

Izboljšanje dinamičnih značilnosti rotorskega sistema z razvojnim algoritmom

Improving the Dynamic Characteristics of a Rotor System using an Evolutionary Algorithm

Hamit Saruhan
(Duzce University, Turkey)

V tem prispevku je povzeta študija optimalnega oblikovanja, potrebnega za izboljšanje dinamičnih značilnosti gibkega, prevesnega rotorskega sistema. Oblikovanje gibkega rotorskega sistema je zapleten postopek, saj ima veliko število geometričnih parametrov hidrodinamičnih ležajev, ki opravljajo pomembno nalogo pri napovedi dinamičnega obnašanja rotorskega sistema. Pri razporedu rotorskega sistema moramo upoštevati veliko oblikovnih zahtev, s katerimi lahko izboljšamo dinamične značilnosti, povezane z rotorjevim hitrostnim razponom. Za izboljšanje dinamičnih značilnosti rotorskega sistema smo uporabili genetski algoritem, za oblikovanje komponent rotorskega sistema pa smo uporabili metodo končnih elementov. Da bi potrdili učinkovitost in uporabnost predlagane metode, smo uporabili tudi metodo izvedljivih smeri; z njo smo dokazali, da je predlagana metoda oblikovanja rotorskega sistema učinkovita in uporabna za izboljšanje dinamičnih značilnosti rotorskega sistema.

© 2007 Strojniški vestnik. Vse pravice pridržane.

(Ključne besede: rotorski sistemi, optimiranje, genetski algoritmi, metode končnih elementov)

In this paper the optimum design for improving the dynamic characteristics of a flexible, overhung rotor system is studied. The design of a flexible rotor system is a complicated process due to the large number of geometrical parameters of hydrodynamic bearings, which play an important role in the prediction of the dynamic behavior of the rotor system. There are a number of design requirements added to the rotor-system configuration that improve the dynamic characteristics within the rotor's speed range. To improve the dynamic characteristics of the rotor system, a genetic algorithm was employed and the modeling of the components of the rotor system was made with the finite-element method. Also, the method of feasible directions was used in order to validate the efficiency and applicability of the proposed method, and it proved that the proposed method in the rotor-system design is very efficient and useful for improving the dynamic characteristics of the rotor system.

© 2007 Journal of Mechanical Engineering. All rights reserved.

(Keywords: rotor systems, optimization, genetic algorithm, finite element methods)

0 UVOD

Glavni namen tega prispevka je bil razvoj praktičnega postopka, s katerim bi rotorski sistem primerno oblikovali. Zahtevnost in dolgotrajnost oblikovanja rotorskega sistema sta terjali uporabo bolj robustne in učinkovite metode optimiziranja. Zato smo pri oblikovanju rotorskega sistema uporabili genetski algoritem, hkrati pa uporabili tudi metodo mogočih smeri, da bi potrdili učinkovitost in uporabnost predlaganega postopka. Genetski algoritem je vodena tehnika naključnega iskanja najboljše rešitve. Postopki iskanja parametrov

0 INTRODUCTION

The major goal in this paper was to develop a practical procedure by which the rotor system could be designed efficiently. The complexity and time-consuming nature of the design process of the rotor system required the use of a more robust and efficient optimization method. From this point of view, the genetic algorithm was employed in the rotor-system design and the method of feasible directions was also conducted to validate the efficiency and applicability of the proposed method. The genetic algorithm is a guided random search

temeljijo na načelu naravne izbire in genetike [5]. Z genetskim algoritmom lahko ustvarimo pomembno ravnotežje med raziskovanjem in izkoriščanjem iskalnega prostora ([7] in [17]). Razvojni algoritmi so novost na področju analize rotorskih sistemov in v literaturi najdemo le njihove delne študije, kot na primer prispevki avtorjev Saruhan idr. [10], Saruhan idr. [11] ter Qin idr. [19].

1 OPTIMIZACIJA POSTOPKOV

Genetski algoritem je prvi predlagal Holland [12], nadalje pa sta ga razvila De Jong [14] in Goldberg [5]. Genetski algoritem je zelo primeren za reševanje problemov s kompleksnimi, nezveznimi in diskretnimi funkcijami. Genetski algoritem vzdržuje populacijo kodiranih rešitev, ki jih vodi k optimalni rešitvi [5]. Tako v iskalnem prostoru išče dobre osebkke in najboljšo mogoče končno rešitev. Namesto da bi se postopek začel z rešitvijo v eni točki v iskalnem prostoru, kakor v primeru numeričnih metod, pa genetski algoritem začne postopek z začetnim naborom naključnih rešitev. Pseudokoda genetskega algoritma je predstavljena na sliki 1. Genetski algoritem se začne z začetnim naborom naključnih rešitev, ki se imenujejo kromosom in so rešitev danega problema. Kromosom je običajno niz z naključnimi kombinacijami stanj 0 in 1, ni pa nujno niz binarnih bitov. Ta niz se razvija prek zaporednih ponovitev, ki se imenujejo generacije. Nizi vsake generacije so ovrednoteni z določenim merilom za njihovo ustreznost. Potem se algoritem nadaljuje in ustvarja novo obliko, dokler niso izpolnjeni zaključni kriteriji. Po ovrednotenju ustreznosti vsakega osebkka v populaciji uporabimo genetska opravila

```

Begin /*genetski algoritem*/
t ← 0;
(začetek) roditelj(t);
(oceni ustreznost vsakega osebkka) roditelj(t);
WHILE (NOT finished) DO LOOP
kombiniraj roditelja(t) da dobiš potomca(t);
oceni potomca(t);
izberi roditelja(t+1)
med roditeljem(t) in potomcem(t);
t ← t + 1; IF populacija konvergira THEN
end
end

```

Sl. 1. Pseudokoda genetskega algoritma

technique. Its parameter search procedures are based on the idea of natural selection and genetics [5]. A remarkable balance between exploration and exploitation of the search space can be made with a genetic algorithm ([7] and [17]). Evolutionary algorithms are new to the field of rotor-system analysis, and in the current literature there are limited studies, such as those of Saruhan et al. [10], Saruhan et al. [11], and Qin et al. [19].

1 OPTIMIZATION PROCEDURES

The genetic algorithm was first proposed by Holland [12] and extended further by De Jong [14] and Goldberg [5]. The genetic algorithm is well suited to the problems with complex, discontinuous, and discrete functions. The genetic algorithm maintains a population of encoded solutions, and guides them towards the optimum solution [5]. Thus, it searches the space of possible individuals and seeks to find the fittest solution. Rather than starting from a single-point solution within the search space, as in numerical methods, the genetic algorithm starts with an initial set of random solutions. The pseudocode of the genetic algorithm is outlined in Fig. 1. The genetic algorithm starts with an initial set of random solutions called a chromosome, representing a solution to the problem at hand. A chromosome is usually a string with random combinations of 0s and 1s, but not necessarily a binary-bit string. The string evolves through successive iterations, called generations. During each generation the strings are evaluated using some measure of fitness. The algorithm then proceeds by generating a new design until the termination criteria have been satisfied. After the evaluation of each individual fitness in the population, the genetic operators, selection,

```

Begin /*the genetic algorithm*/
t ← 0;
(initialize) parent(t);
(evaluate fitness of each individual) parent(t);
WHILE (NOT finished) DO LOOP
recombine parent(t) to yield offspring(t);
evaluate offspring(t);
select parent(t+1)
from parent(t) and offspring(t);
t ← t + 1; IF population has converged THEN
end
end

```

Fig.1. The genetic algorithm pseudocode

– izbiro, križanje in spremembo – da ustvarimo novo generacijo. Po potrebi uporabimo tudi druge genetske posege. Novo ustvarjeni osebkki nadomestijo sedanjo generacijo in začne se ponovno vrednotenje ustreznosti novih osebkov. Pri vsaki naslednji generaciji genetski algoritem ustvari nov nabor kromosomov z uporabo najboljših informacij prejšnjih generacij. Zanko ponavljamo, dokler ne najdemo sprejemljive rešitve.

Metoda izvedljivih smeri je metoda številčnega iskanja, ki se začne z začetno domnevo, se iterativno nadaljuje in na izvedljivem področju išče optimalno rešitev. Metodo izvedljivih smeri je prvi razvil Zoutendijk [6] ter jo kasneje dopolnil Vanderplaats [8]. Metoda izvedljivih smeri temelji na ugotovitvi, da je smer iskanja S_i tista, po kateri že majhen premik ustvari izboljšanje vrednosti namenske funkcije, ne da bi se ob tem porušile dejavne omejitve.

$$X_{i+1} = X_i + \alpha S_i \quad (1),$$

kjer i pomeni število ponovitve, S je smer gibanja, skalarna količina α določa razdaljo gibanja (iskalna količina) v določeni smeri, X_{i+1} pa je končna točka, ki jo dobimo na koncu iteracije i . Izbira vrednosti S_i je odvisna od lege točke X_i . Algoritem je oblikovan takole:

crossover, and mutation, are applied to produce a new generation. Other genetic operators are applied as needed. The newly created individuals replace the existing generation, and re-evaluation is started for the fitness of new individuals. In each succeeding generation, the genetic algorithm creates a new set of chromosomes using the best information from the previous generation. The loop is repeated until an acceptable solution is found.

The method of feasible directions is a numerical search method that starts with an initial guess and proceeds iteratively, searching through the feasible region for an optimal solution. The method of feasible directions was first developed by Zoutendijk [6] and then modified by Vanderplaats [8]. The method of feasible direction is based on the observation that a search direction, S_p is found such that a small move along it would produce an improvement in the objective function value without violating the active constraints.

where i represents the iteration number, S is the direction of movement, the scalar quantity α defines the distance of movement (the search quantity) that must move along the direction, and X_{i+1} is the final point obtained at the end of the i -th iteration. The choice of S_i depends on the position of the point X_i . The algorithm is formulated in the following way:

$$\text{Optimiziraj/Optimize } F(X_i) \quad (2)$$

ob upoštevanju, da je:

Subject to:

$$g_j(X_i) < 0 \quad g_j(X_i) = 0 \quad (3),$$

$j = 1, \dots, \text{Nom} / \text{Ncon}$ (število omejitev/number of constraints)

kjer sta $F(X_i)$ objektivna in g_j omejitvena funkcija, X_i pa je n -vektor spremenljivk oblikovanja. Zahtevi po uporabnosti in izvedljivosti, vezani na vektor iskanja smeri S , sta matematično izraženi takole:

where $F(X_i)$ and g_j are the objective and constraint functions respectively, X_i is an n -vector of design variables. Mathematically, the usability and feasibility requirement for the search direction vector, S , can be expressed as follows:

$$\nabla F(X_i)S \leq 0 \text{ uporabnost/usability} \quad \nabla g_j(X_i)S \leq 0 \text{ izvedljivost/feasibility} \quad (4)$$

kjer sta $\nabla F(X_i)$ gradient namenske omejitve, $g_j(X_i)$ pa gradient dejavne omejitve j , dobljene na točki X_i . Več informacij o opisani tehniki lahko bralci najdejo v sestavku Vanderplaats [8].

where $\nabla F(X_i)$ is the gradient of the objective and $g_j(X_i)$ is the gradient of the j -th active constraint computed at point X_i . The reader can refer to detailed information about this technique in Vanderplaats [8].

2 PREDSTAVITEV PROBLEMA

Rotorski sistem mora biti oblikovan tako, da ob različnih obratovalnih hitrostih deluje brez

2 THE PROBLEM STATEMENT

The rotor system must be designed to operate without excessive vibration throughout its range of

odvečnega vibriranja. Rotorjeva amplituda je funkcija dinamičnih značilnosti rotorja in ležaja. Ležajevi dinamični parametri imajo pomembno vlogo pri napovedi dinamičnega obnašanja rotorskega sistema ter so pomembni pri določanju odzivnosti in stabilnosti rotorskega sistema [13]. Določitev amplitude odzivnosti je zelo zapleteno zaradi asimetrije koeficientov togosti in dušenja pri križno spojeni tekočinski plasti, ki pa sta odvisna od hitrosti rotorja. Glavni cilj študije je uporaba genetskega algoritma in metode mogočih smeri za potrebe zmanjšanja amplitud odziva na različne hitrosti rotorja pri gibkem vrtilnem sistemu. Začetno fazo razvoja oblikovanja rotorja, ki ga podpirajo ležaji, smo vzpostavili z modeliranjem vrtilnega sistema, predstavljenega na sliki 2, ki smo ga delno povzeli po viru Roso [2]. Sistem je sestavljen iz velikega diska (vijak) z rotorjem, ki ga podpirata dva pritrjena hidrodinamična trisegmentna ležaja. Rotorski sistem smo simulirali s kombinacijo 31 končnih elementov in 32 leg. Podrobnosti oblike rotorja so razvidne iz preglednice 1. Hitrost rotorja je v razponu med 5.000 min^{-1} in 40.000 min^{-1} , dva ležaja pa sta nameščena na legah 14 in 24. Značilnosti rotorja in uporabljenega maziva so naslednje: obratovalna hitrost tečaja je 28.000 min^{-1} , zunanje breme tečaja je $1401,19 \text{ N}$, tip maziva je mineralno olje, stopnja kakovosti maziva je ISO VG-32, vstopna temperatura maziva je $46,11^\circ\text{C}$, in vstopni pritisk maziva je $1,757674 \text{ bar}$. Nastavitev izračuna za rotorski sistem temelji na metodi končnih elementov in uporabi metode redukcije matrike. Metoda končnih elementov se je izkazala kot zelo učinkovita za potrebe modeliranja. Njena prednost pred drugimi metodami je v tem, da omogoča večjo natančnost diskretizacije rotorja [16]. Z uporabo metode redukcije matrike, oziroma Guyanove metode redukcije, v algoritmu, ki temelji na končnih elementih, zmanjšamo obseg sistemskih izračunov in njihove stroške, ne da bi s tem bistveno vplivali na točnost rezultatov ([15] in [16]). Z metodo končnih elementov smo določili približek dinamičnega obnašanja rotorskega sistema: rotor smo razdelili na končno število elementov ter nato vsak element označili glede na njegove dinamične značilnosti. Postopno zbiranje posameznih značilnosti rotorjevih elementov, skupaj s sestavljanjem učinkov ležaja in vijaka, privede do splošne oblike enačb gibanja celotnega sistema takole:

operating speeds. The rotor's amplitude is a function of the dynamic characteristics of both the rotor and the bearing. The bearing's dynamic parameters play an important role in the prediction of the dynamic behavior of the rotor system and they are important in determining the response and the stability of the rotor system [13]. The determination of the response amplitude is much involved due to the asymmetry in the cross-coupled fluid film's stiffness and the damping coefficients, which in turn are dependent on the rotor speeds. The main objective here is the use of the genetic algorithm and the method of feasible directions for the minimization of the response amplitudes within the rotor speed range of the flexible rotor system. The initial phase of developing a design methodology for the rotor supported in the bearings was established with the modeling of the rotor system shown in Fig. 2, partially adapted from Roso [2]. The system consists of a large disc (impeller) with the rotor supported in two hydrodynamic fixed three-lobe bearings. The rotor system is simulated by a combination of 31 finite elements and the 32 stations. Details of the rotor configuration are provided in Table 1. The rotor speed ranged from $5,000 \text{ rpm}$ to $40,000 \text{ rpm}$ and the two bearings are located at stations 14 and 24 respectively. The rotor and the lubricant properties used are as follows: journal operating speed, $28,000 \text{ rpm}$, journal external load, 1401.19 Newtons , lubricant type (mineral base), lubricant grade (ISO VG-32), lubricant inlet temperature, 46.11°C , and the lubricant inlet pressure, 1.757674 bar . The formulation for the rotor-system calculation is based on the finite-element method using the matrix-reduction method. The finite-element method has proven to be very effective for modeling. The finite-element method has the advantage over other methods in that it provides greater accuracy for the rotor discretization than the other methods [16]. Using a matrix-reduction method, the Guyan Reduction Method, in the finite-element-based algorithm, reduces the size and the computational cost of the system calculations with no significant effect on the accuracy of the results ([15] and [16]). The finite-element method was developed to approximate the dynamic behavior of the rotor system as follows: the rotor is subdivided into a finite number of elements, and each element is characterized by dynamic properties. The successive assembling of the individual rotor-element characterization along with the assembling of the effect due to the bearing and impeller leads to a general form of equations of motion for the complete system as follows:

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{Q(t)\} \quad (5),$$

kjer je $q = [U_1 \ V_1 \ \Theta_1 \ \Phi_1 \ U_2 \ V_2 \ \Theta_2 \ \Phi_2]^T$ vektor premikov ($U \ V$) v smeri X in smeri Y ter zavrtitve ($\Theta \ \Phi$) okoli osi X in osi Y . Spodnja indeksa 1 in 2 določata oba konca prikaza končnega elementa; $[M]$, $[C]$, $[K]$ pa predstavljajo matrice mase, dušenja in togosti. $\{Q(t)\}$ je vektor vzbujevalnih sil in momentov. Amplitudo rotorjevih premikov pri vsakem vozliščnem mestu smo izračunali tako, da smo najprej iz kompleksnih rezultatov izločili realne rešitve. Na posameznem vozliščnem mestu rotorja ima rešitev naslednjo obliko [2]:

$$U_2 = \left(R(U_{0,2}) + J(U_{0,2}) \right) e^{J\Omega t} \quad (6)$$

$$V_2 = \left(R(V_{0,2}) + J(V_{0,2}) \right) e^{J\Omega t} \quad (7)$$

$$R(U_2) = A_{U_2} \cos \psi_{U_2} \cos \Omega t + A_{U_2} \sin \psi_{U_2} \sin \Omega t \quad (8)$$

$$R(V_2) = A_{V_2} \cos \zeta_{V_2} \cos \Omega t + A_{V_2} \sin \zeta_{V_2} \sin \Omega t \quad (9),$$

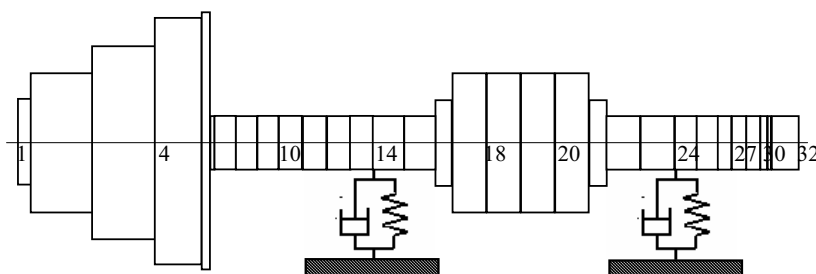
kjer so: R operator realnega dela, J operator imaginarnega dela, A lastni vektor, ζ rotacijski premik okoli osi x , ψ vrtilni zasuk okoli osi y , t čas, Ω pa hitrost vrtenja.

Zaželeno je uporaba tehnik optimizacije, da z njimi določimo in izberemo spremenljivke modela, ki jih lahko uporabimo za optimizacijo rotorskega sistema, ki bo izpolnil izbrane kriterije. Obstaja močno razmerje med funkcijami namena, spremenljivk in kriterijev oblikovanja. Vektor spremenljivk oblikovanja vključuje razmerje med osno dolžino segmenta in premerom tečaja (y_1), razdaljo med segmentom ležaja in obodom (y_2), prečni razmik ležajev (y_3), faktor pomika segmenta (y_4), faktor naprejšnje obremenitve segmenta (y_5), in usmerjenost ležaja glede na obremenitev (y_6) ter je izražen takole:

where $q = [U_1 \ V_1 \ \Theta_1 \ \Phi_1 \ U_2 \ V_2 \ \Theta_2 \ \Phi_2]^T$ is the vector of displacement ($U \ V$) in the X -axis and Y -axis and the rotational displacement ($\Theta \ \Phi$) about the X -axis and Y -axis. Subscripts 1 and 2 identify each end of the finite-element representation, and $[M]$, $[C]$, $[K]$ represents the mass, damping, and stiffness matrices respectively. $\{Q(t)\}$ is the vector of the exciting forces and moments. The amplitude of the rotor displacement at each nodal location is computed by first extracting the real solution from the complex results. The particular solution at a nodal location of the rotor is of the form [2]:

where R is real part operator, J is an imaginary part operator, A is the eigenvector, ζ is the rotational displacement about the x -axis, ψ is the rotational displacement about the y -axis, t is the time, and Ω is the rotation speed.

It is desirable to utilize optimization techniques to evaluate and select the design variables that can be used to optimize the rotor system that will satisfy the criteria placed on them. There is a strong relationship among the design-objective, design-variables, and design-criteria functions. The vector of the design variables includes the pad-axial-length to journal-diameter ratio (y_1), the pad (lobe) to the arc length (y_2), the bearing radial clearance (y_3), the pad offset factor (y_4), the pad preload factor (y_5), and the bearing orientation with respect to the load (y_6) expressed as follows:



Sl. 2. Razpored končnih elementov rotorskega sistema
Fig. 2. Finite-element configuration of the rotor system

Preglednica 1. Rotorjeva razporeditev

Table 1 The rotor configuration

Element rotorja Rotor Element	Lege elementa Element Stations	Dolžina elementa rotorja (mm) Rotor Element Length (mm)	Skupna dolžina el. (mm) Cumulative Element Length (mm)
1	1 2	6,248	6,248
2	2 3	30,142	36,390
3	3 4	30,142	66,532
4	4 5	22,268	88,800
5	5 6	3,810	92,610
6	6 7	2,032	94,642
7	7 8	9,989	104,630
8	8 9	9,989	114,622
9	9 10	9,989	124,612
10	10 11	11,168	135,780
11	11 12	11,168	146,949
12	12 13	11,168	158,117
13	13 14	11,168	169,285
14	14 15	14,744	184,030
15	15 16	14,744	198,775
16	16 17	7,620	206,395
17	17 18	15,875	222,270
18	18 19	15,875	238,145
19	19 20	15,875	254,025
20	20 21	15,875	269,900
21	21 22	8,128	278,028
22	22 23	15,836	293,852
23	23 24	15,836	309,702
24	24 25	10,325	320,014
25	25 26	10,325	330,352
26	26 27	6,350	336,702
27	27 28	6,718	343,408
28	28 29	6,718	350,139
29	29 30	3,048	353,187
30	30 31	15,240	354,711
31	31 32	12,700	367,411

$$X(i) = \begin{bmatrix} (y1), \\ (y2) * (\pi / 180), \\ (y3) * (1 - y5) / 1000, \\ (y4) * 2, \\ (y5) * 2, \\ (y6) * (\pi / 180) \end{bmatrix} \quad (10),$$

kjer je i število oblikovnih spremenljivk. Razmerje med osno dolžino segmenta in premerom tečaja vpliva na nestabilnost, ki jo povzroči tekočinska plast. Ključni parameter, ki ga uporabimo za opis ležajev s pritrjenimi segmenti, je delež konvergentnega segmenta pri celotni dolžini segmenta. To razmerje imenujemo faktor pomika segmenta. Geometrijsko razmerje med segmenti ležaja in tečajem lahko dobimo

where i is the number of design variables. The pad-axial-length to journal-diameter ratio has an affect on the fluid-induced instability. A key parameter used for describing fixed-pad (lobe) bearings is the fraction of the converging pad to full-pad length. This ratio is called the pad-offset factor. A geometric relationship between the bearing pads and the journal can be obtained by constructing the bearing pad

s tem, da ležajne segmente oblikujemo tako, da se njihova središča ne ujemajo s središčem ležaja. S tem na vsakem segmentu ustvarimo konvergentne in divergentne predele tekočinske plasti, zaradi katerih celo v primeru neobremenjenega tečaja v plasti nastane tlak. Ker do pojava pride v odsotnosti tečajev obremenitve, je le-ta v literature poimenovan kot vnaprejšnja obremenitev ležaja. Ker lahko vnaprejšnja obremenitev vpliva na usrediščenost rotorja, lahko na ta način izboljšamo stabilnost rotorskega sistema. Vse oblikovne spremenljivke sistematično preverimo, da ugotovimo učinek vsake kombinacije in dobimo najmanjšo namensko funkcijo glede na oblikovne kriterije. Tako ugotovimo, da se, na primer: prečni razmik poveča ob povečanju najmanjše debeline tekočinske plasti; da izgubo moči lahko premostimo s krajšanjem dolžine ležajnih segmentov; da povečanje premera tečaja povzroči povečanje izgub; da največji vršni tlak segmenta lahko zmanjšamo do najmanjših vrednosti tako, da povečamo osno dolžino ležajnega segmenta in zmanjšamo parameter vnaprejšnje obremenitve ležaja; ter da se začetna nestabilnost poveča ob povečani vnaprejšnji obremenitvi, ki se zmanjša ob povečanju pomika. Omejitve so pogoji, ki jih moramo izpolniti z optimalnim oblikovanjem in ki pomenijo omejitve funkcij oblikovnih kriterijev, kot na primer temperatura plasti, tlak plasti, pretok maziva, obodni pomik, meje stabilnosti ter geometrijske razlike. Temperatura ležaja je pomemben kriterij, ki ga moramo izpolniti, saj v nasprotnem primeru lahko povzročimo okvaro ležajev tečaja in s tem celotnega rotorskega sistema. Učinek tlaka v tekočinski plasti se kaže v gostoti in viskoznosti maziva. Količina tekočine, ki je potrebna ležaju, je tudi faktor delovanja ležaja. Zaradi omejitev stabilnosti je potrebno poznati najmanjšo vrednost logaritmičnega zmanjšanja za primer nestabilnosti, ta nastane pod vplivom sil tekočinskega vzbujanja. Namenska funkcija se nanaša na ostrino resonance, ki sledi načinu, izkazuje največjo obodno amplitudo. Izraz za namensko funkcijo, ki predstavlja rotorjevo amplitudo odziva, je naslednji:

$$F_{\text{objective}} = \sum_{i=1}^{N_{\text{modes}}} \sum_{j=1}^{N_{\text{stations}}} \left(\omega_i / \left(\omega_{a,i} \omega_{b,i} \right) \right) \quad (11)$$

$$\text{Fitness Function} = \sum_{i=1}^{N_{\text{modes}}} \sum_{j=1}^{N_{\text{stations}}} \left(\omega_i / \left(\omega_{a,i} \omega_{b,i} \right) \right) + \sum_{j=1}^{N_{\text{con}}} r_j \left(\max[0, g_j] \right)^2 \quad (12),$$

kjer je $F_{\text{objective}}$ amplituda odziva, N_{stations} so izbrane lege vzdolž rotorja, na katerih je odziv optimiziran,

centers not coinciding with that of the bearing. This would produce converging and diverging film sections along each pad; consequently, fluid film pressures would be generated even with an unloaded journal. Since this condition occurs in the absence of a journal load, it is called, in the literature, a bearing preload. Because the preload can affect the rotor-centerline position, the stability of the rotor system is improved. The design variables are all systematically varied to identify the effects of each combination, finding the minimum objective function along the design criteria, such as the radial clearance increases as the minimum film thickness increases, the power loss decreases by reducing the length of the bearing pads, an increase in the journal diameter would produce an increase in losses, the maximum pad peak pressure is reduced to minimum values by increasing the axial length of the bearing pad and reducing the bearing preload parameter, and the instability threshold increases with larger preloads, which tends to decrease as the offset factor increases. Constraints are conditions that must be met in the optimum design and include restrictions to design criteria functions, such as film temperature, film pressure, lubricant flow, orbital displacement, stability bounds, and geometric inequalities as follows: Bearing temperature is an important criterion that should be met because it can be dangerous enough to give a failure in the journal bearings and thus the whole rotor system. The effect of the pressure in the fluid film is reflected by the density and viscosity of the lubricant. The amount of fluid that needs to be supplied for the bearing is also a factor in the bearing performance. For the stability bounds it is necessary to have a minimum logarithmic decrement value for the mode predicted to become unstable under the process fluid excitation forces. The objective function is referred to as the sharpness of resonance, which aims to track the mode that exhibits the highest orbital amplitude. The statement for the objective function representing the rotor's response amplitude is:

where $F_{\text{objective}}$ is the response amplitude, N_{stations} are selected stations along the rotor where the response

$\omega_{a,i}$ in $\omega_{b,i}$ sta frekvenci na obeh straneh resonance imenovani stranska pasova, N_{con} pa je število omejitev.

Funkcija ustreznosti meri in razvršča vektorje kodiranih spremenljivk ter nato izbere povezave, ki vodijo do najboljših rešitev. Problem optimizacije omejitev smo spremenili v problem optimizacije brez omejitev in ga rešili s kaznovanjem vrednosti namenske funkcije s kvadratno kazensko funkcijo, s katero zagotovimo, da namenska funkcija ustreza vsiljenim omejitvam. V primeru kakršne koli kršitve omejitev je funkcija ustreznosti, ki se nanaša na rešitev, kaznovana in zadržana v izvedljivih področjih oblikovalnega prostora. Za potrebe nadzorovanja in kaznovanja so potrebni kazenski koeficienti, r_j , ki jih uporabimo za različne ravni kršitve posameznih omejitev. Kakor navajajo Homaifar idr. [1], moramo kazenske koeficiente preudarno izbrati, saj so primerne rešitve močno odvisne od vrednosti teh koeficientov.

3 REŠEVANJE PROBLEMA Z GENETSKIM ALGORITMOM

Prvi korak reševanja določenega oblikovalnega problema z genetskim algoritmom je kodiranje oblikovnih spremenljivk kot niz. Ta niz se tipično nanaša na rešitev problema. Namesto da bi začel pri eni sami rešitvi v iskalnem prostoru, kar se zgodi pri numeričnih metodah, se genetski algoritem začne s populacijo rešitev, ki določajo število nizov vsake generacije. Vektorji zveznih oblikovalnih spremenljivk so predstavljeni in diskretizirani natančno do vrednosti ε (za to obravnavo smo določili $\varepsilon = 0,01$). Število števk v binarnem nizu L ocenimo z naslednjim razmerjem [3]:

$$2^L \geq \left[\left(X(i)_{\text{zgomji/upper}} - X(i)_{\text{spodnji/lower}} \right) / \varepsilon \right] + 1 \quad (13),$$

kjer sta $X(i)_{\text{spodnji}}$ in $X(i)_{\text{zgomji}}$ spodnja in zgornja meja za vektor oblikovnih spremenljivk.

Šest oblikovnih spremenljivk kodiramo v binarnem zapisu $\{0, 1\}$, kar prikazuje preglednica 2. Predstavitev vektorja oblikovnih spremenljivk z binarnim nizom $X(i)$ je lahko nastavljena od začetka do konca kot dolgi niz, ki ga imenujemo kromosom. Preglednica 3 prikazuje niz 42 binarnih zapisov, ki označujejo združene vektorje oblikovnih spremenljivk. Z naključno izbranim naborom

is optimizied, $\omega_{a,i}$ and $\omega_{b,i}$ are two frequencies on either side of the resonance known as sidebands, and N_{con} is the number of constraints.

The fitness function measures and rates the coded variables' vector in order to select the fittest strings that lead the solution. The constraint optimization problem was transformed into an unconstrained optimization problem and handled by penalizing the objective function value by a quadratic penalty function, which is used to ensure that the objective function meets the imposed constraints. In the case of any violation of a constraint boundary, the fitness function of the corresponding solution is penalized and kept within the feasible regions of the design space. For controlling the penalization process, the penalty coefficients, r_j , are used for a different level of violation of each constraint. The penalty coefficients have to be judiciously selected, Homaifar et al. [1], because the reasonable solutions importantly depend on the values of these coefficients.

3 APPLYING THE GENETIC ALGORITHM TO THE PROBLEM

The first step in applying the genetic algorithm to the assigned design problem is encoding the design variables as a string. This string typically refers to a solution to the problem. Rather than starting from a single point solution within the search space as in numerical methods, the genetic algorithm is initialized with a population of solutions, which specify the number of strings in each generation. The continuous design variables' vectors are represented and discretized to a precision of ε (for this study, $\varepsilon = 0.01$). The number of digits in the binary string, is estimated from the following relationship [3]:

where $X(i)_{\text{upper}}$ in $X(i)_{\text{lower}}$ are the lower and upper bounds for the design variables' vector respectively.

The six design variables are coded into binary digits $\{0, 1\}$, as shown in Table 2. The binary string representation for the vector of the design variables, $X(i)$, can be placed head-to-tail to form one long string, referred to as a chromosome. Table 3 shows a string of 42 binary digits, denoting the concatenated design variables' vector. A randomly selected set, for this study a 50-string, of potential

Preglednica 2. Kodiranje vektorja oblikovnih spremenljivk v binarnem zapisu

Table 2. Coding of the design variables' vector into binary digits

Vektor oblikovnih spremenljivk Design variables' vector	Spodnja meja Lower limit	Zgornja meja Upper limit	Dolžina niza String length	Binarni niz Binary string	Razrešena vrednost Decoded value
X(1) (= y1)	0,50	1,00	6	0 1 0 1 0 0	0,658
X(2) (= (y2) * (π /180))	1,50	2,00	6	0 1 0 1 0 0	1,658
X(3) (= (y3) * (1 - y5) / 1000)	1,40	1,95	7	1 0 1 0 0 1 1	1,759
X(4) (= (y4) * 2)	1,00	2,00	7	0 0 1 0 0 0 1	1,133
X(5) (= (y5) * 2)	0,00	1,50	8	0 0 1 0 1 0 1 0	0,247
X(6) (= (y6) * (π /180))	0,64	2,37	8	1 0 0 0 1 0 0 1	2,247

Preglednica 3. Nabor začetne populacije

Table 3. A set of the starting population

Začetna populacija/Initial population						
Združeni vektorji spremenljivk od glave do repa/Concatenated variables vectors head-to-tail						
	X(1)	X(2)	X(3)	X(4)	X(5)	X(6)
1	010100	010100	1010011	0010001	00101010	10001001
	0 1 0 1 0 0 0 1 0 1 0 0 1 1 0 0 1 0 0 0 1 0 0 1 0 1 0 1 0 1 0 0 0 0 1 0 0 1					
2	100111	100010	0100101	1100011	10101010	01110110
	1 0 0 1 1 1 1 1 0 0 0 1 0 0 1 0 0 1 1 1 0 0 0 1 1 1 0 1 0 1 0 1 0 0 1 1 1 0 1 1 0					
.	.	.	.	.	.	.
.	.	.	.	.	.	.
50	001101	0111000	1001100	0011100	00011001	10001010
	0 0 1 1 0 1 0 1 0 1 1 1 0 0 0 1 0 0 1 1 0 0 0 0 0 1 1 1 0 0 0 0 0 1 1 0 0 1 1 1 0 0 0 1 0 1 0					

izvedljivih rešitev – za potrebe te obravnave smo izbrali 50 nizov – ustvarimo začetno populacijo.

Nadaljnje populacije nastanejo s postopki izbire, križanja in sprememb. Operator izbire določi člane populacije, ki preživijo in sodelujejo v nastanku nove generacije. Vektor oblikovnih spremenljivk z bolj ustreznimi vrednostmi ima večjo možnost, da preživi in je izbran kot roditelj naslednjih generacij. Obstaja več metod izbire. Izbira, ki deluje v algoritemski kodi, temelji na tekmovanju, ki za potrebe združitve naključnih parov uporablja tehniko mešanja. Ta tehnika prerazporedi populacijo v naključno zaporedje. Izbira na osnovi tekmovanja deluje takole: dvojica osebkov iz paritvene skupine je naključno izbrana in dva najbolj ustrezna osebka bosta izbrana kot roditelja. Vsak par roditeljev ustvari dva potomca, kar je predstavljeno z metodo enoličnega križanja

solutions is initialized to form the starting population.

Successive populations are produced by the operations of selection, crossover, and mutation. The selection operator determines those members of the population that survive to participate in the forming of members of the next generation. The design variables' vector with better fitness values is more likely to survive and be chosen as parents for the successive generation. There are many methods to perform the selection. The selection operator used in the algorithm code is a tournament selection, with a shuffling technique for choosing random pairs for mating. The shuffling technique rearranges the population in a random order for selection. The tournament selection approach works as follows: a pair of individuals from the mating pool is randomly picked and the best-fit two

v preglednici 4. Algoritem temelji na strategiji elitistične reprodukcije. Elitizem prisili genetski algoritem, da iz dane generacije obdrži najboljše osebkke, ki nespremenjeni preidejo v naslednjo generacijo [18]. S tem se zagotovi, da se genetski algoritem približa ustreznemu rešitvi. Povedano z drugimi besedami, elitizem je zaščita pred križanjem in spremembo, ki bi lahko ogrozila trenutno najboljšo rešitev.

V pričujoči obravnavi smo uporabili opravilo enoličnega križanja, pa tudi veliko drugih študij [9] priporoča enolično križanje z verjetnostjo 0,5. Ta poseg je primarni vir novih izvedljivih rešitev in vsebuje iskalni mehanizem, ki učinkovito vodi razvoj skozi iskalni prostor proti optimalni rešitvi. Pri enoličnem križanju ima vsak bit vsakega roditeljskega niza možnost, da se zamenja z ustreznim bitom drugega roditeljskega niza. S tem postopkom naključno pridobimo katerokoli kombinacijo dveh roditeljskih nizov (kromosomov) iz paritvene skupine ter iz roditeljskih nizov nato ustvarimo nove nize potomcev, tako da za vsak bit izvedemo križanje, ki ga izberemo glede na naključno ustvarjeno masko križanja [4]. Kjer je v maski križanja "1", tam je bit potomca kopiran iz prvega roditeljskega niza; kjer pa je v maski "0", tam je bit potomca kopiran iz drugega roditeljskega niza. Drugi niz potomca pa uporablja pravilo, ki je nasprotno pravkar opisanemu pravilu, kar je prikazano v preglednici 4. Za vsak par roditeljskih nizov je naključno ustvarjena nova maska križanja.

Da bi preprečili, da bi se genetski algoritem prezgodaj približal rešitvi, ki ni najboljša, kar se lahko zgodi ob ponavljanju se rabi izbira in križanja, uporabljamo opravilo spremembe. Sprememba je v bistvu postopek naključno spremenjenega dela osebkke, pri katerem stanje bita spremenimo iz 0 v 1 ali obratno, s čimer nastane nov osebek.

V pričujoči razpravi smo uporabili opravilo sprememb s preskokom. Ta ustvari kromosom, ki je

individuals from this pair will be chosen as a parent. Each pair of parents creates two children, as described in the method for uniform crossover, shown in Table 4. The algorithm is based on an elitist reproduction strategy. Elitism forces the genetic algorithm to retain the best individual in a given generation to proceed unchanged into the following generation [18]. This ensures that the genetic algorithm converges to an appropriate solution. In other words, elitism is a safeguard against the operation of a crossover and a mutation that may jeopardize the current best solution.

A uniform crossover operator is used in this study, and a uniform crossover probability of 0.5 is recommended in many studies [9]. This operator is a primary source of new candidate solutions and provides a search mechanism that efficiently guides the evolution through the solution space towards the optimum. In a uniform crossover, every bit of each parent string has a chance of being exchanged with the corresponding bit of the other parent string. The procedure is to obtain any combination of two parent strings (chromosomes) from the mating pool randomly and generate new child strings from these parent strings by performing a bit-by-bit crossover, chosen according to a randomly generated crossover mask [4]. Where there is a "1" in the crossover mask, the child bit is copied from the first parent string, and where there is a "0" in the mask, the child bit is copied from the second parent string. The second child string uses the opposite rule to the previous one, as shown in Table 4. For each pair of parent strings a new crossover mask is randomly generated.

To prevent the genetic algorithm from prematurely converging to a non-optimal solution, which may diversity away by repeated application of the selection and crossover operators, the mutation operator is used. Mutation is basically a process of randomly altering a part of an individual to produce a new individual by switching the bit position from a 0 to a 1 or vice versa.

The jump mutation operator is used in this study. The jump mutation produces a chromosome

Preglednica 4. Enolično križanje

Table 4. Uniform crossover

Maska križanja/Crossover mask	100101110010010111001001011100100101110010
Roditelj 1/Parent 1	101000111010100011101010001110101000111010
Roditelj 2/Parent 2	010101001101010100110101010011010101001101
Potomec 1/Child 1	110000111111000011111100001111110000111111
Potomec 2/Child 2	001101001000110100100011010010001101001000

naključno izbran in vključen v razpon parametra ustreznosti. Obstaja več načinov zaustavitve delovanja genetskega algoritma; po metodi, ki smo jo uporabili v naši razpravi, algoritem ustavimo po določenem številu ustvarjenih generacij. Konvergenca pomeni približevanje enoličnosti. Verjamemo, da se je kromosom približal, ko ima 95% populacije enako vrednost [14]. Osebkij populacije so torej vsi, ali večinoma, enaki ali podobni, ko se populacija približa. Nastavitev parametrov genetskega algoritma za potrebe te razprave je naslednja: dolžina kromosoma = 42, velikost populacije = 50, število generacij = 77, verjetnost križanja = 0,5 in verjetnost spremembe = 0,001.

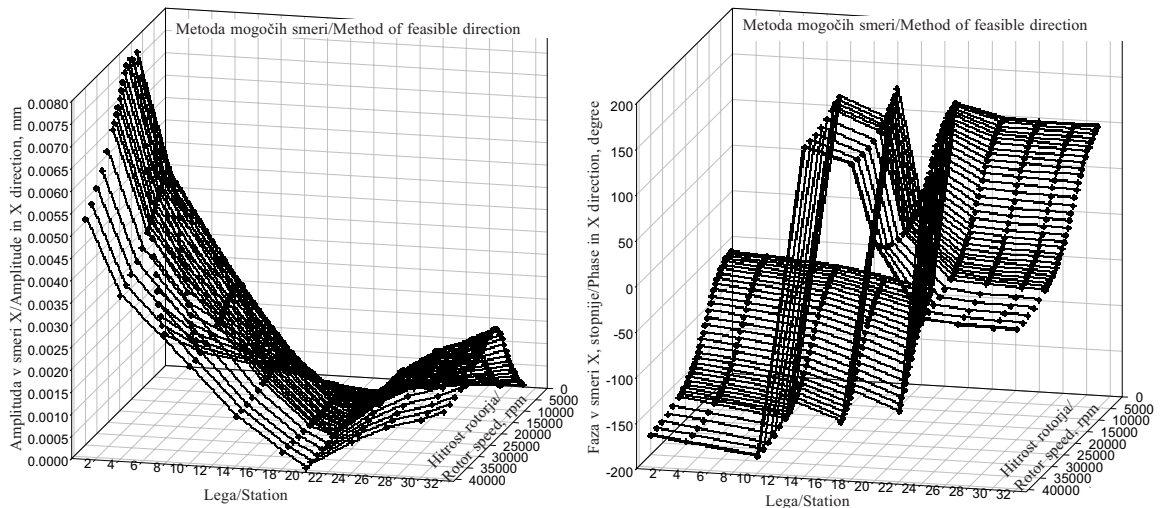
4 REZULTATI

Raziskali smo dinamične značilnosti rotorskega sistema in dobili rezultate, ki omogočajo primerjavo obeh metod optimizacije. Razmerje med faznimi koti amplitud odziva rotorskega sistema v smereh X in Y in hitrostjo rotorja v razponu od 5000 min⁻¹ do 40000 min⁻¹ na posameznih lokacijah je prikazano na slikah 3 do 6. V smereh X in Y, ki sta priležni obema legama ležajev, smo dobili odziv rotorja, da bi določili amplitudo premika. Največji premik smo ugotovili na mestu 1, ki se ujema z lego konice vijaka. V primeru uporabe genetskega algoritma znaša največji premik približno 0,000146 mm v smeri X pri hitrosti 16000 min⁻¹ in 0,000143 mm v smeri Y pri hitrosti 37000 min⁻¹, medtem ko v primeru uporabe metode izvedljivih smeri največji premik znaša 0,000320 mm v smeri X pri hitrosti 19000 min⁻¹ in 0,000323 mm v smeri Y pri hitrosti 19000 min⁻¹. Najmanjši premik pri uporabi genetskega algoritma znaša približno 0,000065 mm v smeri X pri hitrosti 10000 min⁻¹ in 0,000067 mm v smeri Y pri hitrosti 5600 min⁻¹ (na legi 24), medtem pa pri uporabi metode izvedljivih smeri najmanjši premik znaša 0,000020 mm v smeri X pri hitrosti 6400 min⁻¹ in 0,000016 mm v smeri Y pri hitrosti 5600 min⁻¹ (na legi 20). Rezultati so pokazali, da se rotorjevi hitrosti, pri katerih se pojavita največja in najmanjša amplituda, spreminjata. V celoti so mesta koničnih odzivov dobro usklajena, četudi se zdi, da so ob uporabi genetskega algoritma manjša kakor ob uporabi metode izvedljivih smeri. Ti pomembni izsledki ustrezajo določeni specifikaciji vsiljenih omejitev in rotorskemu sistemu omogočijo, da ohrani svojo stabilnost.

that is randomly picked to be in the range of the appropriate parameter. There are many different ways to stop running the genetic algorithm, one method is to stop after a particular number of generations, which is the method used in this study. Convergence is the progression toward uniformity. A chromosome is said to have converged when 95% of the population share the same value [14]. Thus, most or all individuals in the population are identical or similar when the population has converged. The setting parameters of the genetic algorithm for this study are as follows: chromosome length = 42, population size = 50, number of generation = 77, crossover probability = 0.5, mutation probability = 0.001.

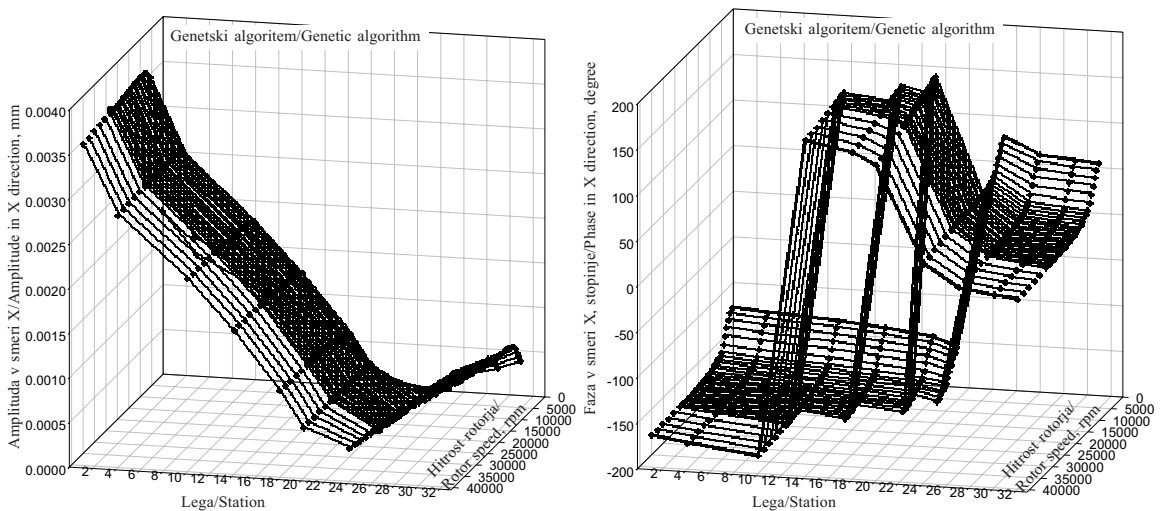
4 RESULTS

The dynamic characteristics of the rotor system were studied and the results are given for comparing both optimization methods. The rotor-system response amplitudes' corresponding phase angles in the X and Y directions versus the rotor speed range from 5000 rpm to 40000 rpm for stations are represented in Fig.3, Fig.4, Fig.5, and Fig.6. The rotor response was obtained in the X and Y directions adjacent to both bearing locations to determine the displacement amplitude. The highest displacement is found at station 1, corresponding to the station at the impeller's nose. The peak displacement is approximately 0.000146 mm in the X direction at 16000 rpm and 0.000143 mm in the Y direction at 37000 rpm using the genetic algorithm, while it is 0.000320 mm in the X direction at 19000 rpm and 0.000323 mm in the y direction at 19000 rpm using the method of feasible directions. The lowest displacement is approximately 0.000065 mm in the X direction at 10000 rpm and 0.000067 mm in the Y direction at 5600 rpm (at station 24) using the genetic algorithm, while it is 0.000020 mm in the X direction at 6400 rpm and 0.000016 mm in the y direction at 5600 rpm (at station 20) using the method of feasible directions. The results showed that the rotor speed at which the highest and the lowest amplitudes occurred varies. Overall, the locations of the peak responses are in good agreement, although they appear to be lower with the genetic algorithm than those using the method of feasible directions. These significant outcomes satisfy the imposed constraint specification and allow the rotor system to maintain its stability.



Sl. 3. Rotorjeva amplituda odziva in fazni kot v smeri X (metoda mogočih smeri)

Fig. 3. The rotor's response amplitude and the phase angle in the X direction (the method of feasible directions)



Sl. 4. Rotorjeva amplituda odziva in fazni kot v smeri X (genetski algoritem)

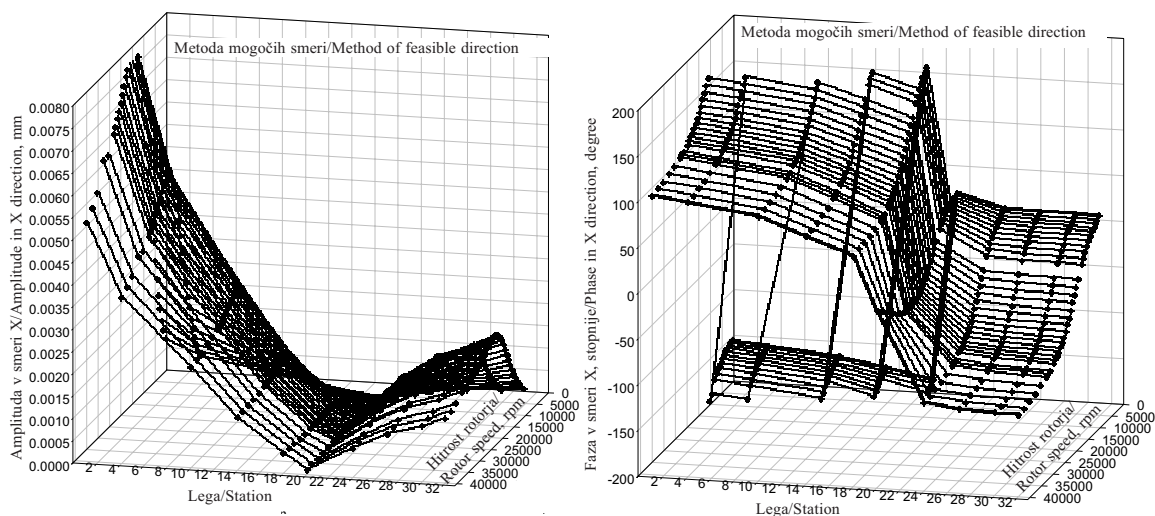
Fig. 4. The rotor's response amplitude and the phase angle in the X direction (the genetic algorithm)

5 SKLEPI

Poglavitni cilj oblikovanja rotorskega sistema je minimalizacija amplitude odziva na različne rotorjeve obratovalne hitrosti. Dinamične značilnosti rotorskega sistema morajo biti oblikovane tako, da pri nobeni obratovalni hitrosti ne pride do čezmerne amplitude odziva. Da bi izračunali odziv gibkega rotorja, ki ga podpirata dva prečna drsna ležaja s pritrjenimi segmenti, smo uporabili genetski algoritem. Da bi dobili čim bolj natančne podatke o amplitudi gibanja rotorskega

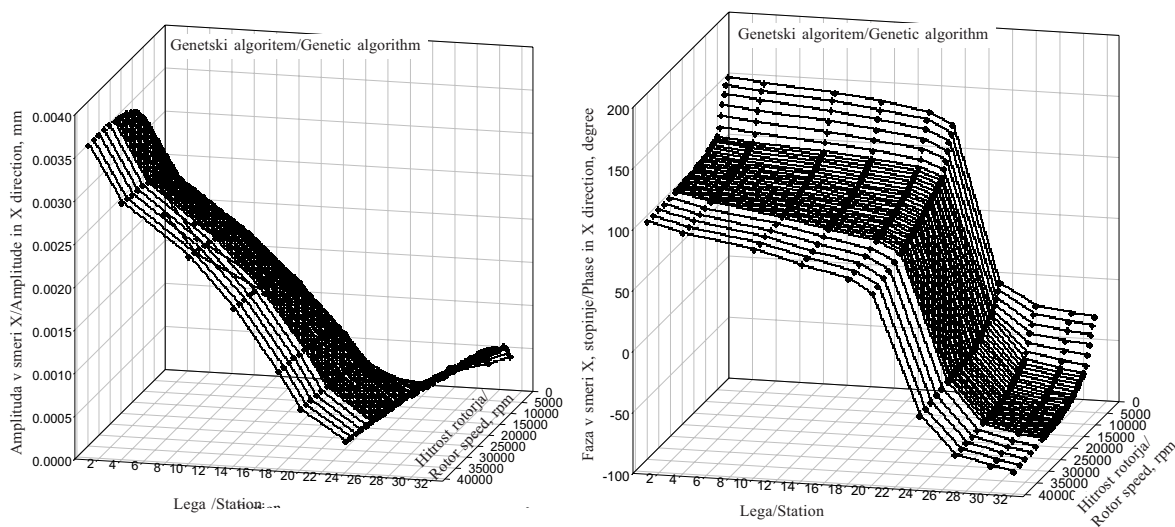
5 CONCLUSIONS

The minimization of the response amplitude within the operating speed range of the rotor system is primary among the design objectives. The dynamic characteristics of the rotor system must be designed to operate without an excessive response amplitude throughout its operating-speed range. A genetic algorithm was employed to compute the response of the flexible rotor supported in two fixed-lobe journal bearings. The finite-element-method-based computer code was coupled



Sl. 5. Rotorjeva amplituda odziva in fazni kot v smeri Y (metoda mogočih smeri)

Fig. 5. The rotor's response amplitude and the phase angle in the Y direction (the method of feasible directions)



Sl. 6. Rotorjeva amplituda odziva in fazni kot v smeri Y (genetski algoritem)

Fig. 6. The rotor's response amplitude and the phase angle in the Y direction (the genetic algorithm)

sistema, smo optimizacijske algoritme združili z računalniško kodo, ki temelji na metodi končnih elementov. Uporaba metode končnih elementov skupaj z genetskim algoritmom pri oblikovanju značilnega prevesnega rotorskega sistema z veliko hitrostjo terja veliko zmogljivost pomnilnika in s tem veliko računalniškega napora. Vendar pa to težavo lahko premostimo z izrabo sodobnih računalniških zmogljivosti. Rezultati, ki jih predstavljamo v tem prispevku, potrjujejo primernost izbrane metode, s katero smo vplivali na amplitudo rotorjevega odziva. Metodo

to these optimization algorithms to extract more accurately the required information about the amplitude of the motion of the rotor system. Using the finite-element method with a genetic algorithm in a typical high-speed overhung rotor-system design requires a significant amount of memory storage, and this requires more computational effort. However, this disadvantage is not significant with the current computing capability. The results presented in this paper demonstrate an approach which possesses considerable suitability for the rotor-amplitude response. The method of feasible

izvedljivih smeri smo uporabili z namenom, da potrdimo učinkovitost in uporabnost predlagane metode ter tako pokažemo, da je predlagana metoda zelo primerna za oblikovanje rotorskega sistema. Za obe metodi smo grafično prikazali spremembe amplitude odziva rotorskega sistema v vodoravni in navpični legi. Iz celotnih rezultatov namenske funkcije smo z genetskim algoritmom dobili boljše rezultate od tistih, ki smo jih dosegli z metodo mogočih smeri. Genetski algoritem omogoča raziskovati številne različne konfiguracije oblikovnih spremenljivk in tako tudi prispeva k boljšemu razumevanju splošnega rotorskega in ležajnega obnašanja.

directions is conducted to validate the efficiency and applicability of the proposed method and, it proved that the proposed method in the rotor-system design is very efficient and useful. Plots of the variation of the rotor system's response amplitudes in the horizontal and vertical directions for both methods are presented. From the overall results of the objective function, the genetic algorithm was able to obtain better results than those obtained using the method of feasible directions. The genetic algorithm allows the exploration of many different configurations of design variables and therefore also contributes to a better understanding of the rotor and the bearing behavior in general.

6 LITERATURA

6 REFERENCES

- [1] A. Homaifar, C.X. Qi, and S.H. Lai (1994) Constrained optimization via genetic algorithms, *Simulation*, 62, (1994), 242-254.
- [2] C.A. Roso (1997) Design optimization of rotor-bearing systems for industrial turbomachinery applications, Ph.D. Dissertation, *University of Kentucky*.
- [3] C.Y. Lin and P. Hajela (1992) Genetic algorithms in optimization problems with discrete and integer design variables, *Engineering Optimization*, 19 (1992), 309-327.
- [4] D. Beasley, D.R. Bull, and R.R. Martin (1993) An overview of genetic algorithms: Part 2. Research topics. *University Computing*, 15 (1993), 170-181.
- [5] D.E. Goldberg (1989) Genetic algorithms in search, optimization, and machine learning reading, *Addison-Wesley*, MA.
- [6] G.G. Zoutendijk (1969) Method of feasible directions. *Elsevier*, Amsterdam.
- [7] G. Mitsuo and C. Runwei (1997) Genetic algorithms and engineering design, *John Wiley, Pub.*, New York.
- [8] G.N. Vanderplaats (1984) Numerical optimization techniques for engineering designs, *McGraw-Hill*.
- [9] G. Syswerda (1989) Uniform crossover in genetic algorithms, *Proceedings of the 3rd International Conference on Genetic Algorithms*.
- [10] H. Saruhan, K.E. Rouch, and C.A. Roso (2001) Design optimization of fixed pad journal bearing for rotor system using a genetic algorithm approach, *International Symposium on Stability Control of Rotating Machinery, ISCORMA-I*, Lake Tahoe, Nevada.
- [11] H. Saruhan, K.E. Rouch, and C.A. Roso (2004) Design optimization of tilting-pad journal bearing using a genetic algorithm approach, *International Journal of Rotating Machinery*, 10(4), (2004) 301-307.
- [12] J.H. Holland (1975) Adaptation in natural and artificial systems, *University of Michigan Press*.
- [13] J.T. Sawicki, R.J. Capaldi, and M.L. Adams (1997) Experimental and theoretical rotordynamic characteristics of a hybrid journal bearing, *Transaction of the ASME*, 119 (1997) 132-141.
- [14] K. De Jong (1975) The analysis and behavior of class of genetic adaptive systems, Ph.D. Dissertation, *University of Michigan*.
- [15] K.E. Rouch (1977) Finite element analysis of rotor bearing systems with matrix reduction, Ph.D. Dissertation, *Marquette University*.
- [16] K.E. Rouch and J.S. Kao (1980) Dynamic reduction in rotor dynamics by the finite element method, *Transactions of the ASME*, 102 (1980), 360-368.
- [17] L. Davis (1991) Handbook of genetic algorithms, *Van Nostrand Reinhold*, New York.

- [18] M. Mitchell (1997) An introduction to genetic algorithms, *The MIT Press*, Massachusetts.
[19] P. Qin, Y. Shen, J. Zhu, and H. Xu (2005) Dynamic analysis of hydrodynamic bearing – Rotor system based on neural network, *International Journal of Engineering Science*, 43 (2005) 520-531.

Avtorjev naslov: Hamit Saruhan
Univerza Duzce
Oddelek za oblikovanje strojev
81620-Duzce, Turčija
hamitsaruhan@hotmail.com

Author's Address: Hamit Saruhan
Duzce University
Mechanical Design Division
81620-Duzce, Turkey
hamitsaruhan@hotmail.com

Prejeto: 26.10.2006
Received:

Sprejeto: 25.4.2007
Accepted:

Odprto za diskusijo: 1 leto
Open for discussion: 1 year