiala obdelovanca.
   - Rezalna moč in sila
     Potrebna rezalna moč za opravilo odrezovanja, ne sme prekoračiti dejanske moči stroja:

2. Implied limitations issuing from the tool characteristics and the machine capacity.
   For the selected tool the tool maker specifies the limitations of the cutting conditions. The limitation on the machine is the cutting power and the cutting force. Similarly, the machining characteristics of the workpiece material are determined by the physical properties.
   – Cutting power and force
     The cutting power required for the cutting operation should not exceed the effective power of the machine tool:

$$P = \frac{F \cdot v}{6122,45 \cdot \eta} \quad (8),$$

kjer je η mehanski izkoristek stroja in je *F* podana z naslednjim obrazcem:

where η is the mechanical efficiency of the machine and *F* is given by the following formula:

$$F = k_F \cdot f^{\beta_2} \cdot a^{\beta_3} \quad (9).$$

Pri vpeljavi enačbe (9) v enačbo (8) dobimo naslednje:

When Equation (9) is introduced into Equation (8) the following is obtained:

$$P = k_n \cdot v \cdot f^{\beta_2} \cdot a^{\beta_3} \quad \text{kjer je/where} \quad k_n = \frac{k_F}{(6122,45 \cdot \eta)} \quad (10).$$

Omejitve moči in rezalne sil so enake:

The limitations of the power and cutting force are equal to:

$$P(v, f, a) \leq P_{max}\ ,\ F(v, f, a) \leq F_{max} \qquad (11).$$

Problem optimizacije rezalnih parametrov je moč zapisati kot naslednji večciljni optimizacijski problem: min $T_p\ (v, f, a)$, min $C_p\ (v, f, a)$, min $R_a\ (v, f, a)$ podrejen omejitvam (7) do (11).

The problem of the optimization of the cutting parameters can be formulated as the following multi-objective optimization problem: min $T_p\ (v, f, a)$, min $C_p\ (v, f, a)$, min $R_a\ (v, f, a)$ subject to constraints (7) to (11).

2 PRILAGODITEV TOPOLOGIJE UNM K PROBLEMU OPTIMIRANJA

2 THE ANN TOPOLOGY ADAPTATION TO THE OPTIMIZATION PROBLEM

Za določitev večprilastne vrednostne funkcije lahko uporabimo popularne večnivojske usmerjene nevronske mreže ali žarkovne nevronske mreže. Večnivojska usmerjena nevronska mreža se je izkazala kot odličen splošni približek nelinearnih funkcij. Če je zmožna približati poljubno funkcijo, potem je z njo mogoče predstaviti poljubno večprilastno posredno funkcijo proizvajalca. UNM potrebuje tri vhodne nevrone za tri parametre: *v, f* in *a*. Če vrednosti *v, f, a* in *y* niso v enakem merilu, je treba vse podatke normalizirati. Izhod iz nevronske mreže je ocenjena večprilastna dejanska vrednost funkcije (*y*), zato je potreben le en izhodni nevron (sl. 2).

Pri postopku optimiranja so uporabljene usmerjene nevronske mreže z dvema ravnema. Vsebovale so 3 nevrone v vhodni ravni in 3, (6) nevronov v skritih ravneh. UNM so bile naučene z naslednjimi parametri: rezalni pogoji (*v, f, a*) in vrednost večprilastne funkcije proizvajalca (*y*). Učenje UNM je bilo izvedeno s podatki, ki vsebujejo 20 učnih vzorcev. Za testiranje naučene mreže je bilo uporabljenih še dodatnih 20 vzorcev. Učenje mreže je takšen postopek vzajemnega nastavljanja uteži na povezavah, da so napake napovedi na učnem nizu najmanjše. Ker je postopek učenja iterativen, je treba celotni učni niz predstavljati mreži tako dolgo, dokler celotna napaka ne doseže najmanjšo sprejemljivo vrednost. Poglavitni cilj pri učenju poljubne nevronske mreže je zmanjšati skupno napako mreže. Srednja absolutna napaka (*SAN - MAE*) je določena z:

For assessing the multi-ttribute value function we can use the popular multilayer feed-forward neural networks or radial basis networks. The multilayer feed-forward neural network has proved to be an excellent universal approximator of non-linear functions. If it is capable of approximating any nonlinear function, then it is possible to represent with it any manufacturer's implicit multi-attribute function. The ANN needs three input neurons for three parameters: *v, f* and *a*. If the values *v, f, a* and *y* are not ON the same scale, all the data must be normalized. The output from the neural network is a real valued multi-attribute value function (*y*), therefore only one output neuron is necessary (Figure 2).

For the optimization process, two-layer feed-forward neural networks were used. They contain three neurons in the input layer, and three, six in hidden layers. The ANN were trained with the following parameters: cutting conditions (*v, f, a*) and the value of the multi-attribute function of the manufacturer (*y*). The training of the ANN was made with the data of 20 training examples. An additional 20 examples were used to test the trained network. Network training is the process of interactively adjusting the interconnection weights in such a way that the prediction errors on the training set are minimized. Since the learning process is iterative, the entire training set will have to be presented to the network over and over again, until the global error reaches a minimum acceptable value. The basic goal when training any neural network is to minimize the overall error of the network. The Mean Absolute Error (MAE) is defined by:

$$(\,|\,y_1 - g(x_1, W)| + |\,y_1 - g(x_1, W))\,| + ... + |\,y_m - g(x_m, W)|\,)\,/\,m \qquad (12),$$

kjer je $z_m = (x_i, y_i)$, $i = 1,...,m$, zaporedne *m* učnih primerov. *W* je utežna matrika mreže in $g(X,W)$ je rezultirajoča funkcija mreže.

Med postopkom učenja in testiranja nevronska mreža izračunava vso naslednjo statistiko:

- Napaka učenja (*NU - ETrn*). Celotna napaka za učni niz, izračunana po enačbi (12).
- Največja napaka učenja (*NNU - ETrnMax*). Določena je kot največja absolutna razlika med napovedanim in želenim izhodom mreže v učnem nizu.
- Napaka Testiranja (*NT - ETst*). Celotna napaka za

where $z_m = (x_i, y_i)$, $i = 1,...,m$, is a sequence of m training examples, *W* is the network weight matrix and $g(X,W)$ is the resulting network function.

In the course of training and testing, the neural network computes all of the following statistics:

- Training error (*ETrn*). The overall error for the Training Set calculated by Equation 12.
- Max Training error (*ETrnMax*). The largest absolute difference between an actual output and its desired output in the Training Set.
- Test error (*ETst*). The overall error for the Test Set

testni niz, izračunana po enačbi (12).
- Največja napaka testiranja (*NNT - ETstMax*). Določena je kot največja absolutna razlika med napovedanim in želenim izhodom mreže v testnem nizu.

Ko je večprilastna vrednostna funkcija ocenjena, bo uporabljena nevronska mreža, da razbere proizvajalčeve celotne prednosti in tako omeji večciljni optimizacijski problem na naslednji enociljni problem iskanja največje vrednosti:

calculated by Equation (12).
- Max Test error (*ETstMax*). The largest absolute difference between an actual output and its desired output in the Test Set.

Once a multi-attribute value function is validated the neural network will be used to decipher the manufacturer's overall preference and the multi-objective optimization problem will be reduced to a single objective maximization problem as follows:

$$\max_{v,f,a} y\left[T_p(v,f,a),\ C_p(v,f,a), R_a(v,f,a)\right]$$

Za ocenitev posameznih učinkov učnih parametrov na performance nevronske mreže je bilo testirano okrog sto mrež. Na podlagi rezultatov lahko podamo naslednje sklepe:
- Stopnje učenja manjše od 0,3 dajo sprejemljive napake napovedi, če pa hočemo čim bolj zmanjšati število ponovitev učenja in doseči majhne napake napovedi, mora biti stopnja učenja med 0,01 in 0.2.
- Za čim večje zmanjšanje napak napovedi je primerna vztrajnost učenja med 0,001 in 0,005. Toda vrednost vztrajnosti učenja ne sme presegati 0,004, če je treba čim bolj zmanjšati število ponovitev učenja.
- Optimalno število nevronov v skritih ravneh je od 3 do 6.
- Naučene mreže s sigmoidno prenosno funkcijo v vseh svojih nevronih dajo najmanjše napake napovedi, medtem ko mreže s hiperbolično in sinusno funkcijo dajo največjo in skoraj največjo napako napovedi.
- Mreže, ki uporabljajo sinusno funkcijo, terjajo najmanjše število ponovitev učenja, nakar sledi arctg, medtem ko mreže, ki uporabljajo hiperbolično, terjajo največje število ponovitev učenja.

To evaluate the individual effects of training parameters on the performance of a neural network about one hundred networks were tested. From the results the following conclusions can be drawn:
- Learning rates below 0.3 give acceptable prediction errors, while learning rates must be between 0.01 and 0.2 to minimize the number of training cycles and obtain low predictions errors;
- To minimize the estimation errors, momentum rates between 0.001 and 0.005 are good. However, the momentum rate should not exceed 0.004 if the number of training cycles is also to be minimized;
- The optimum number of hidden layer nodes is from 2 to 6;
- Networks trained with the sigmoid transfer function in all their neurons give the smallest prediction errors, while those employing the hyperbolic tangent and sine give the highest and next-highest prediction errors, respectively;
- Networks that employ the sine function require the lowest number of training cycles, followed by the arctan, while those that employ the hyperbolic function require the highest number of training cycles;

2.1 Metodologija optimiranja opravila struženja

Za določitev optimalnih rezalnih pogojev je treba izvesti naslednje korake:
1. Vnos vhodnih podatkov
   - tehnološke in pripravljalno zaključne čase (nastavitveni čas, čas menjave orodja, neproduktivni čas orodja),
   - stroške (stroške orodja, stroške dela, režijske stroške),
   - omejitve (dovoljeno območje rezalnih pogojev, F_{max}, P_{max}).
2. Generiranje naključnih rezalnih pogojev.
3. Izračun preostalih veličin ($P, F, SOK, C_p, T, R_a, T_p, y$).
4. Priprava podatkov za učenje in testiranje UNM. Združitev rezalnih pogojev in preostalih izračunanih veličin v podatkovno matriko. Sledi normalizacija podatkov v matriki. Razčlenitev podatkovne matrike na vhodni in izhodni vektor. Razdelitev vhodno – izhodnega vektorja na niza podatkov za učenje in testiranje.
5. Uporaba UNM. Cilj nevronske mre□e je napovedati

2.1 Optimization methodology of the turning operation

To determine the optimal working conditions the following steps must be accomplished:
1. Entering of the input data:
   - technological and preparing/finishing times (set-up time, tool-change time, tool-idle time)
   - costs (tool cost, labour cost, overheads)
   - constraints (permissible range of cutting conditions, F_{max}, P_{max}).
2. Generation of random cutting conditions.
3. Calculation of other values ($P, F, MRR, C_p, T, R_a, T_p, y$)
4. Preparation of data for training and testing of ANN. Uniting of cutting conditions and other calculated values into a data matrix. Normalization of the data in the matrix follows. Breakdown of the data matrix into the input and output vector. Distribution of the input / output vector into the two sets for training and testing.
5. Use of the ANN. The purpose of the neural network is to predict the manufacturer´s value func-

vrednostno funkcije proizvajalca (y) pri poljubno izbranih rezalnih pogojih:

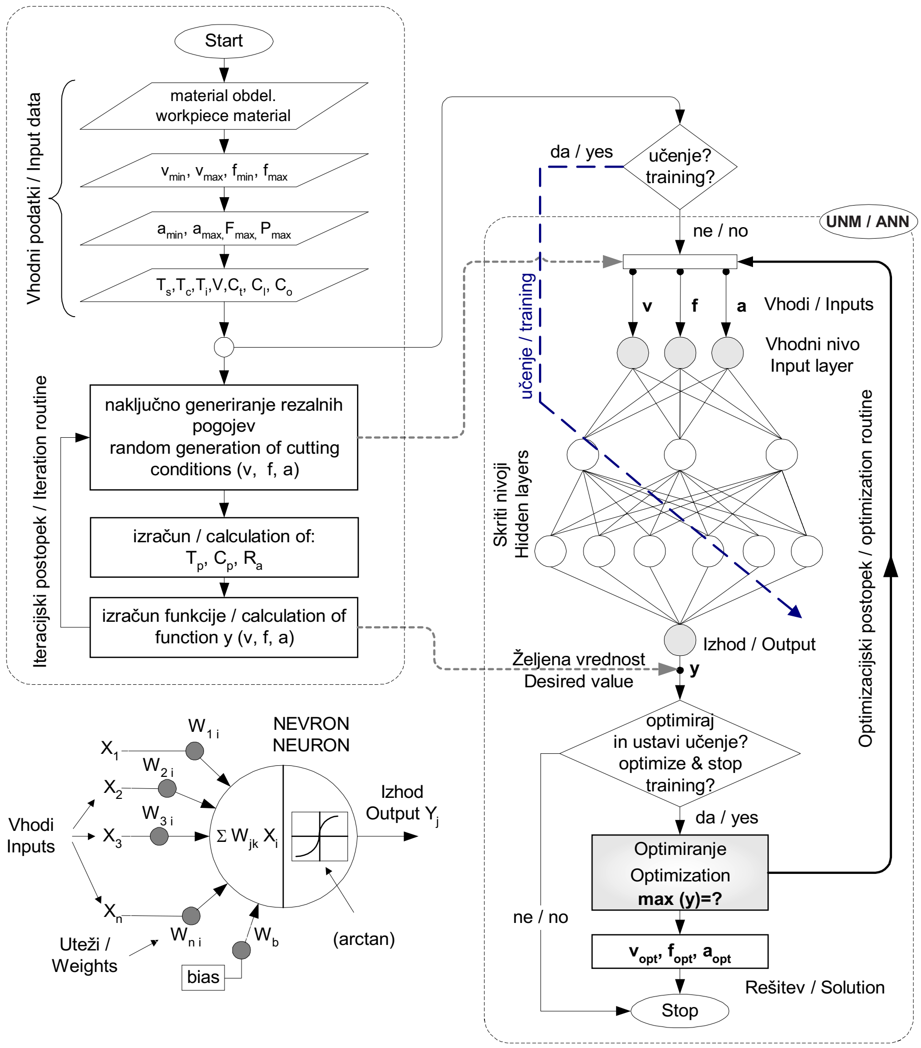
- izbira zgradbe UNM ter iskanje optimalnih parametrov učenja,
- postopek učenja UNM z uporabo niza za učenje,
- testiranje naučene UNM. Testni niz je treba uporabiti za potrditev nevronske mreže, ki je rezultat nadzorovanega učenja. Izkustveni model je izdelan in pripravljen za uporabo, če je testiranje uspešno in je napaka napovedi (*NN - ETst*) v dovoljenih mejah.

6. **Postopek optimizacije**. Rezalni pogoji, pri katerih ima funkcija (y) največjo vrednost, so optimalni rezalni pogoji. Iščemo ekstrem funkcije (y) ob upoštevanju omejitvenih enačb. Ker pa je funkcija (y) podana z ANN, to pomeni, da iščemo ekstrem nevronske mreže. Z omejitvenimi enačbami je podano območje, na katerem iščemo ekstrem. Izpis optimalnih rezalnih pogojev in njim pripadajočih spremenljivk.

tion (y) in the case of randomly selected cutting conditions:

- Selection of the architecture of the ANN and searching for the optimum training parameters.
- Procedure of training the ANN by using the training set.
- Testing of the trained ANN. The testing set is to be used to verify the resultant neural network from supervised learning. If the testing is successful and the error of the prediction of *ETst* is within the permissible limits, the empirical model is finished and ready for use.

6. **Optimization process**; The cutting conditions where the function (y) has the maximum are the optimum cutting conditions. The extreme of the function (y), with consideration of the limitation equations, is searched for. Since the function (y) is expressed with the ANN, it means that the extreme of the neural network is searched for. The area in which the extreme is searched for is defined with the limitation equations. Survey of the optimum cutting conditions and the variables relevant to them.



Sl. 2. *Algoritem predlaganega postopka za optimiranje rezalnih parametrov z matematičnim načelom delovanja nevrona*

Fig. 2. *Algorithm of the proposed approach to cutting-parameter optimization with the mathematical principle of the functioning of the neuron*

7. Grafični prikaz rezultatov in statistike optimiranja. Slika 2 prikazuje algoritem opisanega postopka.

7. Graphical representation of the results and the optimization statistic. Figure 2 shows the algorithm of the described procedure.

3 PRIMER UPORABE

3 AN APPLICATION EXAMPLE

Za demonstracijo predlaganega postopka za optimiranje postopka obdelave je v nadaljevanju obravnavan nazoren primer. Zadana naloga je poiskati optimalne rezalne pogoje za postopek struženja. Na RNK stroju želimo obdelati surovec iz medenine (Cu Zn 39 Pb 2.00; trdota po Brinellu HB =105; natezna trdnost-440 MPa) z orodjem iz hitroreznega jekla. Naloga je poiskati optimalne rezalne pogoje za postopek struženja. Vrednosti koeficientov so statistično določene na podlagi izkustveno izmerjenih podatkov (obstojnost, hrapavost, čas obdelave, rezalna sila).

To demonstrate the proposed approach to machining-process optimization an illustrative example is discussed, as follows. On the CNC lathe we want to machine a brass workpiece (Cu Zn 39 Pb 2.00; Brinell hardness number *HB* =105; Tensile strength-440 MPa) by means of a tool made from HSS. The task is to find the optimum cutting conditions for the process of turning. The values of the coefficients are statistically determined on the basis of the data measured experimentally (tool life, roughness, time of manufacture, cutting force).

Vrednosti koeficientov:

Values of coefficients:

T_s = 0,12 min,	T_c = 0,26 min,	T_i = 0,04 min	V = 231376 mm
C_t = 13,55 \$	C_1 = 0,31 \$/min,	C_0 = 0,08 \$/min	η = 36 %
k = 1,001	x_1 = 0,0088	x_2 = 0,3232	x_3 =0,3144
k_T = 1575134.21	α_1 = 1,70	α_2 = 1,55	α_3 = 1,22
k_F = 1,38	β_1 = 0	β_2 = 1,18	β_3 = 1,26

Ciljne funkcije:

The objective functions:

$$\min T_p = 0{,}16 + 231276\,(1 + 0{,}26/T)/MRR$$

$$\min C_p = (13{,}55/T + 0{,}39) \cdot T_p$$

$$\min\ R_a\ =\ 0{,}0088 \cdot v + 0{,}3232 \cdot f + 0{,}3144 \cdot a$$

$$T = 1575134{,}21 \cdot v^{-1{,}70} \cdot f^{1.55} \cdot a^{-1.22};\ MRR = 1000 \cdot 9{,}81 \cdot v \cdot f \cdot a,\ F = 1{,}38 \cdot f^{1{,}18} \cdot a^{1{,}26},$$

$$P = 0{,}000626 \cdot v \cdot f^{0{,}24} \cdot a^{0{,}11}$$

Omejitve:

The constraints:

$$v_{min} \le v \le v_{max},\ f_{min} \le f \le f_{max},\ a_{min} \le a \le a_{max},\ F \le F_{max},\ P \le P_{max},$$

$$v_{min} = 70\ \text{m/min},\ v_{max} = 100\ \text{m/min},\ f_{min} = 0{,}1\ \text{mm/rev},\ f_{max} = 1{,}8\ \text{mm/rev},$$

$$a_{min} = 0{,}1\ \text{mm},\ a_{max} = 4{,}0\ \text{mm},\ F_{max} = 250\ \text{N},\ P_{max} = 2\ \text{kW}$$

V preglednicah 1 in 2 je seznam dvajsetih vadbenih in dvajsetih testnih primerov. Rezalni pogoji so generirani naključno znotraj predpisanih mej. Druge vrednosti so izračunane po enačbah (1) do (5) pri izbranih rezalnih pogojih. Izbrana je naslednja implicitna vrednostna funkcija proizvajalca [5]:

The Table 1 and Table 2 contain a list of 20 training and 20 testing examples. The cutting conditions are generated at random inside the specified limits. The other values are calculated according to Equations (1-5) with selected cutting conditions. The following manufacturer's implicit value function [5] is selected:

$$z\left(T_p, C_p, R_a\right) = 0{,}42 \cdot e^{(-0{,}22Tp)} + 0{,}36 \cdot e^{(-0{,}32Cp)} + 0{,}17 \cdot e^{(-0{,}26Ra)} + 0{,}05 / \left(1 + 1{,}22 \cdot T_p \cdot C_p \cdot R_a\right) \quad (13).$$

Naučena nevronska mreža je testirana na podlagi vhodno-izhodnih vzorcev 21-40. Celotna napaka *MAE* je 1,5x10^{-4}. Naučena mreža pri poljubnih rezalnih pogojih približa funkcijo (z) z zadovoljivo natančnostjo, zato jo uporabimo za

The trained neural network is tested based on the input-output samples 21–40. The overall *MAE* error is 1.5x10^{-4}. With any cutting conditions the trained network approximates the function (z) with satisfactory accuracy; therefore, it is used for the

Preglednica 1. *Naključni podatki za učenje UNM*
Table 1. *Random data for training of the ANN*

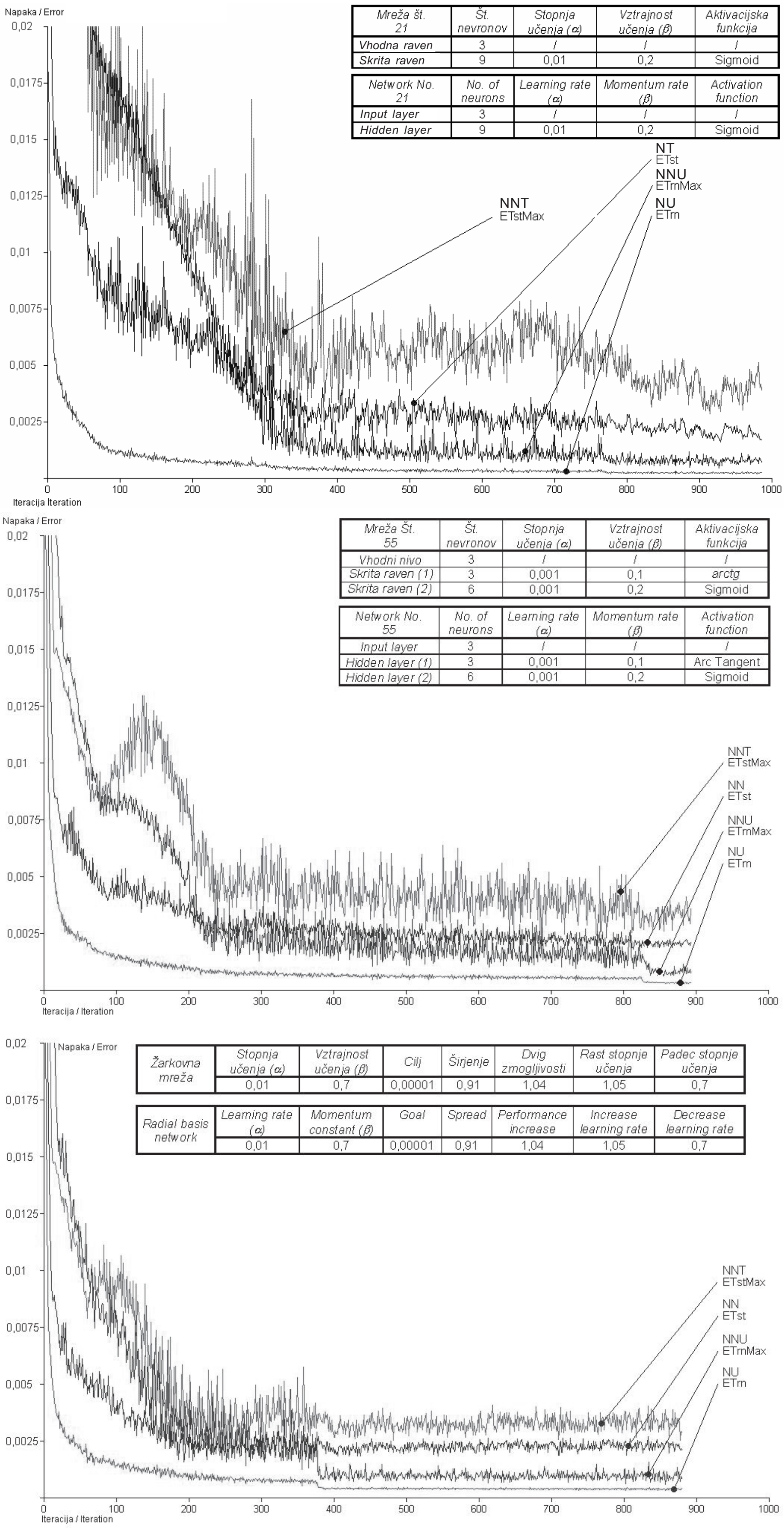
	v m/min	f mm/rev	a mm	T_p min	C_p \$	R_a µm
1.	70,3844	1,6234	3,2082	0,7925	0,3919	2,1527
2.	75,302	0,5613	3,2745	1,8324	0,7571	1,8736
3.	81,0487	0,9458	3,5282	1,0166	0,4621	2,1282
4.	72,9766	1,5974	1,4033	1,5755	0,6767	1,5997
5.	89,59	1,2261	2,9438	0,8768	0,4224	2,1102
6.	77,3172	0,2184	2,8271	5,0068	1,9761	1,6398
7.	76,7329	1,2499	3,419	0,8668	0,4137	2,1541
8.	71,4226	0,8111	1,2602	3,33	1,3376	1,2869
9.	78,3444	1,3788	1,422	1,6674	0,7104	1,5821
10.	74,9697	1,0642	1,5767	2,0003	0,831	1,4994
11.	75,1765	1,1894	1,8672	1,5469	0,661	1,633
12.	79,9521	1,742	1,205	1,5399	0,6681	1,6454
13.	71,0584	0,8159	2,3007	1,8955	0,7854	1,6123
14.	79,8531	1,5932	0,3439	5,4488	2,17	1,3258
15.	87,8129	1,6075	3,5003	0,6245	0,3497	2,4016
16.	71,5664	1,6482	2,8673	0,8454	0,4108	2,0639
17.	74,9438	0,6955	2,7845	1,755	0,7306	1,7597
18.	71,4768	0,971	0,919	3,7881	1,5172	1,2318
19.	85,0128	0,4805	3,8122	1,6294	0,6802	2,1107
20.	78,3126	0,1202	1,2983	19,0971	0,4619	1,1362

Preglednica 2. *Naključni podatki za testiranje UNM*
Table 2. *Random data for testing of an ANN*

	v m/min	f mm/rev	a mm	T_p min	C_p \$	R_a µm
21.	89,9495	0,7281	3,4458	1,1863	0,5219	2,1102
22.	74,553	1,7638	0,2244	8,0028	3,1619	1,2967
23.	82,6487	0,6876	1,2062	3,5362	1,418	1,3288
24.	74,0273	0,2431	1,806	7,2782	2,8602	1,2978
25.	73,8974	1,762	1,1272	1,7375	0,7401	1,5742
26.	87,1717	0,9584	3,3609	0,9852	0,4535	2,1335
27.	79,641	1,6031	1,7164	1,217	0,5464	1,7586
28.	76,9498	1,6444	0,9989	1,9916	0,8362	1,5227
29.	71,2062	0,1035	2,5027	12,71	4,9709	1,4469
30.	71,7795	1,648	2,9632	0,8213	0,4028	2,0959
31.	83,7713	0,1625	1,0278	16,6952	6,5277	1,1129
32.	86,8299	1,1085	1,2473	2,0882	0,8689	1,5145
33.	74,9683	1,6027	3,0694	0,7887	0,3928	2,1427
34.	86,3879	1,6548	2,8	0,8724	0,4092	2,3131
35.	84,4258	0,5777	0,2982	16,0698	6,2926	1,0234
36.	85,9883	0,9272	2,5233	1,3111	0,5716	1,8497
37.	88,8055	1,62	2,0845	0,9329	0,4491	1,9605
38.	79,7766	0,7753	1,1405	3,4408	1,382	1,3112
39.	86,8305	1,1165	1,6594	1,5993	0,6835	1,6467
40.	83,3854	1,2646	2,9355	0,9087	0,4316	2,0654

nadaljevanje postopka optimiranja. Sledi iskanje ekstrema funkcije (y), ki je simulirana z nevronsko mrežo. Vsi koraki postopka se izvedejo samodejno v dveh sekundah. V stolpcu 2 in 3 preglednice 3

continuation of the optimization process. Searching for the extreme of the function (y), simulated by neural network, then follows. All the steps of the process are executed automatically within a time of 2 sec-



Mreža št. 21	Št. nevronov	Stopnja učenja (α)	Vztrajnost učenja (β)	Aktivacijska funkcija
Vhodna raven	3	/	/	/
Skrita raven	9	0,01	0,2	Sigmoid

Network No. 21	No. of neurons	Learning rate (α)	Momentum rate (β)	Activation function
Input layer	3	/	/	/
Hidden layer	9	0,01	0,2	Sigmoid

Mreža Št. 55	Št. nevronov	Stopnja učenja (α)	Vztrajnost učenja (β)	Aktivacijska funkcija
Vhodni nivo	3	/	/	/
Skrita raven (1)	3	0,001	0,1	arctg
Skrita raven (2)	6	0,001	0,2	Sigmoid

Network No. 55	No. of neurons	Learning rate (α)	Momentum rate (β)	Activation function
Input layer	3	/	/	/
Hidden layer (1)	3	0,001	0,1	Arc Tangent
Hidden layer (2)	6	0,001	0,2	Sigmoid

Žarkovna mreža	Stopnja učenja (α)	Vztrajnost učenja (β)	Cilj	Širjenje	Dvig zmogljivosti	Rast stopnje učenja	Padec stopnje učenja
	0,01	0,7	0,00001	0,91	1,04	1,05	0,7

Radial basis network	Learning rate (α)	Momentum constant (β)	Goal	Spread	Performance increase	Increase learning rate	Decrease learning rate
	0,01	0,7	0,00001	0,91	1,04	1,05	0,7

Sl. 3. *Zmanjševanje napak pri nadzorovanem učenju različnih nevronskih mrež*
Fig. 3. *Decrease of errors during supervised training of different neural networks*

Preglednica 3. *Primerjava rezultatov*
Table 3. *Comparison of results*

	UČENJE / TRAINING				PRESKUŠANJE / TESTING		
	z (T_p, C_p, R_a)	y (T_p, C_p, R_a)	z - y		z (T_p, C_p, R_a)	y (T_p, C_p, R_a)	z - y
1.	0,795	0,7945	0,0005	21.	0,7456	0,7442	0,0014
2.	0,6796	0,6786	0,001	22.	0,3257	0,3255	0,0002
3.	0,7666	0,7664	0,0002	23.	0,5474	0,5467	0,0007
4.	0,7153	0,716	-0,0007	24.	0,3516	0,3499	0,0017
5.	0,7846	0,7847	-0,0001	25.	0,698	0,698	0
6.	04443	0,4443	0	26.	0,7703	0,77006	0,00024
7.	0,7853	0,78531	-0,00001	27.	0,7518	0,7502	0,0016
8.	0,5644	0,5655	-0,0011	28.	0,6731	0,6726	0,0005
9.	0,7057	0,7055	0,0002	29.	0,2161	0,216	0,0001
10.	0,6739	0,673	0,0009	30.	0,7927	0,8047	-0,012
11.	0,7179	0,7162	0,0017	31.	0,1829	0,1816	0,0013
12.	0,7172	0,7171	0,0001	32.	0,6641	0,6629	0,0012
13.	0,6813	0,6827	-0,0014	33.	0,7956	0,8146	-0,019
14.	0,4294	0,429	0,0004	34.	0,7872	0,787	0,0002
15.	0,8095	0,8107	-0,0012	35.	0,191	0,1909	0,0001
16.	0,7904	0,7905	-0,0001	36.	0,7383	0,739	-0,0007
17.	0,6913	0,6937	-0,0024	37.	0,781	0,7811	-0,0001
18.	0,5327	0,5289	0,0038	38.	0,5551	0,5532	0,0019
19.	0,6942	0,6941	0,0001	39.	0,7111	0,7122	-0,0011
20.	0,1661	0,1658	0,0003	40.	0,782	0,7808	0,0012

so prikazane po enačbi (13) izračunane vrednosti funkcije (z) ter vrednosti (y), ki jih napove UNM.

Slika 3 prikazuje monotono zmanjševanje vrednosti vseh napak *(NT, NNT, NU NNU*) s številom iteracij med postopkom učenja in preskušanja za različne konfiguracije mrež in različne učne parametre. Najmanjša napaka testiranja je dosežena blizu iteracije 830 z mrežo št. 55. Slika 3 prikazuje zgradbo najboljše nevronske mreže (št. 55).

onds. The columns 2 and 3 of Table 3 show the values of the function (z), calculated according to Equation (13), and the values (y) predicted by the ANN.

Figure 3 shows the uniform falling of the value of all errors *(ETst, ETstMax, ETrn, ETrnMax*) with the number of iterations during the training and testing process for different network configurations and different training parameters. The smallest error of testing (*ETst*) is reached near iteration 830, with network No. 55. Figure 3 shows the architecture of the best neural network (No. 55).

4 OBRAVNAVA REZULTATOV

Izvedeni so potrditveni preizkusi za ovrednotenje usmerjenih in žarkovnih nevronskih mrež. Usmerjene nevronske mreže dajo bolj natančne rezultate, vendar pa terjajo več časa za učenje in testiranje. Žarkovne mreže zahtevajo več nevronov kot standardne usmerjene nevronske mreže z učnim algoritmom vzvratnega širjenja napake (BPN), toda njihova izdelava traja le delček časa, ki je potreben za učenje usmerjene mreže. Preglednica 4 prikazuje izbrane optimalne rezalne parametre ter ustrezajoče vrednosti veličin, ki temeljijo na največjih vrednostih posredne funkcije (y), ki jo napove UNM. Prva vrstica prikazuje optimalne rezane pogoje, izračunane z matematičnim orodjem [9], druga vrstica pa rezalne pogoje, določene s postopkom UNM.

4 DISCUSSION OF RESULTS

Verification experiments are performed to evaluate feed-forward and Radial Basis networks. The Radial basis neural networks require more neurons than the standard feed-forward neural networks with the Back Propagation (BPN) Learning Rule. However, the conceiving of radial basis neural networks lasts only a part of the time necessary for the training of the feed-forward network. Table 4 shows the selected optimum cutting conditions and the corresponding values of the variables based on maximization of the implicit function (y) predicted by the ANN. The first line shows the optimal cutting conditions calculated by the mathematical tool [9], whereas the second line shows the cutting conditions determined by the ANN approach.

Preglednica 4. *Rezultati, pridobljeni z UNM*
Table 4. *Results obtained by ANN*

Model	v m/min	f mm/rev	a mm	T_p min	C_p \$	R_a µm
idelana rešitev [9] ideal solution	87,01	1,8	3,6	0,576	0,341	2,46
UNM / ANN; y	86,6	1,74	3,64	0,576	0,328	2,41

Model	MRR mm³/min	T min	F N	P kW	čas optimiranja s optimization time s
idelana rešitev ideal solution	557598,1	58,6	132,0	0,53	24
UNM / ANN; y	557581,3	60	128,6	0,56	2

Očitno je, da optimizacijski postopek, temelječ na UNM, zagotovi zadovoljiv približek k pravi optimalni rešitvi. Slika 4 prikazuje prostor rešitev, ki je omejen z določenimi omejitvami in ekstrem optimizacijske funkcije s pripadajočimi optimalnimi rezalnimi pogoji.

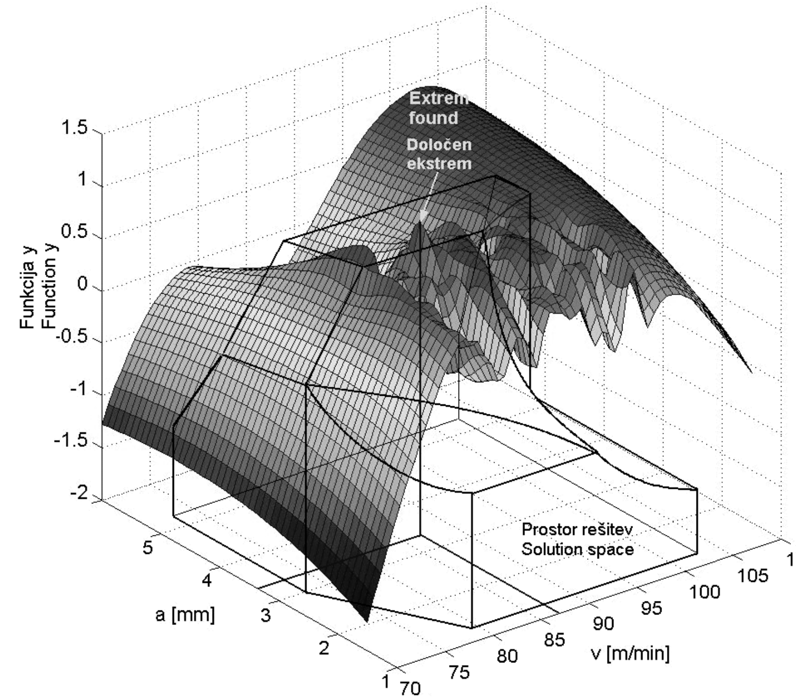
V opisanem delu uporabljena mreža (št. 55) je bila preizkušena s prej citiranimi metodami v literaturi s primerjanjem njenih rešitev z rešitvami iz [6] in [2]. Nevronski algoritem je napisan v MatLab-u 5.3 in deluje na osebnem računalniku.

V preglednici 5 so povzete glavne značilnosti teh problemov. Problem 1 je predlagan postopek z uporabo rutine UNM, ki je predstavljen v prispevku. Problem 2 predstavlja optimizacijski postopek z uporabo genetskih algoritmov. Tako parametri kakor nizi omejitev so enaki kakor v primeru 1. V problemu 3 je uporabljena tehnika LP. Na sliki 3 so prikazani

Clearly, the ANN-based optimization approach provides a sufficient approximation to the true optimal solution. Figure 4 shows the solution space limited by defined constrains and the extreme of the optimization function with relevant optimum cutting conditions.

The network (No.55) used for the work reported here was tested with the problems previously cited in the literature by comparing its solutions with those of [6] and [2]. The neural network algorithm was written in MatLab 5.3 and runs on a PC.

Table 5 summarizes the main features of these problems. Problem 1 is the proposed approach presented in this paper, using the ANN routine. Problem 2 represents the optimization approach using genetic algorithms. Both the parameters and the constraint sets are the same as in Problem 1. Problem 3 uses the LP technique. The user-specified parameters of the neural ap-



Sl. 4. *Z algoritmom UNM določen ekstrem in optimizacijska funkcija (y)*
Fig. 4. *Optimization function (y) with the extreme found by the ANN algorithm*

Preglednica 5. *Primerjava rezultatov med predlagano GA in metodo LP*
Table 5. *Comparison of the results for proposed, GA and LP aproaches*

	Model	Niz omejitev Constraint set	Iteracija Iteration	Optimalna rešitev / Optimum solution				Čas optimiranja s Optimiz. time s
				v_{opt} m/min	f_{opt} mm/rev	a_{opt} mm	C_p $	
1	UNM ANN	obstojnost; rezalna sila; moč; hrapavost površine, tool-life; cutting force [10]; power; surface roughness;	1-100 1-150 1-830 1-1300	97,1 99 86,6 86,3	1,8 1,3 1,74 1,74	3,9 2,9 3,64 3,61	0,62 0,78 0,33 0,34	0,1 0,15 2 4
2	GA [6]	obstojnost; rezalna sila; moč; hrapavost; tool-life; cutting force; power; surface raughness;	1-400 400-800 900-1300	96,9 91,5 87,01	1,8 1,8 1,7	3,1 3,3 3,5	0,69 0,44 0,4	4 8 11
3	LP [2]	rezalna sila; moč; hrapavost površine; stroški obdelave. cutting force; power; surface raughness; cutting cost	1	85	1,8	3,7	0,39	2

parametri nevronskega postopka, ki jih navede uporabnik. V našem primeru so bili po obsežnem eksperimentiranju določeni: zgradba UNM, tip napake, pravilo učenja, vhodna/prenosna funkcija, največje št iteracij, stopnja učenja, vztrajnost učenja, in metoda klasifikacije. Parametri skritih ravni in pravilo učenja so zelo občutljivi na število omejitev. Ti se nastavijo navadno takrat, ko je program naložen.

V preglednici 5 je prikazana primerjava rezultatov za primere 1, 2 in 3. Iz rezultatov primera 1, ki je predstavljen v preglednici 5, je jasno, da predlagan postopek značilno prekaša postopka GA in LP. Predlagan postopek je našel optimalno rešitev 0,33 že pri 1 do 830 iteracijah, medtem ko je pri genetskem postopku potrebno od 900 do 1300 iteracij za dosego rešitve 0,4. To pomeni, da ima predlagan postopek za 22,1% boljšo rešitev kakor postopek GA in za 17,3% boljšo rešitev kakor postopek LP.

5 SKLEP

V prispevku je opisan razvoj nevronskega optimizicijskega postopka za določevanje karakterističnih optimalnih rezalnih parametrov pri opravilih struženja. Rezultati, dobljeni s primerjanjem predlaganega postopka s tistimi iz nedavne literature, potrdijo njegovo učinkovitost. Izvedena je primerjava rezultatov nevronskega postopka z rezultati genetskih algoritmov in metodo linearnega programiranja. V vseh primerih je ugotovljeno, da se bolje obnese v smislu napovedanih vrednosti ciljne funkcije. Čeprav utegne biti modeliranje z nadzorovanim učenjem računsko intenzivno, je predlagan postopek bolj ugoden od interaktivnih postopkov, še posebej v sistemih proizvodnje za

proach are presented in Figure 3. In this case, the architecture of the ANN, the error type, the learning rule, the input/transfer function, the maximum number of iterations, the learning rate, the momentum rate and the classification method were set after extensive experimentation. The hidden-layer parameters and the learning rule are very sensitive to the number of constraints. These are normally set once the software is operational.

The comparison of the results of Problems 1, 2, and 3, respectively, are shown in Table 5. From the results of Problem 1, presented in Table 5, it is clear that the proposed approach significantly outperforms the GA and LP approach. The proposed approach found an optimal solution of 0.33 for as low as 1 to 830 runs, the genetic-based approach required as many as 900 to 1300 runs to find solution of 0.4 This means that the proposed approach has a 22.1% improvement over the solution found by the GA approach, and 17.3% over the LP approach.

5 CONCLUSION

This paper outlines the development of a neural optimization approach to determining the characteristic optimum cutting parameters for turning operations. The results obtained from comparing the proposed optimization approach with those taken from recent literature prove its effectiveness. The results of the neural approach are compared with the results of genetic algorithms and the linear-programming method. In all cases, the proposed approach is found to perform better in terms of the predicted objective function values. Although global preference modelling via supervised learning may be computationally intensive, the proposed approach is more advantageous than interactive approaches, znanega kupca, pri katerih imajo v kratkem času opravka z velikim številom različnih izdelkov. Ker lahko na nevronski mreži temelječ postopek doseže skoraj optimalno rešitev, ga je moč uporabiti za izbiro rezalnih parametrov pri zapletenih obdelovancih, ki terjajo veliko obdelovalnih omejitev. Dobri rezultati, ki jih da ta metoda, pomenijo, da je mogoče metodo vključiti v inteligentni obdelovalni sistem za avtomatizirano načrtovanje sprotnega postopka. Integracija predlaganega postopka z inteligentnim obdelovalnim sistemom bo vodila k zmanjšanju proizvodnih stroškov, zmanjšanju proizvodnih časov, k večji prilagodljivosti pri izbiri rezalnih parametrov in k izboljšanju kakovosti izdelkov.

specially for job-shop production systems, where the products mix is diverse and dynamic. Since the neural-network-based approach can obtain a near-optimal solution, it can be used for the machining-parameter selection of complex machined parts that require many machining constraints. The implication of the encouraging results obtained from the present approach is that such an approach can be integrated online with an intelligent-manufacturing system for automated process planning. The integration of the proposed approach with an intelligent-manufacturing system will lead to a reduction in the production costs, a reduction in production times, flexibility in machining-parameter selection and an improvement of product quality.

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Modeliranje elektromotorjev za potrebe zaznavanja napak

Modelling for Fault Detection of Electric Motors

Andrej Rakar - Đani Juričić

Prispevek podaja semi-fizikalni model za potrebe zaznavanja zgodnjih napak elektromotorjev. Da bi dosegli veliko občutljivost na napake, fizikalni model kombiniramo z modelom, ki temelji na sistemu mehkega sklepanja na podlagi adaptivnih nevronskih mrež (MSSANM - ANFIS). Metodo uporabimo na realnem primeru elektromotorja sesalne enote. Predstavljena sta zgradba modela in hibridni postopek učenja. V prvem koraku najprej identificiramo parametre fizikalnega modela z osnovno metodo najmanjših kvadratov. Nato kompenziramo odstopanje modela z učenjem adaptivne nevronske mreže. Tako lahko ohranimo pomen fizikalnih parametrov. V nadaljevanju so prikazani rezultati zaznavanja električnih napak motorja (iskrenje ščetk, spremembe v električnih parametrih ipd.), kjer je odstopanje fizikalnega modela najbolj izrazito. Diagnostični rezultati kažejo povečano občutljivost na napake, kar omogoča večjo zanesljivost zaznavanja napak. Posledično se zmanjša tudi število lažnih alarmov in spregledanih napak.

(Ključne besede: zaznavanje napak, modeliranje, identifikacija, elektromotorji univerzalni, mreže adaptivne)

A semi-physical model aimed at detection of incipient faults in electric motors is presented. In order to gain high sensitivity to faults a physical model is combined with a black-box model based on an Adaptive-Network-based Fuzzy Inference System (ANFIS) as a corrective term. The method is applied to vacuum-cleaner motors. The architecture and hybrid learning procedure is presented. In the first step, the parameters of the physical model are identified by a simple least-squares method. Then, the modelling error is compensated using an adaptive-network learning procedure. In this way, the meaning of the physical parameters can be preserved. Next, the detection of the electrical faults of the motor – sparking of the brushes, changes in electrical parameters, etc. – are presented, where there is the most significant physical modelling error. The diagnostic results show a higher sensitivity to faults, which enables reliable fault detection. Consequently, the false and missed alarm ratio is reduced as well.

(Keywords: fault detection, modelling, identifications, universal motors, adaptive networks)

0 UVOD

Konkurenčne razmere na trgu silijo proizvajalce v stalno dvigovanje kakovosti in zanesljivosti izdelkov proizvodnje. Težnje gredo praktično v smeri zagotavljanja 100-odstotne brezhibnosti sestavnih delov, s čimer se zmanjšajo stroški servisiranja končnih izdelkov.

V tem prispevku obravnavamo elektromotor sesalne enote proizvajalca Domel d.d., ki je ugleden evropski izdelovalec. Sesalno enoto sestavlja sklop univerzalnega motorja in zračne turbine. Postopek izdelave je razmeroma visoko avtomatiziran, pri čemer je veliko poudarka na zagotavljanju kakovosti s posebnimi postopki statistične kontrole izdelkov. Želja je, da bi bila vsaka sesalna enota po končani montaži podvržena temeljitemu avtomatskemu testu kakovosti, s čimer bi izločili vse enote s pomanjkljivostmi oz. napakami.

0 INTRODUCTION

Competition on the market is forcing companies to steadily increase product quality and reliability. This trend leads to 100% product quality assurance, which means to reduced service costs.

This paper addresses the modelling of vacuum-cleaner motors produced by Domel, one of Europe's largest manufacturers. The unit consists of a universal motor and an air turbine as a load. The production line is highly automated. Priority is given to quality assurance by means of elaborate statistical procedures for quality control of the final products. A future modernisation plan includes automatic quality testing of individual units at the end of the production line, which would eliminate all defective units.

Prototip sistema za končno kontrolo sesalnih enot sestavlja več funkcionalno ločenih modulov [7] (mehansko-električni model, analiza vibracij, analiza hrupa, analiza kakovosti komutacije). V nadaljevanju se omejimo na modeliranje elektromotorjev sesalnih enot za potrebe zaznavanja napak.

V literaturi najdemo kar nekaj pristopov k modeliranju za zaznavanje napak elektromotorjev ([1], [2] in [8]). Vendar so le-ti navadno omejeni na uporabo nominalnih fizikalnih modelov in različnih tehnik identifikacije parametrov. Ko elektromotorje napajamo z izmenično napetostjo, se pojavijo spremembe v magnetnem polju, ki vodijo do nelinearnosti, ki jih je težko pravilno opisati. Posledica tega je veliko odstopanje modela, kar pomeni, da lahko zaznamo le večje napake v delovanju.

Občutljivost na napake lahko povečamo s hibridnim matematičnim modelom, ki ga sestavljata dva dela: fizikalni model in korekcijski člen, ki predstavlja nemodelirano magnetno karakteristiko rotorja in statorja. Identifikacija takega hibridnega modela je pravzaprav postopek učenja, ki ga poznamo pri adaptivnih mrežah. Struktura modela je navadno določena vnaprej, z optimizacijo pa iščemo parametre na podlagi vhodno-izhodnih meritev postopka [6]. V danem primeru smo izbrali sistem mehkega sklepanja na podlagi adaptivnih nevronskih mrež (MSSANM) [5], ki ga je razmeroma preprosto realizirati tudi v praksi.

Prispevek je organiziran takole. Prvo poglavje podaja kratek opis metode MSSANM s hibridnim postopkom učenja. Drugo poglavje je namenjeno modeliranju elektromotorja sesalne enote. Podan je fizikalni model in princip kompenzacije odstopanja modela. Diagnostični rezultati so prikazani v tretjem poglavju. Sledijo še glavni sklepi.

The prototype system for the final quality control of vacuum-cleaner motors consists of several functionally different modules [7]: mechano-electrical model, vibration analysis, noise analysis, and commutation analysis. Next, semi-physical modelling of vacuum-cleaner motors for diagnostic purposes is discussed in more detail.

Some model-based solutions for the fault detection of electric motors are known from the literature ([1], [2] and [8]). However, they are usually limited to nominal physical models and rely on parameter-estimation techniques. But when motors are driven by AC voltage, changes in the magnetic field imply non-linear characteristics that are not considered correctly, leading to a large modelling error. Consequently, only larger faults can be reliably detected.

A way to increase the sensitivity to faults is to use a mathematical model made of two parts, i.e., a physical model and a corrective term that accounts for the unmodelled non-linear magnetic characteristics of the rotor and the stator. The identification of such a hybrid model is based on a learning procedure known from adaptive networks. The structure is usually known in advance, while the parameters are determined by optimisation on the input-output data of the process [6]. In the given example, the Adaptive-Network-based Fuzzy Inference System (ANFIS) [5] was chosen due to its relatively simple implementation in practice.

The paper is organised as follows. The first section describes the ANFIS method with the hybrid learning procedure. It is followed by the modelling of the vacuum-cleaner motor in the second section. The physical model, as well as the principle of modelling-error compensation, is given. The diagnostic results are presented in the third section. The conclusions follow at the end.

1 SISTEM MEHKEGA SKLEPANJA NA PODLAGI ADAPTIVNIH NEVRONSKIH MREŽ - MSSANM

1 THE ADAPTIVE NETWORK-BASED FUZZY INFERENCE SYSTEM - ANFIS

1.1 Zgradba MSSANM

Vzemimo sistem z dvema vhodoma x in y ter enim izhodom $z=f$. Opišemo ga lahko z dvema mehkima praviloma tipa Sugeno-Takagi prvega reda:

1.1 ANFIS Structure

Let us assume a system with two inputs, x and y, and one output, $z=f$. The system can be described by two fuzzy rules of the first-order Sugeno-Takagi type:

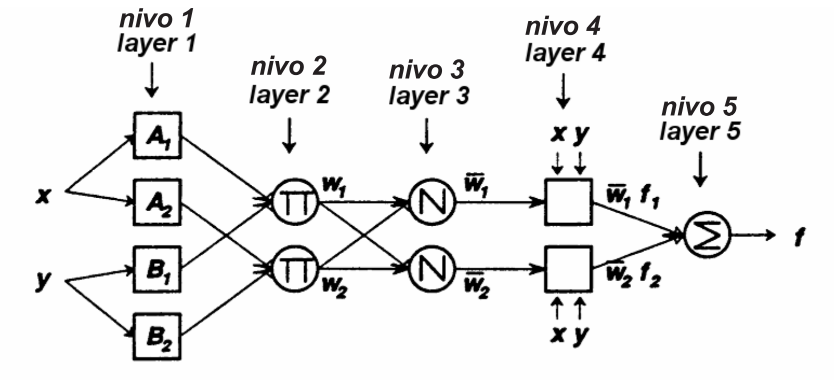
$$\begin{aligned} &\textit{if } x \textit{ is } A_1 \textit{ and } y \textit{ is } B_1 \textit{ then } f_1=p_1x+q_1y+r_1 \\ &\textit{if } x \textit{ is } A_2 \textit{ and } y \textit{ is } B_2 \textit{ then } f_2=p_2x+q_2y+r_2 \end{aligned} \tag{1}$$

Isti sistem lahko predstavimo v obliki mehkega sklepanja na podlagi adaptivnih nevronskih mrež - MSSANM [5], kakor prikazuje slika 1.

Adaptivna vozlišča vsebujejo parametre in so označena s pravokotniki. V postopku učenja se vrednosti teh parametrov ustrezno spreminjajo. Fiksna vozlišča, ki so označena s krogi, izvajajo le

The same system can be represented as an Adaptive-Network-based Fuzzy Inference System (ANFIS), as shown in Figure 1 [5].

Adaptive nodes include parameters and are denoted as squares. In the learning procedure, the parameters change accordingly. The fixed nodes are denoted as circles and have no parameters. Their



Sl. 1. *Primer MSSANM*
Fig. 1. *ANFIS example*

izbrano operacijo in ne vsebujejo parametrov. Adaptivna nevronska mreža je 5-nivojska usmerjenega tipa. Funkcije nivojev in posameznih vozlišč so:

Nivo 1: Vsako vozlišče *i* na tem nivoju je adaptivno s funkcijo:

$$O_i^1 = \mu_{A_i}(x) \quad (2).$$

O_i^1 je stopnja pripadnosti spremenljivke *x* jezikovnim vrednostnim A_i, ki jih opisujejo njihove pripadnostne funkcije. Za pripadnostne funkcije $\mu_{A_i}(x)$ po navadi izberemo funkcijo zvonaste oblike:

$$\mu_{A_i}(x) = \frac{1}{1 + \left[\left(\frac{x - c_i}{a_i}\right)^2\right]^{b_i}} \quad (3),$$

kjer so $\{a_i, b_i, c_i\}$ parametri adaptivnega vozlišča *i* in jih imenujemo *pogojni parametri*.

Nivo 2: Vsako vozlišče *i* na tem nivoju, označeno s Π, je fiksno vozlišče, ki pomnoži vhode O_i^1 in njihov zmnožek poda na izhodu:

$$w_i = \mu_{A_i}(x) \cdot \mu_{B_i}(y) \quad (4).$$

Izhod w_i je torej *utež odločitvenega pravila*. V splošnem lahko namesto zmnožka uporabimo tudi opravilo minimuma.

Nivo 3: Vsako vozlišče *i* na tem nivoju je fiksno vozlišče, označeno z N. Utež odločitvenega pravila w_i normiramo glede na vsoto vseh uteži:

$$\overline{w}_i = \frac{w_i}{\sum w_i} \quad (5).$$

Izhodi $\overline{w}_i$ so torej normirane uteži odločitvenih pravil.

Nivo 4: Vsako vozlišče *i* na tem novoju je adaptivno s funkcijo:

$$O_i^4 = \overline{w}_i f_i = \overline{w}_i (p_i x + q_i y + r_i) \quad (6),$$

function is to perform the predefined operation. The structure is a 5-layer adaptive feed-forward network. The functions of the layers and the particular nodes are as follows:

Layer 1: Each node *i* in this layer is adaptive with a membership function:

O_i^1 is a degree of membership for variable *x* to linguistical terms A_i, which are described by their membership functions. Functions $\mu_{A_i}(x)$ are usually defined as bell-shaped functions:

where $\{a_i, b_i, c_i\}$ denote parameters of adaptive nodes and are called *premise parameters*.

Layer 2: Each node *i* in this layer is a fixed node denoted as Π, the output of which is the product of all the inputs O_i^1:

The output w_i represents the *weight of the decision rule*. In general, the minimum operator instead of the product is also possible.

Layer 3: Each node *i* in this layer is a fixed node denoted as N, which normalises the weight of the decision rule w_i according to the sum of all the weights:

The outputs $\overline{w}_i$ are normalised weights of the decision rules.

Layer 4: Each node *i* in this layer is adaptive with the function:

kjer so parametri $\{p_i, q_i, r_i\}$ funkcije f_i adaptivni parametri vozlišča i in jih imenujemo *posledični parametri.*

Nivo 5: Edino vozlišče na tem noviju je fiksno vozlišče, označeno s Σ, ki izračuna celotni izhod f kot vsoto vseh vhodov O_i^4 v vozlišče:

where $\{p_i, q_i, r_i\}$ denote parameters of the adaptive node i and are called *consequent parameters*.

Layer 5: The only node in this layer is a fixed node denoted as Σ, which calculates the output f as the sum of all the inputs O_i^4:

$$O_1^5 = f = \sum \overline{w}_i f_i \quad (7).$$

Adaptivna nevronska mreža s tako strukturo je funkcijsko enakovredna klasični predstavitvi sistema mehkega sklepanja [5].

The adaptive network with such a structure is functionally equal to the classical representation of the fuzzy inference system [5].

1.2 Hibridni postopek učenja

1.2 Hybrid learning procedure

Iz predlagane strukture (en. 6) je razvidno, da je izhod sistema f linearna kombinacija posledičnih parametrov $\{p_i, q_i, r_i\}$:

It is obvious from the given structure (Eq. 6), that the output of the system f is a linear combination of the consequent parameters $\{p_i, q_i, r_i\}$:

$$f = (\overline{w}_1 x) p_1 + (\overline{w}_1 y) q_1 + (\overline{w}_1) r_1 + (\overline{w}_2 x) p_2 + (\overline{w}_2 y) q_2 + (\overline{w}_2) r_2 \quad (8).$$

Te parametre lahko torej preprosto določimo z metodo najmanjših kvadratov (MNK - LSE) [5]. Enačbo lahko v matrični obliki zapišemo kot:

These parameters can easily be identified by a simple least-squares method [5]. In matrix form, the equation can be written as:

$$AX = B \quad (9),$$

kjer je B vektor izhodov, A matrika linearnih vhodnih enačb in X vektor neznanih posledičnih parametrov.
Vektor ocene parametrov dobimo kot:

where B stands for the input vector, A denotes the matrix of the linear input equations, and X represents an unknown vector of the consequent parameters. The estimates are then given by:

$$\hat{X} = (A^T A)^{-1} A^T B \quad (10).$$

Parametre v nelinearnem pogojnem delu določimo z gradientno metodo [5]. Če α predstavlja pogojni parameter nivoja 1 adaptivne mreže, lahko spremembo izrazimo kot:

The parameters of non-linear conditional part are identified by the gradient method [5]. If α represents a premise parameter in layer 1 of the network, the change is denoted as:

$$\Delta\alpha = -\eta \frac{\partial E}{\partial \alpha} \quad (11),$$

kjer je E izhodno odstopanje in η hitrost učenja, ki jo izrazimo kot:

where E stands for the output error and η for the learning rate, which can be further expressed as:

$$\eta = \frac{k}{\sqrt{\sum_\alpha \left(\frac{\partial E}{\partial \alpha}\right)^2}} \quad (12),$$

kjer je k velikost koraka (dolžina) posameznega gradientnega pomika v prostoru parametrov in vpliva na hitrost konvergence. Mala vrednost k natančno opiše gradientno pot, vendar vodi k počasni konvergenci. Po drugi strani pa z veliko vrednostjo k dosežemo hitro konvergenco, vendar vodi k oscilacijam v okolici optimuma. Problem lahko rešimo s preprostimi hevrističnimi pravili [5].

Celoten postopek učenja poteka v dveh korakih [5]. V vsaki iteraciji najprej na podlagi vhodno-izhodnih podatkov z metodo najmanjših kvadratov določimo posledične parametre. Nato z gradientno

where k is the step size (length) of each gradient transition in the parameter space, and affects the speed of convergence. A small value of k closely approximates the gradient path, but leads to slow convergence. On the other hand, a large value of k leads to fast convergence, but causes oscillations around the optimum. The problem can be solved by simple heuristic rules [5].

The overall learning procedure is as follows [5]. First, at each iteration step, the consequent parameters are identified by a least-squares method based on given input-output data. Then, the gradient metodo na podlagi izhodnega odstopanja določimo še pogojne parametre, ki predstavljajo nelinearni del (vzvratno širjenje).

method is used to identify the premise parameters in the non-linear part based on the current output error (back-propagation).

2 ELEKTROMOTOR SESALNE ENOTE

2.1 Opis

Elektromotor sesalne enote je enofazni komutacijski motor, ki je po konstrukciji in principu delovanja enak enosmernemu motorju. Znan je tudi po imenu univerzalni motor, ker ga lahko napajamo z izmenično ali enosmerno napetostjo. Ker sta navitji statorja in rotorja zaporedno vezani, tako da teče isti tok skozi obe navitji, dosežemo največji možni mehanski vrtilni moment. Tak elektromotor ima tudi velik startni vrtilni moment. Glavno slabost predstavlja komutacija, ki je povezana z obrabo ščetk, kar močno vpliva na življenjsko dobo naprave.

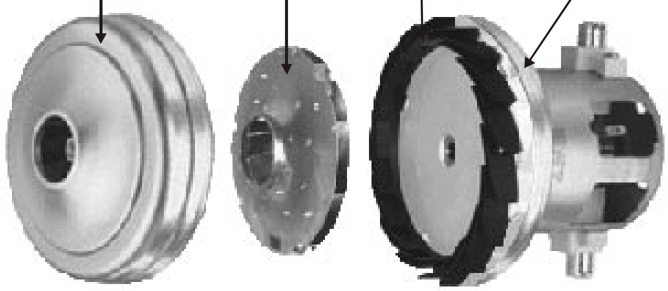
Glavne sestavne dele sesalne enote prikazuje slika 2. Turbinsko kolo, pritrjeno na osi motorja, z devetimi lopaticami ustvarja zračni tok skozi odprtino na pokrovu zračne turbine. Vloga difuzorja je usmeriti zračni tok skozi režo med statorjem in rotorjem za potrebe hlajenja motorja. Nazivna vrtilna frekvenca obravnavanih motorjev je 550 s^{-1}.

2 THE VACUUM-CLEANER MOTOR

2.1 Description

The vacuum-cleaner motor is a single-phase commutation motor whose design and working principle are the same as in DC motors. It is also referred to as universal motor because it can be run by an AC or a DC voltage supply. Owing to the fact that the stator and rotor windings are connected in series and the load current flows through the excitation windings, the largest motor torque is achieved. This electric motor also has a big start-up torque. The main weak point is the commutation, i.e., problems of sparking and brush wear, which seriously affect the device's lifetime.

The main parts of the vacuum-cleaner motor are shown in Figure 2. The fan impeller with nine shovels mounted on the motor's shaft generates the airflow through the hole in the cover. The diffuser then directs the airflow through the orifice between the stator in order to cool the motor. The nominal rotational speed of such motors is 550 s^{-1}.



Sl. 2. *Sestavni deli sesalne enote*
Fig. 2. *Components of the vacuum-cleaner motor*

2.2 Fizikalni model

Strukturo analitičnega modela na podlagi fizikalnih zakonitosti podajajo naslednje enačbe:
električni del:

2.2 Physical model

The physical laws governing the motor are given by the following equations:
electrical part:

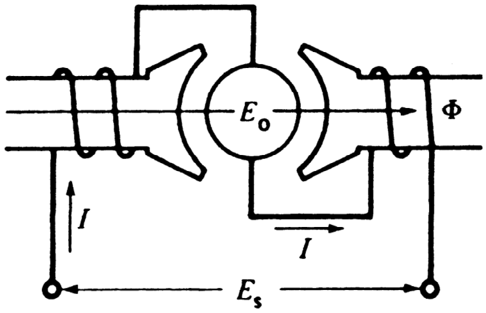
$$u(t) = i(t)(R_v + R_a) + K \cdot i(t) \cdot \omega(t) + (L_v + L_a)\frac{di(t)}{dt} \qquad (13),$$

mehanski del: / *mechanical part:*

$$J\frac{d\omega(t)}{dt} = K \cdot i^2(t) - \mu_0 - \mu_1\omega(t) - \mu_2\omega^2(t),\ \omega>0 \qquad (14).$$

Pomen parametrov je naslednji: R_v in R_a predstavljata upornosti navitij statorja in rotorja, L_v in L_a sta induktivnosti statorja in rotorja, K pomeni

The meaning of the parameters is as follows: R_v and R_a stand for the stator and rotor resistances, L_v and L_a are the stator and rotor inductances, K



Sl. 3. *Vezava motorja*
Fig. 3. *Motor wiring*

koeficient magnetnega fluksa ter J konstanto vztrajnosti. Zračno turbino kot breme opišemo s koeficienti suhega μ_0, viskoznega μ_1 in turbulentnega μ_2 trenja.

Vhod v sistem predstavlja napajalna napetost $u(t)$. Dvoje stanj: tok $i(t)$ in vrtilna frekvenca $\omega(t)$ sta merljiva in predstavljata izhoda sistema. Vezavo motorja prikazuje slika 3. Ker sta navitji statorja in rotorja vezani zaporedno, lahko identificiramo le skupno upornost R in induktivnost L navitja.

Motor napajamo z izmenično napetostjo po hitrostnem profilu, ki vzbudi celotno dinamično območje sistema. Nato vse parametre identificiramo z metodo najmanjših kvadratov v zveznem časovnem prostoru. Meritve zajemamo s frekvenco vzorčenja 10 kHz, podatke pa nato še filtriramo z nizkoprepustnim Butterworth-ovim filtrom z mejno frekvenco 250 Hz. Ujemanje dobljenega fizikalnega modela z dejanskim motorjem prikazuje slika 4. Prikazana je efektivna vrednost toka $i(t)$ in vrtilna frekvenca $\omega(t)$.

Odstopanje modela definiramo kot razliko med ocenjeno in izmerjeno vrednostjo izhoda sistema:

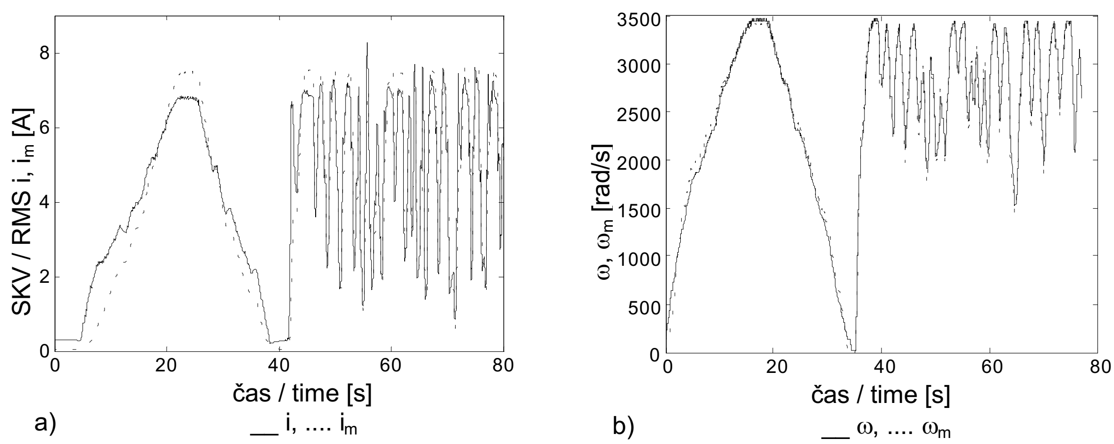
represents the magnetic-flux coefficient, and J is the inertia constant. The air turbine as a load is characterised by the dry friction μ_0, the viscous friction μ_1, and the turbulent friction μ_2 coefficients.

The supply voltage $u(t)$ represents the process input. The two states, current $i(t)$ and rotational speed $\omega(t)$, are measurable and represent the system outputs. The electrical wiring is given in Figure 3. As the stator and rotor windings are connected in series, only the joint resistance R and the inductance L can be identified.

The motor is driven by AC voltage with a profile suitable for stimulating all the dynamical modes of the system. Then, all the parameters are identified by a least-squares method in the continuous time domain. The measurements are sampled at 10 kHz and filtered by a low-pass Butterworth filter with a cut-off frequency of 250 Hz. The comparison between the obtained physical model and the actual motor is given in Figure 4. Here, the RMS value of the current $i(t)$ and the rotational speed $\omega(t)$ are shown.

The modelling error is defined as the difference between the estimated and the measured output of the system:

$$e_{electrical} = i_m(t) - i(t) \quad \text{in / and} \quad e_{mechanical} = \omega_m(t) - \omega(t) \qquad (15).$$



Sl 4. *Ujemanje fizikalnega modela za a) električni in b) mehanski del*
Fig.4. *Physical model validation for a) electrical and b) mechanical part*

V danem primeru imamo 20-odstotno odstopanje pri električnem delu in 5-odstotno odstopanje pri mehanskem delu. Medtem ko je točnost mehanskega modela zadovoljiva, pa točnost električnega modela ni sprejemljiva za potrebe zaznavanja napak [4]. Sklepamo, da je tako veliko odstopanje posledica nemodelirane nelinearne magnetne karakteristike (npr. histereza, nasičenje jedra), ki je posledica izmeničnega napajanja motorja. Razlago v nadaljevanju poenostavimo tako, da obravnavamo le električni model motorja.

2.3 Kompenzacija odstopanja modela

Večjo občutljivost na napake lahko dosežemo s kompenzacijo odstopanja modela ([3] in [4]). Tu fizikalni model kombiniramo s sistemom mehkega sklepanja na podlagi adaptivnih nevronskih mrež NSSANM, opisanega v prejšnjem poglavju. Tako hkrati ohranimo pomen osnovnih parametrov fizikalnega modela, ki so potrebni pri morebitni izolaciji napak [4]. Glavni problem pri zaznavanju napak predstavljajo t.i. nestrukturirana odstopanja modela z neznanimi parametri, za katere ne poznamo fizikalnega ozadja. V tem primeru je za sprotno kompenzacijo v realnem času najprimernejši *vzporedni* hibridni model [9].

Princip kompenzacije odstopanja modela prikazuje slika 5. Potrebni vhodi v adaptivno mrežo so vstop procesa, izstop modela in odstopanje modela (ostanek). Med fazo učenja uporabimo dejansko odstopanje, med sprotno rabo pa uporabimo oceno odstopanja. V nasprotnem primeru bi se lahko izničilo tudi odstopanje zaradi napak v delovanju motorja, ki jih tako ne bi bilo mogoče zaznati.

2.4 Hibridni model

V danem primeru izberemo kot vhod v nevronsko mrežo vrednosti napetosti $u(t)$, toka $i(t)$ ter vrtilne frekvence $\omega(t)$, izhod pa predstavlja odstopanje modela toka. Pri prvih poskusih

The results show an error-to-signal ratio of roughly 20% for the electrical part and 5% for the mechanical part. While the accuracy of the mechanical model is acceptable, the obtained electrical model is unacceptable for detection purposes [4]. It is assumed that such a big error is caused by the unmodelled non-linear magnetic characteristic (i.e., hysteresis, magnetic saturation) as the motor is driven by an AC voltage. For simplicity, only the electrical model will be elaborated.

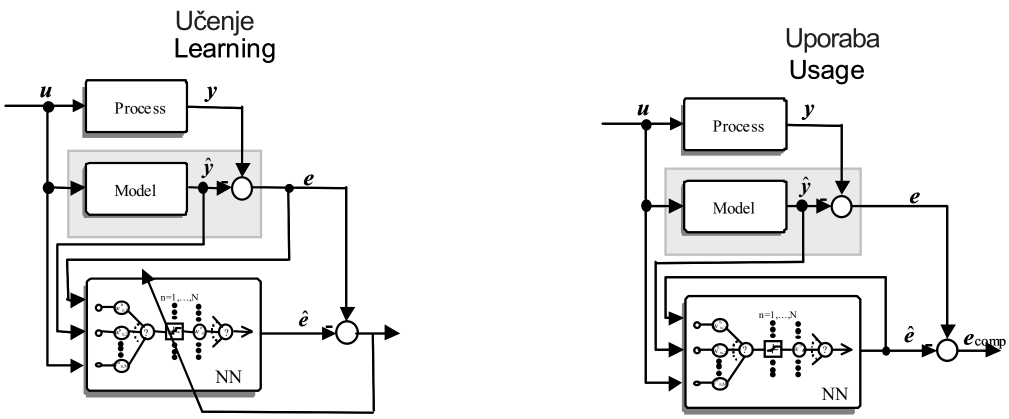
2.3 Compensation of the modelling error

To achieve a higher fault sensitivity, the compensation of the modelling error can be employed ([3] and [4]). This is done by combining the physical model with a black-box model based on ANFIS introduced in the previous section. By keeping the nominal model description, the physical parameters that are necessary for possible fault isolation are preserved [4]. The main problem of fault detection is caused by a non-structured modelling error with unknown parameters and an unfamiliar theoretical background. In this case, a *parallel* hybrid model seems suitable for online compensation in real time [9].

The principle of compensation of the modelling error is shown in Figure 5. The necessary inputs to the adaptive network are the process input, the model output, and the modelling error (residual). During the learning stage, the actual error is used, while during the online usage, the estimated error is utilised. Otherwise, the error caused by faulty operation of the motor could also be compensated, which would make it undetectable.

2.4 Hybrid model

In the given case, the supply voltage $u(t)$, the current $i(t)$ and the rotational speed $\omega(t)$ were chosen as inputs to the adaptive network, while the modelling error of the current was chosen as the



Sl. 5. *Princip kompenzacije napake modela*
Fig. 5. *Principle of modelling-error compensation*

modeliranja smo uporabili tudi več zakasnjenih vhodov zaradi pričakovane nelinearnosti s spominom (histereza). Vendar smo dobili zadovoljivo točnost modela že s preprosto statično relacijo.

Za vsak vhod smo izbrali tri pripadnostne funkcije, kar nam da model NSSANM z naslednjimi lastnostmi:
- število vozlišč: 91
- število linearnih parametrov: 108
- število nelinearnih parametrov: 27
- število mehkih odločitvenih pravil: 27

Dobljeni hibridni model identificiramo v dveh korakih. Najprej identificiramo parametre fizikalnega modela z metodo najmanjših kvadratov. Nato izvedemo postopek učenja adaptivnih mrež (poglavje 1.2), da kompenziramo odstopanje nominalnega modela (en. 13).

output. Preliminarily, several delayed inputs were also considered due to the expected nonlinearity with memory (i.e., hysteresis). However, acceptable model accuracy was achieved with a simple static relation.

Three membership functions were chosen for each input, resulting in the following ANFIS model structure:
- number of nodes: 91
- number of consequent parameters: 108
- number of premise parameters: 27
- number of fuzzy decision rules: 27

The resulting hybrid model is identified in two steps. Firstly, parameters of the physical model are estimated by a simple least-squares method. Then, a learning procedure for adaptive networks (Section 1.2) is applied in order to compensate the errors resulting from the nominal model (Eq. 13).

3 DIAGNOSTIČNI REZULTATI

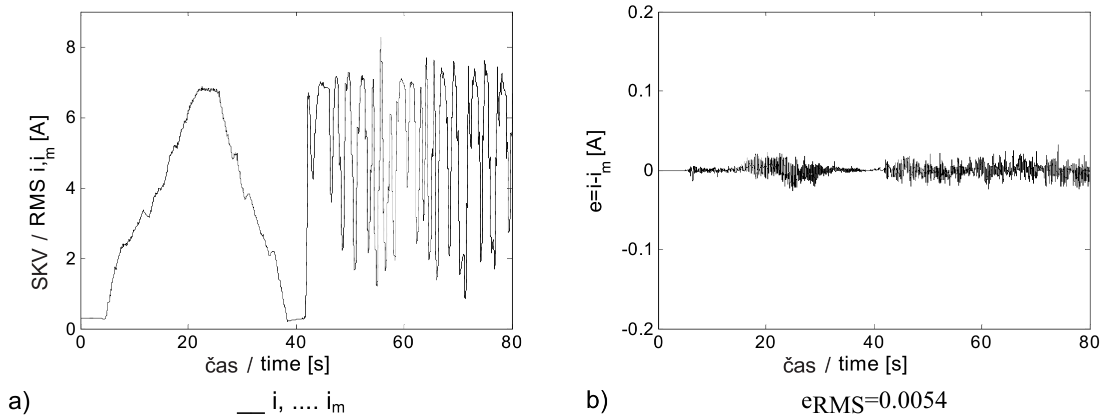
3.1 Vrednotenje

Vrednotenje modela je potekalo na množici 10 motorjev. Slika 6 prikazuje potek izhoda električnega dela enega izmed dobrih motorjev in ocene hibridnega modela ter pripadajoče odstopanje *e*.

3 DIAGNOSTIC RESULTS

3.1 Validation

The validation was performed on a series of 10 motors. Figure 6 shows the time plots of the electrical part for one of the fault-free motors with its estimated hybrid model output and the resulting residual *e*.



Sl. 6. *Ujemanje hibridnega modela*
Fig. 6. *Validation of the hybrid model*

Vidimo, da dosežemo odlično ujemanje modela z dejanskim motorjem, saj je efektivno odstopanje manj kot 1% in je na sliki 6 a) praktično nevidno. Poudariti je treba, da identificiramo parametre modela le enkrat za izbrani tip motorja, zaznavanje napak pa poteka na osnovi ocene modela.

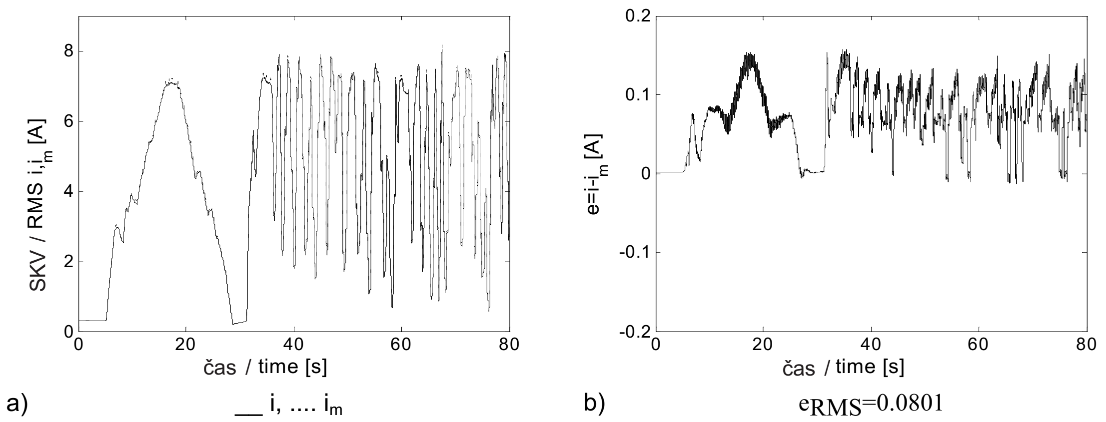
The results show that the error-to-signal ratio reduces to roughly less than 1% and is therefore practically invisible in Figure 6 a). It is important to note that the model parameters are identified only for each type of motor and that the estimated model is then used in fault detection.

3.2 Zaznavanje napak

V nadaljevanju isti hibridni model uporabimo na primeru motorja z okvaro na električnem delu (iskrenje ščetk). Obravnavamo le nenadne napake, saj je bil namen diagnostičnega sistema zaznavanje

3.2 Fault detection

The same hybrid model is further applied to the motor with a fault in the electrical part (sparking of the brushes). Only abrupt faults are considered, as the purpose of the diagnostic system was to detect



Sl. 7. *Ujemanje modela na motorju z okvaro*
Fig. 7. *Hybrid model applied to faulty motor*

prirojenih napak na koncu proizvodne linije. Slika 7 prikazuje ujemanje modela z dejanskim motorjem.

Vidimo, da se efektivno odstopanje poveča več kot 10-krat, kar omogoča zanesljivo zaznavanje napake motorja.

inherent faults at the end of the production line. The output is shown in Figure 7.

The results show that the model discrepancy increases more than 10 times and can therefore be used as a reliable feature for fault detection.

4 SKLEP

Predstavili smo zaznavanje napak elektromotorjev sesalnih enot z matematičnim modelom. Zaznavanje napak poteka na osnovi zakonov o ohranitvi energijske bilance sistema. Vsako odstopanje med izmerjenimi in ocenjenimi vrednostmi pomeni prisotnost napake. Zato vsako odstopanje modela neposredno vpliva na občutljivost na napake.

Da bi izničili vpliv nemodeliranih nelinearnosti, uporabimo princip kompenzacije odstopanja modela s pomočjo adaptivnih nevronskih mrež (NSSANM). Diagnostični rezultati na realnih napravah potrjujejo bistveno zmanjšanje odstopanja modela, kar omogoča večjo občutljivost na napake. Posledično se zmanjša tudi število lažnih alarmov in spregledanih napak.

Ob vsaki zamenjavi tipa motorja pa je treba poskrbeti za ustrezno vzbujanje, ki zajame celotno dinamično območje delovanja. Tudi sposobnost osamitve napak je omejena le na električni oz. mehanski del. Do določene mere lahko dosežemo večjo ločljivost z dodatno uporabo klasičnih metod ocenjevanja parametrov.

4 CONCLUSION

A model-based fault detection of vacuum-cleaner motors is presented. The fault detection relies on energy balance conservation laws. The discrepancy between the measured and the predicted values reflects the presence of a fault. Any modelling error directly affects the sensitivity to faults.

To account for unmodelled non-linear characteristics, the principle of compensating the modelling error by ANFIS is chosen. The diagnostic results on real devices show a significant reduction of the modelling error, which enables higher fault sensitivity. Consequently, the false and missed alarm ratio is reduced as well.

However, good excitation during the learning phase for each motor type is required, which stimulates all the dynamical modes of the system. Also, the isolation ability is limited to either the electrical or the mechanical part. To some extent, differentiation is possible by further employing classical parameter-estimation techniques.

5 ZAHVALA

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Relativne prečne vibracije valjev tiskarskega stroja, ki pritiskajo drug ob drugega preko gumijaste obloge

The Relative Transversal Vibrations of Printing-Press Cylinders that are Pressed Against Each Other via an Elastic Blanket

Vytautas Kazimieras Augustaitis - Nikolaj Šešok

V prispevku predstavljamo rezultate analitične, računalniško podprte raziskave relativnih prečnih vibracij valjev v rotacijskem ofsetnem stroju za obojestransko tiskanje. Predstavljamo postopek izvirne metode, s katero smo izvedli raziskavo in ki temelji na računalniški simulaciji.

Tiskarski stroj sestoji iz naslednjih valjev, ki se, v času delovanja tiskarskega stroja, vrtijo in pritiskajo drug ob drugega prek tanke (približno 2 mm) elastične, gumirane tkanine (gumijasta obloga): dveh valjev za ploščo, na katerih sta pritrjeni tiskarski šabloni, in dveh valjev z gumijasto oblogo, med katerima drsi papirni trak, potreben za tiskanje. V poteku raziskave smo ocenili upogibe valjev, pa tudi elastičnost in dušenje gumijaste obloge ter ležajnih enot valjev. Ugotovili smo, da te vibracije povzročajo spremembe v pritisku med valji, s čimer zmanjšujejo tudi kakovost tiska. Potem ko smo raziskali značilnosti prostih in vsiljenih relativnih vibracij valjev, smo se odločili, da bomo intenzivnost vibracij zmanjšali z uporabo valjev z identično dinamično odzivnostjo. Predstavljamo podatke, pridobljene z ekperimentalnim raziskovanjem, ki kažejo vpliv vibracij pritiska med valji na kakovost tiska.

(Ključne besede: tiskanje, ofset, stroji tiskarski, vibracije)

In this paper we present the results of a computer-aided analytical investigation of the relative transversal vibrations of the cylinders in a web-offset double-sided printing press. An original method for carrying out the investigation, using a computer simulation, is presented.

The printing press consists of the following cylinders that rotate during its operation and are pressed against each other via a thin (about 2 mm) elastic, rubberized cloth (called a blanket): two plate cylinders, with printing forms attached to them, and two blanket cylinders, with a paper tape moving between them for the printing. During the investigation, the deflections of the cylinders as well as the elasticity and damping of the blanket and the cylinders' bearing units were assessed. These vibrations caused changes in the pressure between the cylinders, thus reducing the quality of the prints. After investigating the features of the free and forced relative vibrations of the cylinders, it was decided to reduce the intensity of the vibrations by using cylinders with identical dynamic responses. Data from the experimental investigation that show the impact of the variations of the pressure between the cylinders on the quality of the prints are presented.

(Keywords: printing, offset printing, printing press, vibrations)

0 UVOD

V pričujočem prispevku predstavljamo raziskavo relativnih prečnih vibracij med valjema za ploščo in valjema z gumijasto oblogo v rotacijskem ofsetnem stroju za obojestransko tiskanje, ki uporablja metodo računalniške simulacije za zmanjšanje intenzivnosti teh vibracij. Med postopkom delovanja tiskarskega stroja se odtisi prenesejo s površine valjev, prevlečenih s tanko plastjo (približno 2 mm) gumirane tkanine (gumijasta obloga), na papirni trak, ki se pomika skozi stroj. Odtisi se prenesejo iz

INTRODUCTION

In this paper we present an investigation into the relative transversal vibrations between the plate and blanket cylinders in a web-offset double-sided printing press using a computer-simulation method in order to reduce the intensity of these vibrations. During the operation of the printing press the prints are transferred onto a paper tape, which is moving through the printing press, from the surface of the cylinders that are covered with a thin (approximately 2 mm) rubberized cloth (blanket). The tiskarskih šablon (navlaženih s tiskarskim črnilom), ki sta pritrjeni na valja za ploščo, na gumijasto oblogo. Vsi valji se vrtijo in pritiskajo drug ob drugega po celotni dolžini. Valji so nameščeni tako, da se vsi vrtijo in pritiskajo drug ob drugega prek elastične gumijaste obloge: na sredini tiskarskega stroja sta dva valja z gumijasto oblogo, ki pritiskata drug proti drugemu (med njima drsi trak papirja), medtem pa valja za ploščo pritiskata proti drugi strani valjev z gumijasto oblogo. Ta tip tiskarskega stroja je zelo pogost in v nadaljevanju so navedene podrobnosti njegovega delovanja.

Pri tem načinu tiskanja je treba določiti pritisk med vrtečimi se valji, ki pritiskajo drug ob drugega prek gumijaste obloge ([1] do [3]). Če valji vibrirajo, se spreminja tudi njihov pritisk. Posledica vibracij je poslabšanje kakovosti odtisov in s tem tudi zmanjšanje produktivnosti tiskarskega stroja. To pomeni, da je vibriranje, ki spremlja postopek tiskanja, resen problem; da bi ga razrešili, smo uporabili metodo računalniške simulacije.

Doslej so bile opravljene že mnoge raziskave vibracij rotorjev (gredi, valjev itn.), ki se vrtijo v ležajih [4]; vendar pa te raziskave niso vključevale proučevanja vibracij rotorjev, ki pritiskajo drug ob drugega prek tanke elastične tkanine. Opravljene so bile, na primer, študije valjčne opreme, ki vsebujejo kovinske liste (tu tanek kovinski list drsi med vrtečima se valjema), vendar pa rezulatov analiz teh pojavov ne moremo prenesti na tiskarsko panogo [5].

Pričujoča študija poleg raziskav vibracij valjev prikazuje tudi to, kako lahko spremenjen pritisk med valji učinkuje na kakovost tiskarskih odtisov.

Rezultati naše raziskave vibracij valjev so vsesplošno uporabni. Naše ugotovitve lahko prenesemo tudi na primere valjev rotacijskih ofsetnih tiskarskih strojev, ki se po številu valjev in njihovi namestitvi sicer razlikujejo od primerov, opisanih v pričujoči študiji.

1 VPLIV PRITISKA VALJEV NA KAKOVOST TISKANJA

Ni nam uspelo najti kakršnih koli zanesljivih in podrobnih eksperimentalnih podatkov o vplivu pritiska valjev na kakovost ofsetnega tiskanja, kar je preprečevalo, da bi ocenili vpliv relativnih prečnih pomikov valjev stroja, ki jih povzroča vibriranje, na kakovost tiskanja. Zato smo se odločili izvesti eksperimentalno raziskavo vpliva pritiska na kakovost ofsetnega tiskanja. S strojem Heidelberg Speedmaster 52-2-P [1] smo, pri različnih pritiskih, tiskali dvobarvne slike (rumena in črna), skupaj s stopenjskim nadzorom sive lestvice in usmerjenimi črtami. Pritisk smo spreminjali s sočasnim spreminjanjem razdalje med osema valja za ploščo in valja z gumijasto oblogo ter osema tiskovnega valja in valja z gumijasto oblogo. Ta razdalja, λ, je

prints are transferred onto the blanket from the printing forms (moistened with printing ink) that are attached to the plate cylinders. All the cylinders are in rotation and are pressed against each other along their generatrices. The cylinders are positioned in such a way that all of them rotate and press against each other via an elastic blanket: there are two blanket cylinders pressed against each other in the middle of the press (the paper tape moves between them), and the plate cylinders are pressed against the other sides of the blanket cylinders. This type of printing press is very common, and more details are provided below.

With this type of printing the pressure between the rotating cylinders that are pressed against each other via the blanket must be fixed ([1] to [3]). If the cylinders tend to vibrate, this pressure varies as well. The result of vibration is a deterioration in the quality of the prints and a reduction in the productivity of the printing press. This means that the problem of vibration during printing is a serious one, and so we have used a computer-simulation method in an attempt to solve it.

There are many investigations of the vibrations of rotors (shafts, cylinders, etc.) rotating in bearings [4]; however, the vibrations of rotors that are pressed against each other via a thin elastic cloth were not studied during these investigations. For example, there are some studies on metal-sheet rolling equipment (a thin metal sheet moves between rotating rollers); however, the problems discussed are not related to the printing trade [5].

In this study, in addition to investigating the vibrations of cylinders, we have looked at how varying the pressure between the cylinders can have an effect on the quality of the prints.

The results of our investigation into the vibrations in cylinders can be universally applied. Our findings can be applied to the cylinders of web-offset printing presses where the number of cylinders and their layout differ from those described here.

1 THE INFLUENCE OF PRESSURE ON THE PRINTING QUALITY

We were not able to find any reliable and detailed experimental data on the influence of pressure on the quality of offset printing. This makes it difficult to evaluate the influence of the relative transversal shifts of the cylinders in the press, which are caused by vibration, on the quality of the printing. Therefore, an experimental investigation of the influence of pressure on the offset-printing quality was carried out. Two color images (yellow and black) with a control-step gray scale and narrow lines were printed on a Heidelberg Speedmaster 52-2-P press [1] at various pressures. The pressure was changed by altering the distance between the axles of the plate-and-blanket and the blanket-and-press cylinders simultaneously. This distance, λ, is expressed in μm:

izražena v μm: λ = 0μm in pomeni, da se površine valjev le rahlo dotikajo (med njimi ni pritiska); povečani λ pa označuje povečanje relativnega pritiska. Normalen pritisk tiskanja je dosežen, ko je λ = 35μm. Čeprav ta metoda ne omogoča, da bi določili absolutne vrednosti pritiska, pa omogoča, da razumemo povezavo med prečnimi pomiki valjev in kakovostjo tiskanja.

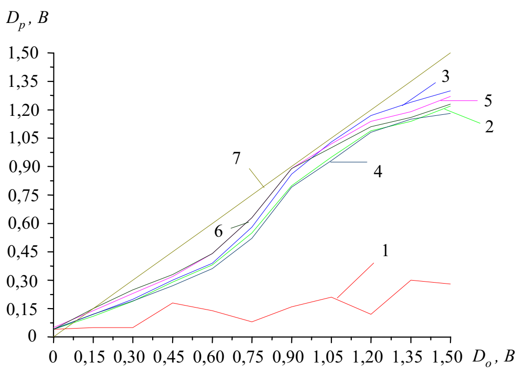
Za določitev kakovosti tiskanja smo uporabili naslednja kriterija: (a) natančnost poltonske reprodukcije (odvisnost optične gostote odtisa D_p od optične gostote izvirnika D_o, izmerjene na stopenjski sivi lestvici; (b) spremembo širine usmerjene črte in velikosti zaslonskih točk. Optično gostoto smo merili z merilnikom gostote Macbeth T-297 (z modrim filtrom za rumeni tisk) z natančnostjo ± 0,02B. Velikost elementov smo izmerili z mikroskopom (povečava: 24^x, točnost: ±0,01 mm).

Rezultati tega preizkusa kažejo na znatne spremembe optične gostote tiska, ki jih povzročijo različne razdalje med valjema v raziskovanem obsegu 8 do 55 μm, in ki posledično vodijo do znatno spremenjenega pritiska. Znatno se spreminjata tudi velikost točk na rastru in širina usmerjene črte. Dobljeni rezultati so prikazani na diagramih 1, 2 in 3.

λ = 0μm means that the cylinders' surfaces are only touching (no pressure); and increasing λ means increasing the relative pressure. The normal printing pressure is achieved when λ = 35μm. Although this method does not allow us to know the absolute values of pressure, it does allow us to relate the transversal shifts of the cylinders to the printing quality.

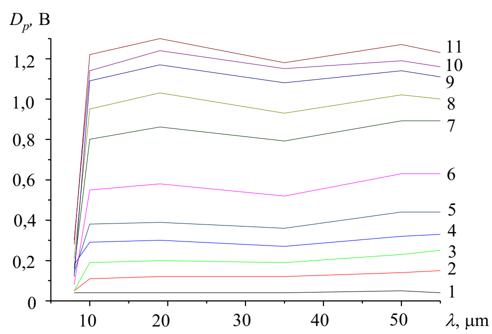
The printing quality was characterized as follows: (a) by the accuracy of the halftone reproduction (the dependence of the optical density of the print D_p on the optical density of the original D_o, measured on the step gray scale; and (b) by the change in the width of the narrow line and the size of the screen dots. The optical density was measured with a Macbeth T-297 densitometer (with a blue filter for the yellow print) with an accuracy of ± 0.02B. The size of the elements was measured using a microscope (magnification: 24^x, accuracy: ±0.01 mm).

The results of the experiment show that the changes in the optical density of a print, which are caused by changes in the distance between cylinders in the investigated range 8 to 55 μm, and consequently changes in the pressure, are considerable. The size of the raster points and the width of a line vary considerably as well. Examples of diagrams showing the obtained results are presented in Figs. 1, 2 and 3.



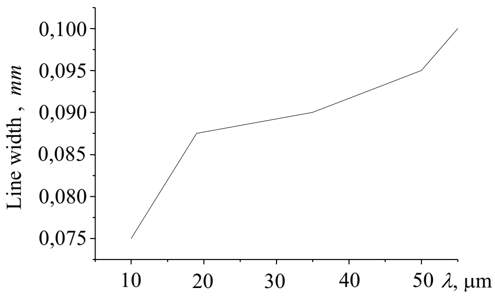
Sl. 1. *Spreminjanje optične gostote rumene nadzorne skale v odnosu do sprememb λ, v razdalji med valjema z gumijasto oblogo in valjema za ploščo: 1- razdalja = 8 μm; 2- razdalja =10 μm; 3- razdalja = 19 μm; 4- razdalja = 35 μm; 5- razdalja = 50 μm; 6- razdalja = 55 μm; 7- idealna reprodukcija poltonov; Do in D_p sta optični gostoti izvirnika in odtisa*

Fig. 1. *The variation of the optical density of the yellow control scale versus changes, λ, in the distance between the blanket and the plate cylinders: 1, distance = 8 μm; 2, distance =10 μm; 3, distance = 19 μm; 4, distance = 35 μm; 5, distance = 50 μm; 6, distance = 55 μm; 7, the ideal reproduction of halftones; Do and D_p are the optical densities of the original and the print*



Sl. 2. *Odvisnost optične gostote (rumena nadzorna skala) od sprememb λ, v razdalji med valjema z gumijasto oblogo in valjema za ploščo: 1 – polje N1 odtisa nadzorne skale (D_o = 0,00); 2 - N2 (0,15); 3 - N3 (0,30); 4 - N4(0,45); 5 - N5(0,60); 6 - N6(0,75); 7 - N7(0,90); 8 - N8(1,05); 9 - N9(1,20); 10 - N10(1,35); 11 -N11(1,50)*

Fig. 2. *The dependence of the optical density (yellow control scale) on the changes, λ, in the distance between the blanket and plate cylinders: 1 – field N1 of the control scale print (D_o = 0.00); 2 - N2 (0.15); 3 - N3 (0.30); 4 - N4(0.45); 5 - N5(0.60); 6 - N6(0.75); 7 - N7(0.90); 8 - N8(1.05); 9 - N9(1.20); 10 - N10(1.35); 11 - N11(1.50)*



Sl. 3. *Odvisnost širine posamezne črte od spremembe λ, v razdalji med valjema z gumijasto oblogo in valjema za ploščo*

Fig. 3. *The dependence of the width of a separate line on the change, λ, in the distance between the blanket and the plate cylinders*

2 PREDMET RAZISKAVE

Raziskovali smo absolutne in relativne prečne vibracije valjev z gumijasto oblogo in valjev za ploščo pri rotacijskem ofsetnem tiskarskem stroju in se pri tem posebej osredotočili na relativne vibracije med valji, z namenom, da bi zmanjšali njihovo intenzivnost. Naše proučevanje je vključevalo naslednje sklope:

- preučevanje prostih prečnih vibracij valjev;
- preučevanje vsiljenih vibracij, sproženih kinematično z netočnostjo krogljičnih ležajev v valjih in z vibracijami okvira tiskarskega stroja ter z netočnostjo delovnih površin valjev (ovalnost itn.);
- preučevanje vibracij, ki jih povzročata zaponki gumijaste obloge na vrtečih se valjih, ki pritiskajo drug ob drugega.

Da bi raziskali ta problem, smo razvili splošno metodo analogno-digitalnega proučevanja prečnih vibracij valjev z gumijasto oblogo in valjev za ploščo pri rotacijskem ofsetnem tiskarskem stroju.

Da bi bili rezultati raziskave čimbolj pomembni, smo preučevanje opravili na pogosto rabljenem ofsetnem tiskarskem stroju za obojestransko tiskanje s štirimi valji, od katerih imata dva valja gumijasto oblogo in med njima drsi papirni trak, druga dva pa sta valja za ploščo (tiskarski stroji s šestimi ali tremi valji se prav tako uporabljajo, čeprav bolj redko; in metoda ter računalniški program, uporabljena v naši raziskavi, se lahko prenašata tudi na te stroje).

Shema tiskarskega stroja je prikazana na sliki 4. Stroj sestoji iz valjev z gumijasto oblogo, (2) in (3), ki po celotni dolžini pritiskata drug ob drugega in imata delovno površino obloženo z plastjo elastičnega gumijastega materiala (6). Papirni trak (5) drsi med dvema valjema z gumijasto oblogo. Valja za ploščo sta prikazana z (1) in (4).

Premeri delovnih površin vseh valjev so enaki in valji se vrtijo prek zobnikov z enako vrtilno hitrostjo. Valji se vrtijo na krogličnih ležajih (7).

2 OBJECT OF THE INVESTIGATION

The problem we examined was the absolute and relative transversal vibrations of the blanket and plate cylinders of a web printing press, paying particular attention to the relative vibrations between cylinders in order to reduce their intensity. This study included:

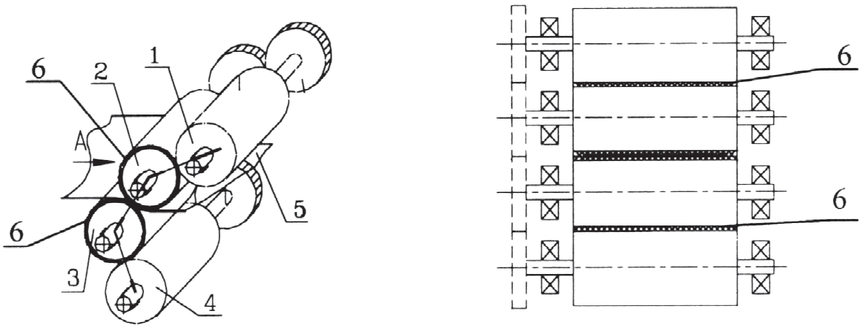
- an examination of the free transversal vibrations of the cylinders;
- an examination of the forced vibrations, excited in a kinematic way by the inaccuracy of the ball bearings in the cylinders as well as the vibrations of the frame of the press, the inaccuracies of the working surfaces of the cylinders (ovality, etc);
- an examination of the vibrations caused by the blanket locks of the blanket cylinders on the rotation of cylinders that are pressed against each other.

In order to investigate the problem a universal method for an analog-digital examination of the transversal vibrations of the blanket and plate cylinders of web printing presses has been developed.

To make the problems under discussion directly relevant, a widely used double-sided offset printing press with four cylinders, consisting of two blanket cylinders with the paper tape running between them, and two plate cylinders, was chosen as the subject (printing presses with six and three cylinders are also used, although more rarely; however, the method and the software used in this work, also apply to them).

A schematic diagram of the printing press is shown in Fig. 4. It consists of the blanket cylinders (2) and (3), pressed against each other, with their working surfaces coated with a layer of elastic rubber-like blanket material (6) along the generatrices of the cylinders. The paper tape (5) runs between the blanket cylinders. The plate cylinders are (1) and (4).

The diameters of the working surfaces of all the cylinders are the same, and the cylinders are rotated with the same rotational speed via gears. The cylinders rotate on ball bearings (7).



a) b)

Sl. 4. *Tiskarski stroj (a - skupina valjev, b - razgrnitev pogleda v smeri A)*
Fig. 4. *The printing press (a - cylinders' group, b - unfolded view in direction A)*

3 DINAMIČNI IN MATEMATIČNI MODEL TISKARSKEGA STROJA

Za potrebe raziskovanja prečnih vibracij valjev smo izdelali dinamični model preučevanega sistema. Shema tega modela je prikazana v diagramu 5. Z uporabo modela lahko ocenimo prečne krivine valjev in odstopanja, ki jih le-te povzročajo, elastičnost krogličnih ležajev v valjih (upoštevajoč dušenje), nenatančnosti ležajev ter elastičnost in dušenje gumijastih oblog. Delovne površine valjev (z napakami ali brez njih) so razdeljene v valjaste končne elemente in mesta, na katerih so montirani ležaji, imajo obliko prisekanega stožca.

Gumijasti oblogi sta simulirani s pomočjo ločenih, elastičnih elementov, skupaj z dušenjem; ti elementi povezujejo zaključke končnih elementov dveh sosednjih valjev. Elastičnost gumijastih oblog je nelinearna. Za to raziskavo vibracij je elastičnost linearizirana v materialih svoje statične deformacije, ob tem ko valji pritiskajo drug ob drugega. Togost in dušenje ločenih elastičnih elementov, ki simulirajo gumijasto oblogo in ležajne enote, sta izračunani na podlagi literature [6] do [9].

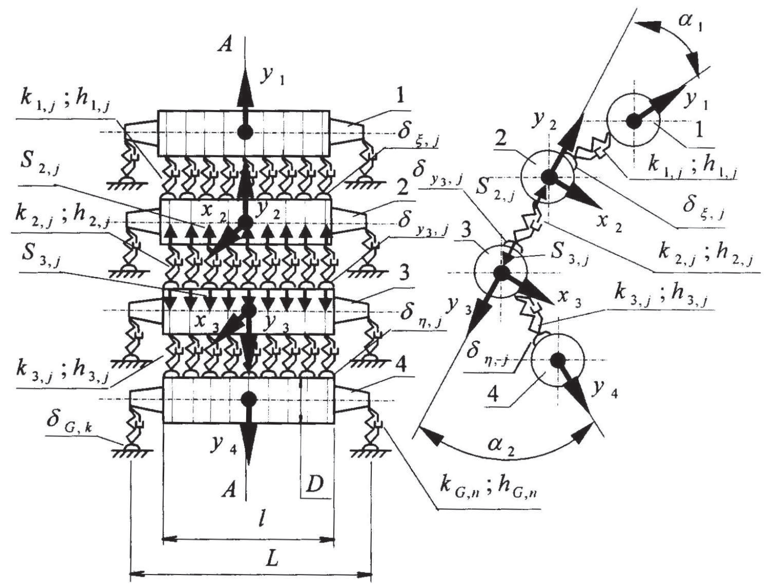
Kroglični ležaji in njihova nenatančnost so simulirani na poenostavljen način, tako da so njihove značilnosti v približku enake značilnostim elastičnih in dušilnih elementov (koeficienta togosti in upora sta k in h z ustreznimima indeksoma). Nenatančnost ležajev je simulirana s kinematično vzbujevanimi elementi (ti so povezani v zaporedje z elastičnimi in dušilnimi elementi); njihova velikost $\delta_{G,k}$ se spreminja glede na vnaprej določeno zakonitost (slika 5). Kinematično vzbujanje sistema prek dna okrova je simulirano enako kakor nenatančnost ležajev. Razlikujejo se le specifične oblike njunega kinematičnega vzbujanja $\delta_{G,k}$. Netočnosti delovnih površin valjev (odstopanja od idealne površine valja) so simulirane s kinematično vzbujevanimi elementi,

3 A DYNAMICAL AND MATHEMATICAL MODEL OF THE PRINTING PRESS

For the investigation of the transversal vibrations of the cylinders a dynamic model of the system under examination was set up. The scheme of the model is presented in Fig. 5. The model evaluates the transversal bends of the cylinders and the deviations caused by them, the elastic shifts of the ball bearings in the cylinders (including damping), the inaccuracies of the bearings, and the elasticity and damping of the blankets. The working surfaces of the cylinders (with or without holes) are divided into cylindrical finite elements, and the places where the bearings are fitted have the shape of a truncated cone.

The blankets are simulated by discrete spring-type elastic elements with damping; these elements connect the ends of the finite elements of two adjacent cylinders. The elasticity of the blankets is non-linear. For this investigation of the vibrations the elasticity is linearized in the media of its static deformation pressing of the cylinders against each other. The stiffness and damping of the discrete elastic elements that simulate the blanket and the bearing units are calculated on the basis of references [6] to [9].

The ball bearings and their inaccuracy are simulated in a simplified way by approximating them with elastic and damping elements (their coefficients of stiffness and resistance are k and h, respectively, with the corresponding indexes). The inaccuracy of the bearings is simulated by kinematic excitation elements (they are connected in series with the elastic and damping elements), and their size $\delta_{G,k}$ varies according to the set regularity (Fig. 5). The kinematic excitation of the system via the foundations is simulated in the same way as the inaccuracy of the bearings. Only the specific expressions of the kinematic excitation $\delta_{G,k}$ differ. The inaccuracies of the working surfaces of the cylinders (the deviations from the ideal surface of a cylinder) are simulated by



Sl. 5. *Shematični prikaz splošnega dinamičnega modela tiskarskega stroja; y_1 do y_4, x_2, x_3 so posplošene koordinate, ki določajo elastične linearne pomike srednjih delov valjev pa tudi smeri vibracij valjev, izbranih za namen raziskave*

Fig.5. *Schematic diagram of the general dynamic model of the printing press; y_1 to y_4, x_2, x_3 are the generalized coordinates defining the elastic linear shifts of the middle parts of the cylinders, which also show the directions of the vibrations of these cylinders, chosen for the research*

spreminjajo se glede na vnaprej določene zakonitosti $\delta_{\xi,j}$, $\delta_{y3,j}$, $\delta_{\eta,j}$.

Tovrstna simulacija netočnosti med valji je prikazana na skliki 5. Vsak kinematično vzbujevan element simulira netočnost površin dveh valjev, ki se na določeni točki dotikata prek gumijaste obloge. Na sliki 5 so prikazane le linearne posplošene koordinate y_1 do y_4, x_2 in x_3, ki določajo pomike osrednjih delov valjev (druge koordinate, ki določajo elastične pomike končnih elementov, niso prikazane). V dinamičnem modelu so koordinate, ki opisujejo absolutne vibracije valjev in so uporabljene v postopku našega izračuna, zamenjane s posplošenimi koordinatami, ki opisujejo relativne vibracije med valji.

Zaradi zahtevnosti dinamičnega modela (dinamični model, prikazan v diagramu 5, ima 168 prostostnih stopenj) je matematični model (enačbe vibracij), ki je nastal na podlagi dinamičnega modela, oblikovan tako, da uporablja poseben algoritem in posebno programsko opremo. Za potrebe poenostavitve in avtomatizacije oblikovanja enačb preučevani sistem vibracij umetno razdelimo na preproste, neodvisne podsisteme in izdelamo pomožne dinamične modele teh podsistemov. To dosežemo z umetno "prekinitvijo" dotika robov elementov, ki simulirajo gumijasto oblogo, z enim od dveh valjev; oba valja sta sicer prek teh elementov vključena v celoten dinamični model. V začetni fazi se enačbe vibracij oblikujejo posebej za vsak posamezen podsistem, kasneje pa se enačbe vibracij, s posebnimi povezovalnimi enačbami, tudi za celoten sistem.

Gumijasto oblogo po vsej dol□ini pritrdimo na ustrezni valj. Za njeno pritrditev uporabljamo

kinematic excitation elements, varying according to the set regularities $\delta_{\xi,j}$, $\delta_{y3,j}$, $\delta_{\eta,j}$.

Such a simulation of the inaccuracies between the cylinders is shown in Fig. 5. Each kinematic excitation element simulates the inaccuracies of the surfaces of both cylinders, contacting via the blanket, at a specific point. In Fig. 5 only the linear generalized coordinates y_1 to y_4, x_2 and x_3, identifying the shifts of the middle parts of the cylinders, are indicated (other coordinates, identifying the elastic shifts of the finite elements, are not shown). In the dynamic model, the coordinates describing the absolute vibrations of the cylinders that are used in the course of the calculation are replaced with generalized coordinates describing the relative vibrations between the cylinders.

Because of the complexity of the dynamic model (the dynamic model shown in Fig. 5 has 168 degrees of freedom), the mathematical model (the equations of the vibrations), which is developed from it, is formed using a special algorithm and software. In order to simplify and computerize the formation of the equations the vibration system under examination is artificially divided into simpler, independent sub-systems, and auxiliary dynamic models of the sub-systems are developed. This is achieved by an artificial "disconnection" of the ends of the blanket-simulating elements from one of two cylinders, which are connected by the elements in the overall dynamic model. Initially, the equations of the vibrations are formed separately for each sub-system, and then, using specially developed link equations, the equations of the vibrations for the overall system are formed.

The blanket is fitted to a blanket cylinder along its generatrix. Special locks in the shape of thin metal posebni zaponki v obliki tankih kovinskih ploščic. Med vrtenjem valjev delovne površine ti zaponki pritiskata druga ob drugo prek gumijaste obloge in povzročata utrip udarcev. Posledica tega je, da valja pričneta vibrirati. Kota vrtenja valjev z gumijasto oblogo, (2) in (3), sta naravnana tako, da se zaponki obeh valjev dotakneta v istem trenutku vrtenja. V tem trenutku pride do udarca, ki povzroča vibracije valjev. V pričujoči študiji izračunavamo le udarec med valjema z gumijasto oblogo (2) in (3), (lahko pa bi izračunali tudi udarca med valji (1) in (2) ali (3) in (4)).

Udarec simuliramo z utripnimi silami $S_{2,k}$ in $S_{3,k}$, ki delujejo vzdolž koordinat $y_{2,i}$ in $y_{3,i}$ (sl. 5). Oblika pulziranj je polsinusoidna (sl. 6), to je $S_{j,k}=A_{j,k}\cdot\sin\nu t$, kadar je $0 \le t \le \pi/\nu_s$ in časovno obdobje π/ν_s kratko.

Oblikovanju dinamičnih modelov posameznih podsistemov sistema, prikazanega na sliki 5, sledi oblikovanje matematičnega modela (enačbe vibracij), ki poteka v dveh fazah. V prvi fazi s programsko opremo in na podlagi dinamičnih modelov posameznih podsistemov oblikujemo enačbe prostih vibracij. Za ta namen uporabimo programsko opremo BEMSK [9], ki je posebej prilagojena izvajanju tovrstnih rešitev. Ta programska oprema je bila zasnovana za vzpodbujanje prostih prečnih vibracij gredi (v tem primeru gre za valja za ploščo in valja z gumijasto oblogo) in uporablja metodo končnih elementov, pri čemer upošteva elastičnost in dušenje njunih ležajev.

Enačba za vsak podsistem, na primer za podsistem k-th, je naslednja:

plates are used for this fitting. During the rotation of the cylinders, the working surfaces are pressed against each other via the blanket, and such locks excite shock pulses. The result is that the cylinders begin to vibrate. The angles of rotation of the blanket cylinders (2) and (3) are adjusted in such a way that the locks of both cylinders come into contact at the same moment during their rotation. At that moment the shock that causes the vibrations of the cylinders appears. In this study only the shock between the blanket cylinders (2) and (3) is evaluated (it could, however, be evaluated between the cylinders (1) and (2), and between (3) and (4)).

The shock is simulated by the force pulses $S_{2,k}$ and $S_{3,k}$, acting along the coordinates $y_{2,i}$ and $y_{3,i}$ (Fig. 5). The shape of the pulses is half-sinusoidal (Fig. 6), i.e., $S_{j,k}=A_{j,k}\cdot\sin\nu t$, when $0 \le t \le \pi/\nu_s$, and the time period π/ν_s is short.

Having obtained the dynamic models of the sub-systems of the system, shown in Fig. 5, the mathematical model (the equations of the vibrations) is formed in two stages. In the first stage a computer-aided formation of the equations of free vibrations according to the dynamic models of separate sub-systems is carried out. In order to do this we used BEMSK software [9], specially modified to solve the above-mentioned problems. The software was designed for the development of the free transversal vibrations of shafts (in this case the plate and blanket cylinders), using the method of finite elements, and taking into account the elasticity and damping of their bearings.

The equations for each sub-system, for example, the k-th sub-system, are as follows:

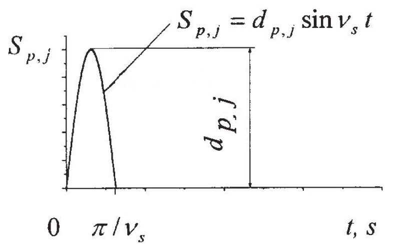
$$[A]_k \{\ddot{q}\}_k + [B]_k \{\dot{q}\}_k + [C]_k \{q\}_k = 0 \quad (k = 1,...,m) \qquad (1),$$

kjer so $[A]_k$, $[B]_k$, in $[C]_k$ matrike vztrajnosti, dušenja in togosti k-tega podsistema; $\{q\}_k$ je vektor njegovih posplošenih koordinat, čigar komponente so posplošene koordinate, ki določajo lego k-tega podsistema; m = 6 pa označuje števílo podsistemov.

V drugi fazi, po opravljenem izračunu zunanjih vzbujevalnih sil, ki delujejo na podsisteme in po kinematičnem vzbujanju ležajev, sestavimo

where $[A]_k$, $[B]_k$, and $[C]_k$ are the matrices of the inertia, the damping and the stiffness of the k-th sub-system; $\{q\}_k$ is the vector of its generalized coordinates, the components of which are the generalized coordinates identifying the position of the k-th system; *and m* = 6, the number of sub-systems.

In the second stage, after an evaluation of the external excitation forces affecting the sub-systems, and



Sl. 6. *Približek spreminjanja sil $S_{p,j}(t)$, ki se pojavi kot posledica udarca zaponk*

Fig. 6. *The approximation of the variation of the forces $S_{p,j}(t)$, appearing as a result of the shock caused by the locks*

pomožen sistem enačb vibracij, pri katerem povezave med podsistemi še niso ocenjene:

the kinematic excitation of the bearing, an auxiliary system of the equations of vibrations is formed where the links between the sub-systems are not yet evaluated.

$$[A]_0\left\{\ddot{q}\right\}_0+[B]_0\left\{\dot{q}\right\}_0+[C]_0\{q\}_0=\{P(t)\}_0 \quad (2),$$

kjer je matrika $[A]_o$ sestavljena iz matrik $[A]_k$, ki so na njeni diagonali; matriki $[B]_0$ in $[C]_0$ sta sestavljeni iz analogno nameščenih matrik $[B]_k$ in $[C]_k$; $\{q\}_0$ – je vektor, čigar komponente so posplošene koordinate, ki so vključene v vse enačbe (1); $\{P(t)\}_0$ – je vektor posplošenih zunanjih sil, iz katerih se sestavijo od nič različne komponente posplošenih sil, ki vplivajo na posamezne podsisteme:

where the matrix $[A]_o$ is composed of the matrices $[A]_k$ located on its diagonal, the matrices $[B]_0$, $[C]_0$ – of the analogously situated matrices $[B]_k$ or $[C]_k$; $\{q\}_0$– the vector with which the components are the generalized coordinates included into all the equations (1); $\{P(t)\}_0$ – the vector of the generalized external forces with which non-zero components are formed of the generalized forces affecting separate sub-systems:

$$\{P(t)\}_0=\{F(t)\}_0+\{F_B(t)\}_0 \quad (3),$$

kjer je $\{F(t)\}_0$ vektor, pri katerem so od nič različne kompnente posplošene sile udarcev zaponk $S_{j,k}$; $\{F_B(t)\}_0$ je vektor, s katerim se sestavijo od nič različne koordinate elementov nenatančnosti ležajev pri kinematičnem vzbujanju prek dna okrova in netočnosti delovnih površin valjev.

S pomožnim sistemom enačb vibracij (2) in povezovalnih enačb ter ob uporabi posebnega algoritma in programske opreme DJOINX [9], ki sta prilagojena za naše potrebe, lahko ustvarimo splošni sistem enačb, ki opisujejo vibracije celotnega sistema:

where $\{F(t)\}_0$ is the vector with which non-zero coordinates are the generalized forces $S_{j,k}$ of the blows of the locks; $\{F_B(t)\}_0$ is the vector with which non-zero coordinates are formed of the elements of the inaccuracy of bearings on a kinematic excitation via the foundation and the inaccuracies of the working surfaces of the cylinders.

Having the auxiliary system of the equation of vibrations (2) and the link equations, and using a special algorithm and the software DJOINX [9], modified for this case, the general system of equations describing the vibrations of the total system is obtained:

$$[A]\left\{\ddot{q}\right\}+[B]\left\{\dot{q}\right\}+[C]\{q\}=\{P(t)\} \quad (4),$$

kjer je $\{q\}$ vektor posplošenih koordinat, ki enoznačno določi lego tiskarskega stroja pri vibriranju; $[A]$, $[B]$, $[C]$ – kvadratne matrike vztrajnosti, dušenja in togosti sistema pri redu n; $\{P(t)\}$ je vektor posplošenih sil, ki ga določimo z uporabo vektorja $\{P(t)\}_0$.

where $\{q\}$ is the vector of the generalized coordinates, monosemantically identifying the position of the printing press on vibrations; $[A]$, $[B]$, $[C]$ – the square matrices of inertia, damping and stiffness of the system of the n-th order; $\{P(t)\}$ is the vector of the generalized forces, found using the vector $\{P(t)\}_0$.

4 REŠITVE ENAČB

Za nadaljnjo računalniško analizo prostih in vsiljenih vibracij tiskarskega stroja uporabljamo sistem enačb (4), čigar rešitve dobimo z uporabo modalne metode, temelječe na uporabi normaliziranih koordinat Bulgakova (NBK) ([9] in [10]). Uporabljamo posebne algoritme in programsko opremo DDINCHAR, ki je razvita na njihovi podlagi in prirejena potrebam naših raziskovanj. Potek rešitve je naslednji:

Sprva določimo korene karakteristične enačbe in lastnih vektorjev sistema (4), ki predstavljajo tudi oblike lastnih nihajnih načinov valjev ob upoštevanju dušenja. Nato, na podlagi normaliziranih koordinat Bulgakova, sestavimo enačbe (4). V primeru naše raziskave vsak kompleksni skupni koren $\varepsilon_h \pm i\omega_h$ ustreza dvema diferencialnima enačbama prvega reda v normaliziranih koordinatah

4 SOLUTIONS OF THE EQUATIONS

For a further computer analysis of the free and forced vibrations of the printing press the system of equations (4) is used, with which solutions are found using the modal method based on an application of the normalized Bulgakov's coordinates (NBK) ([9] and [10]). Special algorithms and the software DDINCHAR, developed on their basis and modified to solve the problems under discussion, were used. The course of the solution is the following.

The roots of the characteristic equation and the eigenvectors of the system (4), which are also the shapes of the eigenvibrations of the cylinders, taking into account the damping, are found. Next, equations (4) are formed in normalized Bulgakov's coordinates. In the case under examination each complex joint root $\varepsilon_h \pm i\omega_h$ corresponds to two differential equations of the first order in the normalized Bulgakov's coordinates

Bulgakova, ζ_h in ζ_{n+h}, ki ju ne omejujejo druge enačbe:

$$\begin{cases} \dot{\zeta}_h - \varepsilon_h \zeta_h - \omega_h \zeta_{n+h} = \Phi_h(t); \\ \dot{\zeta}_{n+h} + \omega_h \zeta_h - \varepsilon_h \zeta_{n+h} = \Phi_{n+h}(t); \end{cases} \quad (5),$$

kjer sta Φ_h(t) in Φ_{n+h}(t) komponenti 2*n*-razsežnega vektorja $\{\Phi(t)\}$, ki ga dobimo pri določeni premeni vektorja $\{P(t)\}$.

Rešitve enačb (5) zlahka dobimo na analitičen način; algoritme njihovih rešitev pa zlahka programiramo. Ko pridobimo vrednosti koordinat ζ_h in ζ_{n+h}, lahko določimo tudi vrednosti koordinat $\{q\}$.

Iz opisanih enačb smo razvili programsko opremo, s katero lahko raziščemo vibracije valjev za ploščo in valjev z gumijasto oblogo, ki so povezani prek gumijaste obloge. Poglavitna prednost te metode je razčlenjenost zahtevnega sistema (4) v veliko bolj preproste, neodvisne podsisteme, ki omogočijo oceniti linearno dušenje sistema, in za katere praktično ne vpeljemo nobenih omejitev.

Z uporabo iste metode lahko pridobimo tudi podatke za dušene proste vibracije sistema.

ζ_h and ζ_{n+h}, not bound with other equations:

where: Φ_h(t), Φ_{n+h}(t) are the components of the 2*n*-dimensional vector $\{\Phi(t)\}$, found on a certain transformation of the vector $\{P(t)\}$.

The solutions of equations (5) are easily found in an analytical way; the algorithms of their solutions are easily programmed. Having obtained the values of the coordinates ζ_h and ζ_{n+h}, the values of the coordinates $\{q\}$ can be found as well.

On the basis of the above-described equations the software was developed to investigate the vibrations of the plate and the blanket cylinders connected via the blanket. The main advantage of this method is a division of the complicated system (4) into much simpler, independent sub-systems to evaluate the linear damping of the system, to which practically no restrictions are applied.

In addition, the data for damped free vibrations of the system can be found using the same method.

5 PREČNE VIBRACIJE VALJEV

5 TRANSVERSAL VIBRATIONS OF THE CYLINDERS

Raziskali smo absolutne in relativne vibracije valjev. Posebno pozornost smo posvetili relativnim prostim in vsiljenim vibracijam valjev vzdolž naslednjih koordinat (sl. 5):

Absolute and relative vibrations of the cylinders were examined. A particular attention was paid to the relative free and forced vibrations of the cylinders along the following coordinates (Fig. 5):

$$\begin{aligned} \gamma_{1,2} &= y_1 - y_2 \cos\alpha_1 - x_2 \sin\alpha_1; \\ \gamma_{3,4} &= y_4 - y_3 \cos\alpha_2 - x_3 \sin\alpha_2; \\ \gamma_{2,3} &= y_2 + y_3;\ \gamma_x = x_2 - x_3. \end{aligned} \quad (6).$$

Po spremembi posplošenih koordinat (razlike) $\gamma_{1,2}$, $\gamma_{2,3}$ in $\gamma_{3,4}$ pride do spremembe pritiska med valji, ki pritiskajo drug ob drugega prek gumijaste obloge in kakovost tiska se poslabša. Vibracije vzdolž γ_x tudi niso zaželene.

Relativne prečne vibracije valjev v smeri posplošenih koordinat $\gamma_{1,2}$, $\gamma_{2,3}$ in $\gamma_{3,4}$ so v nadaljnjem besedilu imenovane *relativne vibracije v smereh pritiska valjev;* relativne vibracije valjev z gumijasto oblogo, ki potekajo v smeri pravokotno na prej omenjene vibracije in vzdolž posplošene koordinate γ_x pa so imenovane *relativne obodne vibracije valjev z gumijasto oblogo*.

Oblike vsiljenih resonančnih harmoničnih vibracij se rahlo razlikujejo od značilnih oblik lastnega nihajnega načina. Resonančne frekvence so v približku najpogosteje enake naravnim frekvencam. Poleg tega so prehodne frekvence vibracij valjev, ki jih povzročajo udarci zaponk gumijaste obloge, frekvence prostih vibracij. Določitev naravnih frekvenc sistema omogoča vpogled v dragocene podatke o vsiljenih vibracijah. Večino naše pozornosti namenimo raziskavi

After changing the generalized coordinates (differences) $\gamma_{1,2}$, $\gamma_{2,3}$, $\gamma_{3,4}$ a change in the pressure between the cylinders that are pressed against each other via the blanket takes place, and the quality of the prints deteriorates. Vibrations along γ_x are also not desirable.

The relative transversal vibrations of the cylinders in the directions of the generalized coordinates $\gamma_{1,2}$, $\gamma_{2,3}$, $\gamma_{3,4}$ are referred to in the remainder of the text as the *relative vibrations in the pressing directions of the cylinders;* and the relative vibrations of the blanket cylinders in the direction perpendicular to these vibrations, along the generalized coordinate γ_x, are referred to as the *relative tangential vibrations of the blanket cylinders*

The shapes of the forced resonance harmonic vibrations differ slightly from the eigenshapes of the eigenvibrations, and the resonance frequencies most frequently approximately coincide with the natural frequencies. In addition, the frequencies of the vibrations of the cylinders on the transients, which are caused by the shocks of the blanket locks, are the frequencies of the free vibrations. Determining the natural frequencies of the system provides valuable information about the forced vibrations. Most attention relativnih vibracij v smereh pritiska valjev. Preiskujemo pa tudi odvisnost relativnh obodnih vibracij valjev z gumijasto oblogo od relativnih vibracij.

5.1 Proste vibracije

Proučevali smo korene karakteristične enačbe preučevanega sistema, naravne frekvence (imaginarni deli korenov) in oblike lastnih nihajnih načinov $\{V\}_h$, pri čemer smo upoštevali tudi dušenje sistema. Izkazalo se je, da kadar so vsi parametri (izmere, masa, togost in dušenje) in dinamične karakteristike vseh valjev enaki, lahko ugotovimo specifične značilnosti prostih vibracij stroja (takšen stroj odslej imenujemo stroj z enakimi valji).

Če je izpolnjen omenjeni pogoj, potem so tri najnižje naravne frekvence tiskarskega stroja enake isti ponovljeni naravni frekvenci: $\omega^*=\omega_1=\omega_2=\omega_3$. Ponovijo se tudi koreni karakteristične enačbe: $\gamma_{1,2}$, $\gamma_{2,3}$ in $\gamma_{3,4}$. Frekvenca ω^*, ki je enaka najnižji naravni frekvenci kateregakoli valja z elastično oporo, ustreza trem različnim oblikam lastnih nihajnih načinov $\{V\}_1$, $\{V\}_2$, $\{V\}_3$. V smereh pritiska valjev ni nobenih modalnih relativnih vibracij s frekvenco ω^*.

Slika 7a prikazuje dejanske dele oblik relativnih lastnih nihajnih načinov tiskarskega stroja z različnimi valji. Valja z gumijasto oblogo (2 in 3) sta votla in njune dinamične karakteristike se razlikujejo od karakteristik valjev za ploščo (1 in 4) glede na najnižjo naravno frekvenco ω_1. (Imaginarni deli niso prikazani, ker so v našem primeru zelo majhni.)

Na osi x je razdalja l med oporama valjev nespremenljiva. Krivulja 1 ustreza obliki relativnih vibracij vzdolž posplošene koordinate $\gamma_{1,2}$, krivulja 2 ustreza koordinati $\gamma_{2,3}$, krivulja 3 ustreza koordinati $\gamma_{3,4}$ in krivulja 4 ustreza koordinati γ_x. Obliki relativnih lastnih nihajnih načinov, ki ustrezata naravnim frekvencam ω_2 in ω_3, sta enaki. To pomeni, da so

is paid to investigating the relative vibrations in the pressing directions of the cylinders. The dependence of the relative tangential vibrations of the blanket cylinders on these vibrations is examined as well.

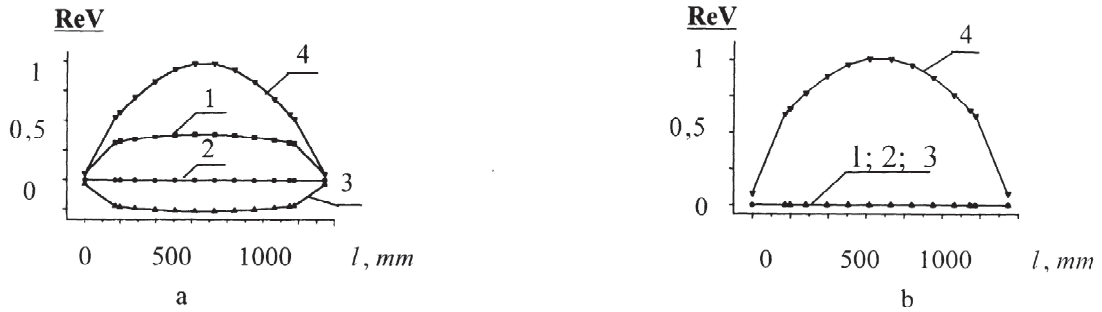
5.1 Free vibrations

The roots of the characteristic equation of the system under discussion, the natural frequencies (the imaginary parts of the roots), the shapes of the eigenvibrations $\{V\}_h$ were examined, taking into account the damping in the system. It was shown that if all the parameters (such as dimensions, mass, stiffness, and damping) and the dynamic characteristics of all the cylinders are the same, the specific features of the free vibrations of the equipment (such equipment hereinafter is referred to as equipment with the same cylinders) are obtained.

If the above-mentioned condition is satisfied, the three lowest natural frequencies of the printing press become equal to the same repeated natural frequency $\omega^*=\omega_1=\omega_2=\omega_3$. The roots $\gamma_{1,2}$, $\gamma_{2,3}$, $\gamma_{3,4}$ of the characteristic equation are repeated as well. The frequency ω^*, equal to the lowest natural frequency of any of the cylinders with elastic supports, corresponds to three different shapes of eigenvibrations $\{V\}_1$, $\{V\}_2$, $\{V\}_3$. No modal relative vibrations with the frequency ω^* in the pressing directions of the cylinders remain.

Fig. 7a shows the real parts of the shapes of the relative eigenvibrations of a printing press with different cylinders. The blanket cylinders (2 and 3) are hollow and their dynamic characteristics differ from those of the plate cylinders (1 and 4) in terms of the lowest natural frequency ω_1. (The imaginary parts are not shown, because in this case they are very small.)

On the x axis the distance l between the supports of the cylinders is fixed. The curve 1 corresponds to the shape of the relative vibrations along the generalized coordinate $\gamma_{1,2}$, the curve 2 corresponds to $\gamma_{2,3}$, the curve 3 corresponds to $\gamma_{3,4}$ and the curve 4 corresponds to γ_x. The shapes of the relative eigenvibrations corresponding to the natural frequencies ω_2 and ω_3 are the analogous. This



Sl. 7. *Značilne oblike relativnih prečnih vibracij valjev, ki ustrezajo trem najnižjim naravnim frekvencam (prikazani so le realni deli, imaginarni so premajhni): a – za sistem z različnimi valji; b – za sistem z enakimi valji*

Fig. 7. *The eigenshapes of the relative transversal vibrations of the cylinders, corresponding to the three lowest natural frequencies (only the real parts, the imaginary parts are small): a – a system with different cylinders; b – a system with the same cylinders*

proste vibracije valjev s frekvencami ω_1, ω_2 in ω_3, kakor tudi vsiljene harmonične resonančne vibracije v razponu teh frekvenc, zadovoljivo določene s posplošenimi koordinatami y_1 do y_4, x_2 in x_3, ki so prikazane v diagramu 5. (Vibracije drugih delov valjev, ki ustrezajo isti frekvenci, se razlikujejo le po velikosti).

Slika 7b prikazuje realne komponente ene izmed značilnih oblik vibracij enoličnih (trdnih) valjev v smereh njihovih pritiskov, ki ustrezajo ponovljeni naravni frekvenci ω*. Krivulje 1, 2, 3, prikazane v diagramu 7a, ležijo na isti ravni črti in kažejo, da so preostale zgolj relativne obodne proste vibracije valjev z gumijasto oblogo (krivulja 4, diagram 7b). Na enak način lahko določimo dve drugi značilni obliki prostih vibracij (le-ti tu nista prikazani), ki ustrezata frekvenci ω*.

5.2 Vsiljene vibracije

Relativne periodične vibracije v smereh pritiska valjev, ki jih vzbudimo na kinematični način, smo raziskovali z uporabo amplitudno-frekvenčnih odzivov tiskarskega stroja z enakimi in tudi z različnimi valji. Kinematično harmonično vzbujanje, ki povzroča vibracije valjev, za katere smo izmerili amplitudne in frekvenčne odzive, je v približku enako harmoničnim funkcijam $\delta_k(vt)$. Le-te simulirajo nenatančnosti valjčnih ležajev oziroma vibracij dna okrova tiskarskega stroja.

6 REZULATATI IN OBRAVNAVA

Za frekvence do 500 Hz smo pridobili naslednje rezultate:

a) Intenzivnost harmoničnih vibracij pri tiskarskem stroju z enoličnimi valji kakor tudi intenzivnost periodičnih relativnih vibracij v smereh pritiska valjev je v vseh primerih manjša kakor pri tiskarskem stroju z različnimi valji. Intenzivnost relativnih obodnih vibracij ima v obeh primerih enak red.
b) V primeru tiskarskega stroja z različnimi valji smo najbolj intenzivne vibracije v smereh pritiska valjev opazovali v resonančnih področjih, ki ustrezajo najnižjim naravnim frekvencam, ω_1 do ω_4, tiskarskega stroja. V primeru enakih valjev ne pride do resonančnih vibracij v razponu ponovljene naravne frekvence ω*: intenzivnost vibracije določajo zgolj resonančna področja, ki ustrezajo višjim naravnim frekvencam.
c) Intenzivnost vsiljenih harmoničnih vibracij v smereh pritiska valjev v frekvenčnem razponu do 500Hz se znatno spreminja v odvisnosti od narave vzbujanja $\delta_k(vt)$ (vrednosti amplitud, lege njihovega delovanja in fazni pomiki med posameznimi vzbujanji). Takšni učinki so še posebej opazni pri tiskarskem stroju z enakimi valji.

means that the free vibrations of the cylinders with the frequencies ω_1, ω_2 and ω_3, as well as the forced harmonic resonance vibrations in the media of these frequencies, are sufficiently well identified by the generalized coordinates y_1 to y_4, x_2 and x_3 shown in Fig. 5. (The vibrations of the other parts of the cylinders corresponding to the same frequency differ only in terms of scale).

Fig. 7b shows the real components of one eigenshape of the vibrations of uniform (solid) cylinders in the directions of their pressing, corresponding to the repeated natural frequency ω*. The curves 1, 2, 3, shown in Fig. 7a, lie on the same straight line, showing that only the relative tangential free vibrations of the blanket cylinders (curve 4, Fig. 7b) remained. In the same way, two other eigenshapes of the free vibrations (not shown here), corresponding to the frequency ω*, are found.

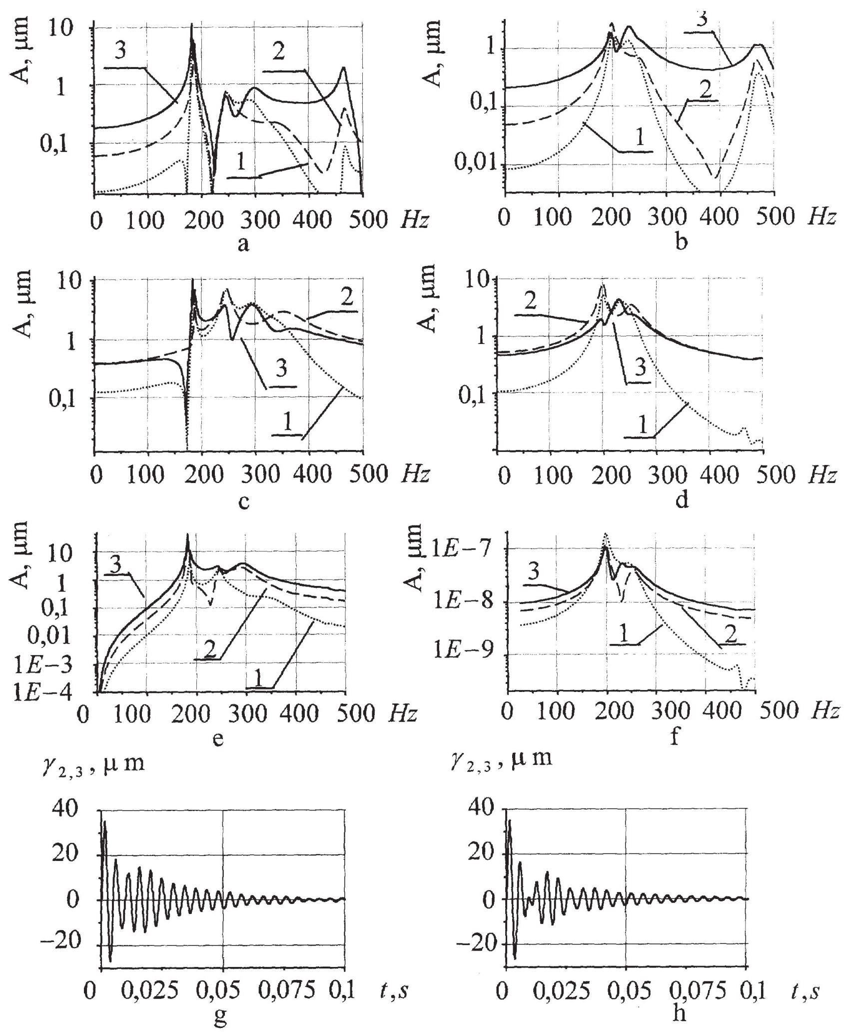
5.2 Forced vibrations

Relative periodic vibrations in the pressing directions of the cylinders, excited in a kinematic way, were explored by an application of the frequency response method to a printing press with the same, and with different, cylinders. The kinematic harmonic excitation causing the vibrations of the cylinders, for which the amplitude and frequency responses were measured, is approximated with the harmonic functions $\delta_k(vt)$. They simulate the inaccuracies of the cylinders' bearings or the vibrations of the foundation of the press.

6 RESULTS AND DISCUSSION

For frequencies up to 500 Hz the following results were obtained.

a) For a printing press with uniform cylinders the intensity of the harmonic vibrations, as well as the periodic relative vibrations in the pressing directions of the cylinders, is in all cases less than in a printing press with different cylinders. The intensity of the relative tangential vibrations is of the same order in both cases.
b) For a printing press with different cylinders the most intense vibrations in the pressing directions of the cylinders are observed in the resonance zones that correspond to the lowest natural frequencies, ω_1 to ω_4, of the press. If the cylinders are the same, there are no resonance vibrations in the media of the repeated natural frequency ω*: the intensity of the vibration is defined only by the resonance zones corresponding to higher natural frequencies.
c) The intensities of the forced harmonic vibrations in the pressing directions of the cylinders in the frequency range up to 500Hz vary considerably, depending on the character of the excitations $\delta_k(vt)$ (the values of their amplitudes, their locations of action and the phase shifts between separate excitations). Such an effect is particularly noticeable in a printing press with the same cylinders.



Sl. 8. *Amplitudno-frekvenčni odzivi relativnih prečnih vibracij valjev tiskarskega stroja (a, c, e – za stroje z različnimi valji; b, d, f – za stroje z enakimi valji; krivulja 1 – amplitudno-frekvenčni odzivi za $\gamma_{1,2}$, krivulja 2 – amplitudno-frekvenčni odzivi za $\gamma_{2,3}$, krivulja 3 – amplitudno-frekvenčni odzivi za $\gamma_{3,4}$) in relativne vibracije valjev z gumijasto oblogo, ki jih povzročajo udarci zaponk gumijastih oblog (g – različni valji, h – enaki valji)*

Fig. 8. *The amplitude and frequency responses of the relative transversal vibrations of the cylinders of a printing press (a, c, e – for presses with the different cylinders; b, d, f – for presses with uniform cylinders; the curves 1 – the amplitude and frequency responses according to $\gamma_{1,2}$, the curves 2 – the amplitude and frequency responses according to $\gamma_{2,3}$, the curves 3 – the amplitude and frequency responses according to $\gamma_{3,4}$) and the relative vibrations of the blanket cylinders caused by the shocks of the blanket locks (g – the different cylinders, h – the same cylinders)*

d) Amplitudno-frekvenčni odziv relativnih obodnih vibracij valjev z gumijasto oblogo pri tiskarskem stroju z enakimi valji ima le en resonančni vrh v razponu najnižje naravne frekvence katerega koli posameznega valja. Kadar pa so valji različni, pride do več manjših resonančnih vrhov. Primeri pridobljenih amplitudno-frekvenčnih odzivov so prikazani v diagramih 8a do 8f. Diagrama 8a, 8b prikazujeta amplitudno-frekvenčne odzive za vibracije, ki jih vzbudi netočnost levega ležaja valja za ploščo (4). Diagrama 8c, 8d prikazujeta vibracije, ki jih vzbudi enaka netočnost ležajev obeh valjev z gumijasto oblogo (3). V prvem primeru

d) In the amplitude and frequency response of the relative tangential vibrations of the blanket cylinders in a printing press with the same cylinders there is only a single resonance peak in the media of the lowest natural frequency of any separate cylinder. When the cylinders are different, several smaller resonance peaks appear. Examples of the obtained amplitude and frequency responses are presented in Fig. 8a–f. In Fig. 8a, b the amplitude and frequency responses for vibrations excited by an inaccuracy in the left-hand bearing of the plate cylinder (4) are shown. Fig. 8c, d shows the vibrations excited by the same inaccuracy of the bearings of both blanket cylinders (3). In the (a, b) je bila raven vibracij pri tiskarskem stroju z enakimi valji zmanjšana za približno desetkrat; tudi v drugem primeru (c, d) je bila raven vibracij zmanjšana, a v manjšem obsegu. Bistveno zmanjšanje vibracij istih valjev pa dosežemo v primeru navpičnega vzbujanja vibracij, ki ga povzroča vibriranje dna okrova tiskarskega stroja (Diag. 8e, 8f). Raziskovali smo tudi relativne vibracije v smereh pritiska valjev, ki jih povzročajo udarci zaponk gumijastih oblog. Vsak udarec povzroči prehodne pojave, ki so sestavljeni iz dušenih prostih vibracij. Pridobili smo naslednje rezultate.

e) Frekvence prehodnih pojavov približno ustrezajo dvem ali trem najnižjim naravnim frekvencam tiskarskega stroja.
f) V prehodnih pojavih, vzbujenih pri tiskarskem stroju z enakimi valji, ni komponent s ponovljeno naravno frekvenco ω^*.
g) Opazili smo povečanje relativnih pomikov med valji v obdobju vibriranja prvega prehodnega pojava, ko delujejo sile $S_{p,j}$ (prva amplituda relativnih vibracij prehodnega pojava je znatno višja od kasnejših amplitud).

Sliki 8g in 8h prikazujeta relativne vibracije med valjema z gumijasto oblogo (vzdolž posplošene koordinate $g_{2,3}$) v smereh pritiska valjev, ki jih povzročajo udarci zaponk gumijaste obloge. Za prikazana primera velja, da sta raven in trajanje vibracij v stroju z enakimi valji in v stroju z različnimi valji približno enaka, čeprav ne vsebujeta komponente, ki bi ustrezala ponovljeni naravni frekvenci ω^* prehodnega pojava, prikazanega na diagramih 10, h. Vzrok za to stanje je v dejstvu, da se v preučevanem primeru naravni frekvenci f_4, f_5 tiskarskega stroja z enakimi valji zgolj malenkostno razlikujeta od najnižjih frekvenc f_1, f_2 tiskarskega stroja z različnimi valji.

6.1 Vibracije, ki jih povzročajo nenatančnosti delovnih površin valjev

Predpostavljali smo, da so netočnosti na delovnih površinah valjev periodične. V času vrtenja valjev smo tovrstne netočnosti simulirali kot periodično kinematično vzbujanje. Dobljene učinke smo ocenili s pomočjo amplitudno-frekvenčnih odzivov. Pri tiskarskem stroju z enakimi valji smo opazili rahlo znižanje ravni vibracij.

7 ZANESLJIVOST REZULTATOV

Glede na dejanski sistem, ki je bil predmet naše raziskave, kakovost programske opreme in metode raziskave, obstajata dva poglavitna dejavnika, ki določata primernost dinamičnega in matematičnega modela. Primernost dinamičnega modela (računalniška

first case (a, b) the level of vibrations in the printing press with the same cylinders was reduced by about 10 times, and in the second case (c, d) it also was reduced, but not to such an extent. A very significant reduction in the vibrations of the same cylinders is obtained for the vertical excitation of vibrations via the vibrating foundation of the press (Fig. 8e, f). Relative vibrations, caused by the shocks of the blankets locks, in the pressing directions of the cylinders were explored as well. Each shock generates transients, consisting of damped free vibrations. The following results were obtained.

e) The frequencies of the transients are about the two or three lowest natural frequencies of the printing press.
f) There are no components with the repeated natural frequency ω^* in the transients excited in a printing press with the same cylinders.
g) An increase in the relative shifts between cylinders within the period of the vibration of the first transient, when the forces $S_{p,j}$ act, was observed (the first amplitude of the relative vibrations of the transient is considerably higher than the subsequent ones)

In Fig. 8g and 8h the relative vibrations between blanket cylinders (along the generalized coordinate $\gamma_{2,3}$) in the pressing directions of the cylinders, caused by the shocks of the blanket locks, are shown. For the shown cases, the level and duration of the vibrations in a printing press with the same cylinders and a printing press with different cylinders are approximately the same, although there is no component corresponding to the repeated natural frequency ω^* in the transient shown in Fig. 10h. This is caused by the fact that in the example under discussion the natural frequencies f_4, f_5 of the printing press with the same cylinders differ insignificantly from the lowest frequencies f_1, f_2, of the printing press with different cylinders.

6.1 Vibrations caused by an inaccuracy in the working surfaces of the cylinders

We have considered that the inaccuracies in the working surfaces of the cylinders may be periodic in character. During the rotation of the cylinders, such inaccuracies are simulated as a periodic kinematic excitation. There effects are also evaluated, using amplitude and frequency responses. A slight reduction in the level of vibrations was found in a printing press with the same cylinders.

7 THE RELIABILITY OF THE RESULTS

Two main factors determine the appropriateness of the dynamic and mathematical models in terms of the real system under investigation and the quality of the software and the method of investigation. The appropriateness of the dynamic model (the shema) temelji na dejstvu, da je le-ta zadovoljivo podroben in sestavljen iz elementov, ki simulirajo deformacijo valjev, pa tudi elastičnost ter dušenje gumijaste obloge in ležajev, saj uporablja metode omenjene v literaturi in dokazane s preizkusi ([2], [3], [6] do [8]). Za potrebe oblikovanja in izvedbe matematičnega modela (enačbe vibracij) smo uporabili metode in programsko opremo, ki so bili prevejeni v praksi [9]. Zaradi navedenega menimo, da so dobljeni rezultati dovolj zanesljivi.

8 SKLEPI

1. Predstavljena metoda računalniške simulacije prostih in vsiljenih prečnih vibracij valjev za ploščo in valjev z gumijasto oblogo rotacijskega ofsetnega stroja za obojestransko tiskanje je primerna za ocenitev delovanja stroja.
2. Pokazali smo, da se v primeru, ko so dinamični modeli in parametri vseh valjev enaki, tri najnižje naravne frekvence valjev, ki so med seboj povezani, ponovijo in da med valji ni več modalnih relativnih vibracij, ki bi jim ustrezale. S tem je zmanjšana intenzivnost prostih in vsiljenih relativnih vibracij.
3. Pokazali smo, da spreminjanje razdalje in s tem pritiska med valji, ki ga povzroči vibriranje valjev, lahko znatno spremeni kakovost tiskanja.

scheme of computing) is based on the fact that it is sufficiently detailed and is formed of elements that simulate the deformation of the cylinders as well as the elasticity and damping of the blanket and the bearings using methods mentioned in the references and proved in experiments ([2], [3], [6] do [8]). For the formation and solution of the mathematical model (equations of vibrations), the methods and software tested in practice were applied [9]. For this reason, it is considered that the reliability of the obtained results is sufficient.

8 THE CONCLUSIONS

1. The developed computer-simulation method for the free and forced transversal vibrations of the plate and blanket cylinders of the printing press of a double-sided web-offset printing press is appropriate for assessing the performance of the press.
2. It was shown that if the dynamic models and the parameters of all the cylinders are the same, the three lowest natural frequencies of the cylinders connected with each other are repeated, and no modal relative vibrations corresponding to them remain between the cylinders. This reduces the intensity of the free and forced relative vibrations
3. It was shown that varying the distance and, consequently, the pressure between the cylinders caused by the vibration of cylinders can result in a significant change to the printing quality.

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Sistem za razporejanje in zmanjševanje stroškov proizvodnje

A Scheduling System for Minimizing the Costs of Production

Peter Bubeník

Prispevek opisuje uporabo tehnike za razporejanje proizvodnih naročil na ravni delavniške proizvodnje. Možnost dejanskega uvajanja za razporejanje naročil v podjetju je odvisno od posodabljanja plana proizvodnje in podatkov v proizvodni delavnici.

(Ključne besede: razporejanje, načrtovanje proizvodnje, razporejanje delavniško, simuliranje)

This paper discusses the use of simulation techniques for work-order scheduling at the factory-floor level of production. The ability to implement a simulation effectively for factory scheduling is dependent upon the availability of shop-floor data and the response time for the evaluation process.

(Keywords: scheduling, production planning, shop floor scheduling, simulations)

0 UVOD

Delavniški razpored ima pomembno vlogo pri upravljanju proizvodnega sistema. Odločati se je treba, ob upoštevanju celotnih ciljev, o rokih dobave, zmanjševanju stroškov, povezanih z zalogami blaga.

Upoštevanje vseh spremenljivk, ki vplivajo na zmožnost določenega razporeda, je zelo zahtevno in je praktično nemogoče pri večini proizvodnih opravil. Če se stroški proizvodnje zvečujejo, obstaja možnost za izrazite spremembe, predvsem s sestavljanjem proizvodnih razporedov za učinkovitejše postopke.

Kakovostni proizvodni razpored včasih vsebuje veliko spornih ciljev. Če se zmanjša prepustnost proizvodnje, bo idealni razpored imel naslednje lastnosti:
- križajo se dobavni roki;
- stroški zalog so na sprejemljivi ravni;
- naprave, kader in drugi omejeni viri so dobro izkoriščeni in uravnotežijo potek proizvodnje;
- prilagajanje je lahko hitro tudi ob nagli spremembi (napake na napravah, premalo vstopnega materiala itn.).

Načrtna proizvodnja in razpored imata pomembno vlogo pri doseganju ciljev v današnjem, pogosto se spreminjajočem konkurenčnem okolju. Primarni cilji načrtovanja in razporejanja v modernem proizvodnem okolju so naslednji:

0 INTRODUCTION

Shop-floor scheduling is an important task in managing a production system. A complex decision must be made, which impacts on global objectives such as meeting delivery due dates and minimizing the inventory of cost.

Attempting to consider all of the variables that which determine the effectiveness of a particular schedule is highly interrelated and has not been possible in most manufacturing operations. In the case of manufacturing-cost increases there are major productivity improvements to be realized by making the production scheduling for the process more effective.

The quality of a production schedule involves many – sometimes conflicting – objectives. While maximizing throughput is certainly an important consideration, an ideal schedule will also have the following characteristics:
- Delivery due dates are met.
- Inventory costs are maintained at acceptable levels.
- Equipment, personnel and other limited resources are well utilized and have balanced workloads.
- Adaptations can be made quickly in the event of an unexpected change (equipment failure, raw-material shortage, etc.).

Production planning and scheduling play a key role in helping management achieve its goals in this ever-changing and competitive environment. The primary objectives of production planning and scheduling in the modern manufacturing environment are as follows:

- časovno omejena proizvodnja, če je načrtovana in obljubljena;
- zmanjševanje t.i. polproizvodnje (polizdelkov);
- zmanjševanje zalog končne proizvodnje;
- zmanjševanje izkoriščanja razpoložljivega kapitala in drugih virov;
- povečanje zmogljivosti s krajšanjem časa proizvodnje;
- zmanjševanje stroškov proizvodnje.

1 TEHNIKE RAZPOREDA

Ni lahko optimizirati razpored v praksi ob upoštevanju vseh omenjenih ciljev. Izbere se eden od več proizvodnih razporedov za poudarjanje odvisnosti perečih proizvodnih skupin. Na splošno mora biti sprejet kompromis – uravnotežena rešitev posameznih ciljev. Proizvodna razporeditev v praksi poteka na več različnih načinov.

Najpogosteje se uporabljajo ročni postopki. V večini primerov vodja delavnice ali operater stroja vnese pripravljeno nalogo v zaporedje in naslednji zagon stroja. Merila, ki se uporabljajo v takšnih okoliščinah, pogosto kažejo ukrepe, ki se vrednotijo, ni pa nujno, da velja za vse cilje podjetja. Pogosto se uporablja načrtna tabla, ki prikazuje stanje dejanskih nalog in vizualno shemo razporeda.

Veliko analitičnih načinov postopka razporeditve je razvrščanje v skladu z odpravnimi pravili. Takšne metode uporabljajo pravila, ta dajejo prednost nalogam, ki čakajo na nadaljnjo obdelavo. Učinkovitost razporeda se lahko zelo razlikuje glede na nekatera izbrana pravila, tipe proizvodnih obratov in kombinacije izbranih nalog. Napoved zmogljivosti odpravnih pravil s tradicionalnimi metodami je zapleteno, hkrati pa so pravila od primera do primera omejena in se večinoma zelo težko uvajajo v proizvodni delavnici.

Vodje »poklicno« sovražijo analize. Z uporabo analiz in računalnikov ter grafičnih konstrukcij, ki jih imajo dandanes vodje na voljo, lahko zelo hitro dobijo odgovor glede analize razporeda proizvodnih naročil ali naročil za nadaljnjo proizvodnjo, ali pa lahko prejmejo informacijo v preprosti in razumljivi obliki.

Glavna prednost izdelanih podatkovnih tehnologij in računalnikov je nadzor proizvodne delavnice sproten. Le-ta omogoča dostop in ravnanje s podatki za proizvodnjo v dejanskem času in v okviru realnih možnosti.

Načrtovanje izdelavnih zmogljivosti II (NIZ II - MRP II) je razširilo cilje načrtovanju izdelavnih zmogljivosti (NIZ - MRP) in mu dodalo veliko novih vidikov proizvodnega vodenja. Obenem pa za podjetje izračuna njegovo zmogljivost, kar omogočajo moduli za zmogljivostno načrtovanje in zbiranje delavniških podatkov.

Sistemi razpolagajo z učinkovitimi tehnikami za določanje dolgoročnega terminskega razporeda in

- Produce, on time, what has been planned and promised.
- Minimize work in process.
- Minimize the inventory of finished goods.
- Maximize the utilization of capital assets and other resources.
- Increase throughput by reducing the manufacturing time.
- Minimize the cost of production.

1 SCHEDULING TECHNIQUES

It is difficult to optimise a schedule over all these characteristics in practice. From most production schedules, choose one to focus on, depending on the current production objectives. Generally, a trade off must be made to reach a balance between the objectives. Production scheduling is done in many ways in practice.

The most common methods of scheduling are purely manual techniques. In the most straightforward form, the department foreman, or the machine operator, selects the job to run next from those jobs waiting in front of the machine. The criteria used in this circumstance often reflects the measures by which he is evaluated, and may not reflect overall business objectives. Job status control boards are also used to visually layout schedules.

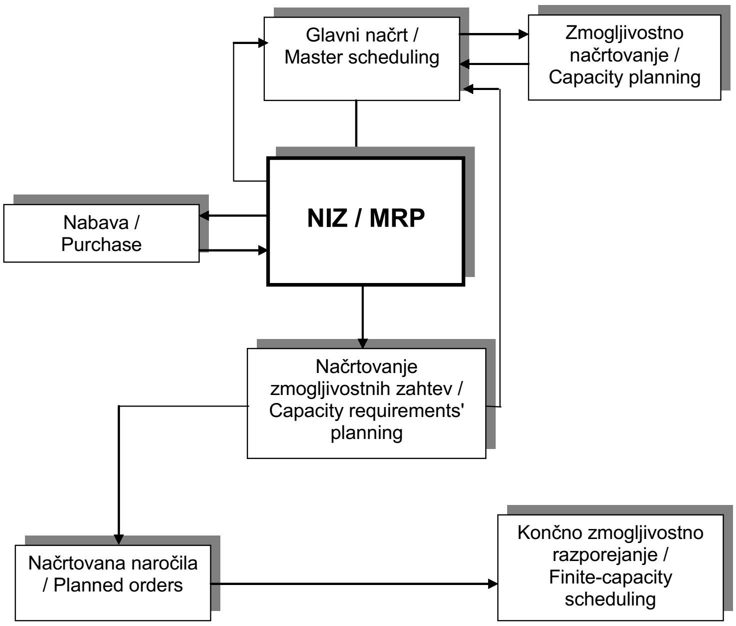
A more analytical approach to scheduling involves sequencing by dispatching rules. This method uses rules that prioritise the jobs waiting for processing. The effectiveness of the schedule may vary widely depending on the particular rule selected, the type of production facility, and the mix of jobs to be produced. It is difficult to predict the performance of dispatching rules by traditional methods. They are also limited in the scope of what they consider and are often hard to implement on the shop floor.

Managers have historically disliked having to wait a long time for analysis. With the computing capabilities and graphics constructs that are now available, managers can not only get a quick response for an analysis of work-order scheduling or work-order release, they can also receive the information in an easily understood form.

The major advances in database technologies have been made, and the computer is now a common sight on the shop floor. These improvements make the access to and manipulation of data for real-time factory control a real possibility.

MRP II (Manufacturing Resource Planning) expanded the scope of MRP to consider many other facets of production-facility management. In addition to sophisticated factory-accounting capabilities, modules for capacity planning and shop-floor data collection were also provided.

These techniques are effective for longer-term scheduling of order launching, but lack the de-



Sl.1. *Načrtovanje zmogljivosti podjetja*
Fig.1. *Enterprise resource planning*

izvedbo naročil, vendar pa ne zadostujejo za drobne potrebe in dejanski vsakdanji razpored. Načrtovanje zmogljivosti podjetja (NZP - ERP) se pojavlja kot razširjena oblika NIZ II z zmožnostmi integracije proizvodnih procesov s finančnimi operacijami in končnim zmogljivostnim razporejanjem (KZR - FCS).

2 KAJ JE KZR ?

Tradicionalni sistemi NIZ II predpostavljajo brezkončne zmogljivosti in preprosto sporočanje o preobremenjenih virih. Ročno je treba uravnotežiti načrte z uporabo povratne informacije iz funkcije načrtovanja zmogljivosti.

KZR pa nasprotno rešuje dejanske omejitve za glavno planiranje. Ta način sestavljanja razporeda je optimiziran za končno dosegljive proizvodne zmogljivosti.

Programska oprema za KZR je učinkovita zbirka programov, ki se na tem načelu uporabljajo za proizvodno podjetje. Znajo identificirati kritične in nekritične vire za optimizacijo razporeda proizvodnje. Optimizirajo osnovne faktorje proizvodnje preko končnih vnaprejšnjih razporeditev kritičnih virov po načelih OPT (Optimizacija proizvodne tehnologije) in menedžerski prednostni politiki.

KZR usklajuje proizvodnjo na osnovi povratnega razporeda neomejujočih sestavnih delov proizvodnega okolja. To zagotavlja odpravljanje materiala v delavnico ob primernem času, da izpolnimo zahteve razporeda za kritična omejujoča področja, ko ohranjamo majhne zaloge.

Z uvajanjem KZR-a v obratih bomo hitro spoznali naslednje dejanske izmerljive prednosti (preglednica 1).

tail necessary for effective day-to-day production scheduling. ERP (Enterprise Resource Planning) emerged as an extension of MRPII, with the ability to integrate a company’s manufacturing processes with financial transactions and FCS (Finite Capacity Scheduling).

2 WHAT IS FCS ?

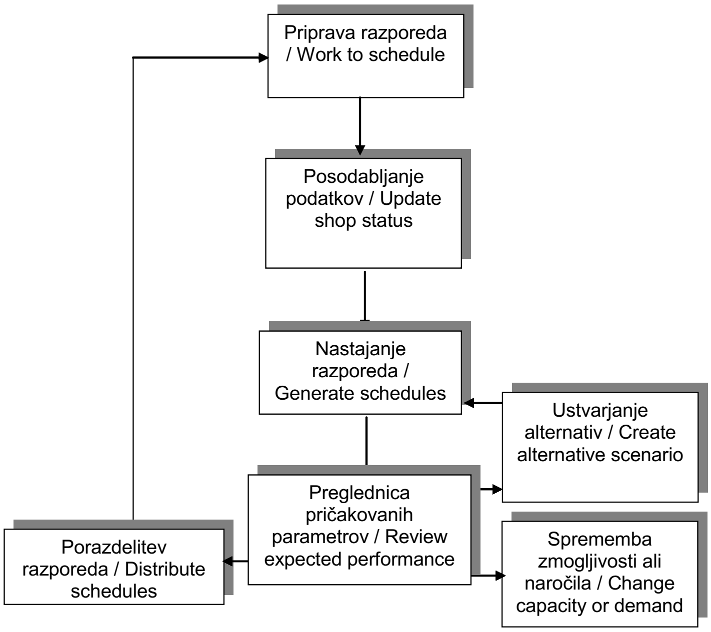
Traditional MRPII assumes infinity capacity and simply notifies you when resources are overutilized. You must then manually balance plans using feedback from the capacity-planning function.

FCS technology, on the other hand, provides true constrained privatisation for master planning. This means schedules recommended by the FCS are optimised the finite capacity available.

The FCS software is a powerful suite of programs that apply these principles to any manufacturing business. FCS identifies the critical and non-critical resources for optimised scheduling. FCS provides the optimised pacing of production by finitely forward-scheduling the critical resources according to the OPT (Optimalization Production Technology) principles and the management prioritisation policy.

FCS synchronises production by backward-scheduling the non-constraining parts of the manufacturing environment. It ensures the release of materials to the floor at the proper time to meet the needs of the schedule for critical constraining areas while maintaining a lean inventory.

By implementing the FCS system in plants, we will quickly realize the following quantifiable real benefits (Tab.1).



Sl. 2. *Postopek načrtovanja na osnovi KZR*
Fig.2. *The FCP Planning Process*

Preglednica 1.
Table 1.

Prednosti **Benefit**	**Potencial izboljšave** **Improvement potentional**
zmožnost dobave delivery performance	10 - 20 %
začeta proizvodnja work in process reduction	20 - 25 %
skrajšanje časa uvrščanja setup time reduction	50 %
izraba strojev machine utilization	15 - 25 %
zmanjšanje čakalnih dob reduction in idleness	15 - 20 %
izkoristek vzdrževanja maintenance crew utilization	10 - 15 %

3 PREDLOG IN DELO S SISTEMOM RAZPOREJANJA

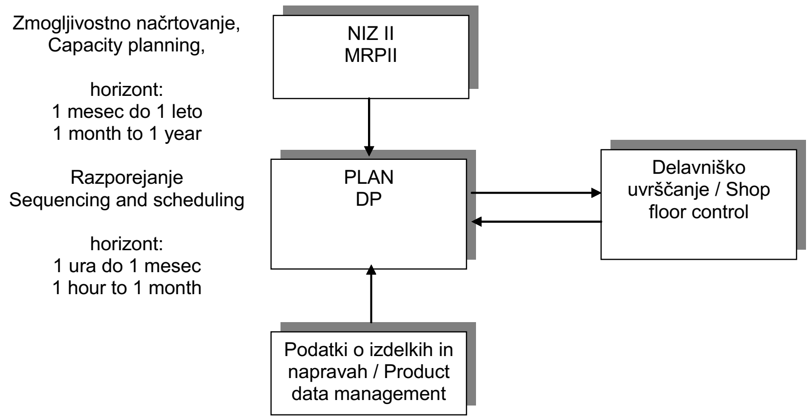
Na zahtevo podjetja Matador, Dopravné pásy, a. s. je bil izdelan osnutek elektronske načrtne table “PlanDP”. Podatki o naročilu / stranka, številka naročila, količina, datum dobave/ se naložijo iz sistema NIZ II v PlanDP in vsi podatki o proizvodnih opravilih (operativni časi, čas uvrščanja) se shranijo v podatkovno bazo PlanDP.

Postopek načrtne proizvodnje ima dve ravni. Zgornja raven je dolgoročni razpored in tradicionalna načrtna proizvodnja. Ta raven napoveduje oceno zmogljivosti in potrebnih virov na podlagi podatkov o prodaji ali pridobljenih naročil strank za sorazmerno velik časovni horizont (informacije se nalagajo iz sistema NIZ II.).

3 DESIGN AND WORKING WITH THE SCHEDULING SYSTEM

At the request of the division Dopravné pásy, MATADOR, a.s. we designed the electronic planning board “PlanDP”. Data of order (customer, order number, batch size, due date) are downloaded from the MRPII system into PlanDP and all the information of product operations (processing times, setup time) are held in the Plan DP database.

The production-planning process has two layers. The top layer represents long-range scheduling or traditional production-planning and control. This layer forecast the capacity and resources needed, based on estimated sales or orders for a relatively large time horizon (information loaded from the MRP II system).



Sl.3. *Postopek načrtovanja proizvodnje*
Fig.3. *Production-Planning Process*

Druga raven prikazuje podrobnosti razporeda opravil, predstavlja jo časovno okno naročila za nekaj ur in dni. Natančno uvrščanje je ugotovljeno za vsako napravo posebej. Načrtni mojster – razpošiljavec se najbolj osredotoči na to raven.

PlanDP se lahko uporabi kot grafični MPS (Glavno načrtovanje), kjer se naročila nalagajo z informacijami o izdelku v PlanDP, ki dokončno razporedi proizvodnjo. Ta korak se ponavlja, če proizvodni razpored ni v nasprotju s predpisanim ciljem. Cilj lahko določi vodstvo npr. najmanjše stroške proizvodnje itn.

»Srce in duša« predloženega KZR je zaporedje. Zaporedje je pravzaprav elektronska načrtna tabla, kjer so prikazani proizvodni viri in opravila.

V spodnji polovici slike, so prikazani vsi proizvodni viri in razporejena opravila, preprosto berljivi v obliki gantograma. Zunaj pogleda zaporedja so individualna okna virov z barvnimi ikonami, ki se uporabljajo za prikaz vnesenih opravil.

Postopek zaporedja:
1. Sistem naloži naročila in podatke o izdelku (številko naročilo, količino, kosovnik, termin dobave, tehnološki postopek).
2. Sistem uredi naročila glede na tip proizvodnega postopka in roka dobave.
3. Odmerja blago iz naročil, zmanjšuje število naprav – spremembe izbire.
4. Pošilja delo vseh kompletov, pravočasno za vsak stroj posebej, če stroj ne dela in je pripravljen za delo.
5. Sistem analizira cilje (rok dobave, najmanjše količine zamenjave začeto proizvodnjo, predpostavljeni čas proizvodnje).
6. Če razpored ni v nasprotju s predpisanimi cilji, je mogoče preklicati naloge in spremeniti zaporedje, operater spremeni količine, varianto tehnologije in vstop dejanskega časa naloge.

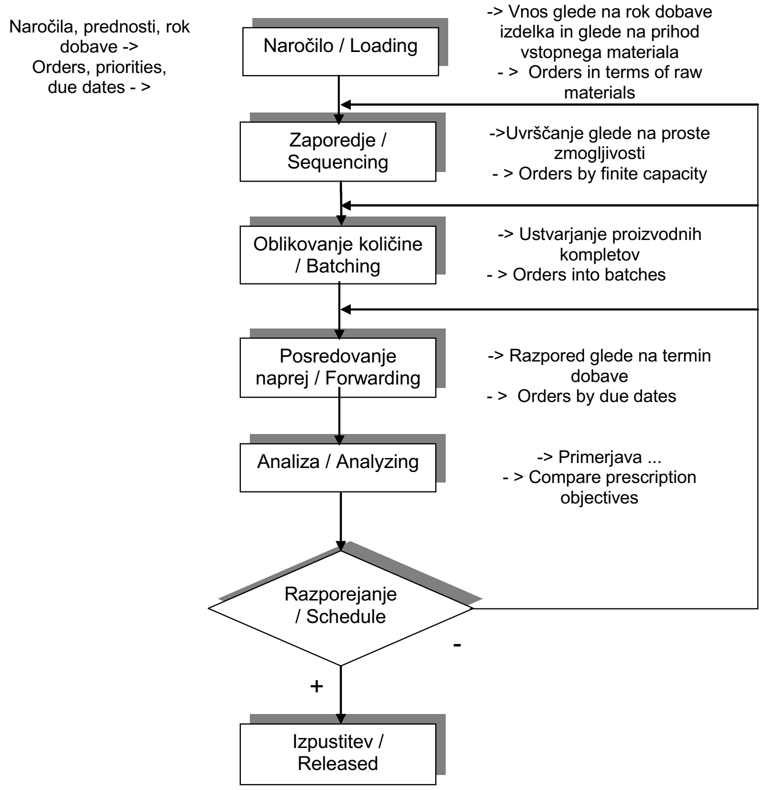
The second layer represents detailed or operational scheduling, here the time frame is of the order of hours to several days. The exact sequencing is determined for each machine. The scheduler concentrates most of his effort on this layer.

PlanDP can be used as a graphical MPS (Master Production Schedule) where orders are loaded with product information to PlanDP, which provides a finite schedule. This step is performed repeatedly until the schedule meets a prescription objective. This objective may be handed down from management, such as minimizing production costs, short lead times, etc.

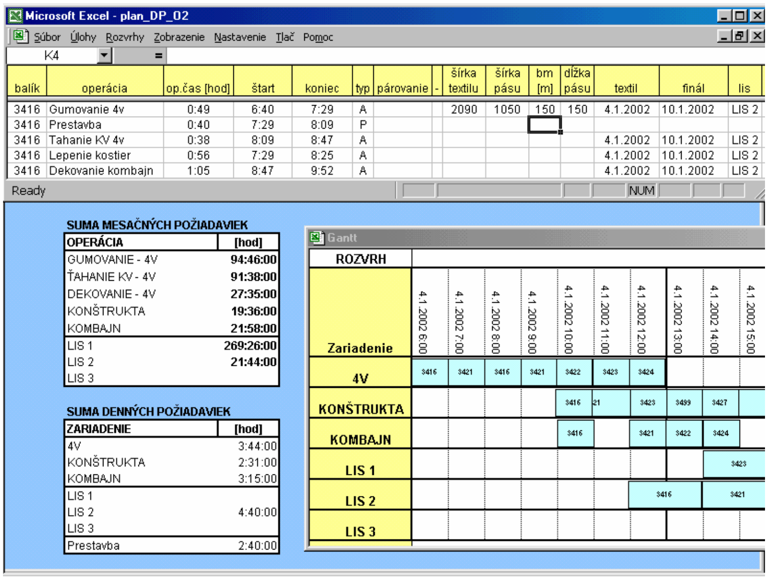
The heart and soul of the design of FCS is the sequencer. The sequencer is essentially an electronic planning board where resources and the operations scheduled for processing on each resource are displayed.

In the bottom half of the screen the sequence overview displays each resource and the operations scheduled on them in an easy-to-read Gant format. Above the sequence overview are the individual resource windows with colourful icons used to represent the loaded operations.

Sequencer process:
1. System loading orders with product information (number of orders, quantity, bill of materials, due date, technologies).
2. System sequencing orders by type of production technologies, due date.
3. Making batches from orders by minimizing the amount of set-up time.
4. Forwarding jobs for all batches on the time line for each machine, when the machine is not busy, jobs waiting.
5. System analysing objective (meeting of due date, minimum amount of set-up time, work in process, lead time).
6. If schedule does not meet a prescription objective, it has the possibility to unload jobs and change a sequence, operators can change a batch, vary technologies and enter actual operation times.



Sl.4. *Model „PlanDP“*
Fig.4. *Model PLANDP*



Sl.5. *Načrtna tabla “ PlanDP“*
Fig.5. *Planning board PLAN DP*

7. Če je razpored pripravljen za naročilo v proizvodnjo, KZR ponudi osnovne alternative razporeda, ki so dostopne za tisk.
8. Vnesi novo naročilo in se vrni na korak št. 1.

Sistem je programiran s pomočjo ”Visual Basic for Application“ v okolju MS Excel.

7. When a schedule is ready to be released, FCS offers you basic alternatives of the printed reports available.
8. New orders added, back to step 1.

The system has been written in the Visual Basic Application for the MS Excel environment.

4 SKLEP

Interaktivni sistem za razporejanje, ki je bil zasnovan za nastajanje sprejemljivega razporeda in spremembo sedanjega razporeda, sestavlja razpored zelo hitro in z razpoznavanjem kritičnih in nekritičnih virov. Razporejevalnik ima interaktivno orodje za učinkovito in pravočasno načrtovanje sprememb v proizvodnem obratu.

Učinkovitost predlaganega osnutka se testira v dejanskem proizvodnem postopku. Proizvodnja se je zadnjih deset dni občutno spremenila in se bo v najbližji prihodnosti spreminjala še naprej. Izvedene spremembe:

- Sistem zmanjša število zamud naročil in krajša čas proizvodnje z boljšo proizvodno kombinacijo naročil.
- Več možnosti proizvodnega razporeda omogoča pravočasno izvedbo naročila.
- Čas proizvodnje se zmanjšuje zaradi krajšega časa, potrebnega za spreminjanje izbire.
- Zahteva za pravočasno dostavo naročila zmanjšuje začeto proizvodnjo in stroške.

Ta prispevek je podprla znanstvena ustanove slovaške vlade – št. 1/7212/20.

4 CONCLUSION

The interactive scheduling systems that have been presented to generate a feasible schedule and to revise the existing schedule make a schedule very quickly by identifying the critical and non-critical resources. The dispatcher has interactive tools for effective planning changes on the shop floor in time.

The effectiveness of the proposed concept has been tested in a real manufacturing process. Manufacturing has been undergoing a significant change in the last decade and will continue to change for the foreseeable future. Some of the changes are as follows:

- The system reduces the number of delay orders and introduces shorter leadtimes by a better mix of orders.
- Many variants of sequencing make it possible to meet due dates.
- Lead times are minimized by decreasing the amount of set-up time.
- Demands to deliver just-in-time minimize work-in-process and reduce costs.

This paper was supported by the Scientific Grant Agency of Slovak Government – Grant No. 1/7212/20.

5 LITERATURA
5 REFERENCES

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Personal Events

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- seznam literature in
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Besedilo naj bo pisano na listih formata A4, z dvojnim presledkom med vrstami in s 3 cm širokim robom, da je dovolj prostora za popravke lektorjev. Najbolje je, da pripravite besedilo v urejevalniku Microsoft Word. Hkrati dostavite odtis članka na papirju, vključno z vsemi slikami in preglednicami ter identično kopijo v elektronski obliki.

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[2] Čuš, F., J. Balič (1996) Rationale Gestaltung der organisatorischen Abläufe im Werkzeugwesen. *Proceedings of International Conference on Computer Integration Manufacturing,* Zakopane, 14.-17. maj 1996.

[3] Oertli, P.C. (1977) Praktische Wirtschaftskybernetik. *Carl Hanser Verlag,* München.

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