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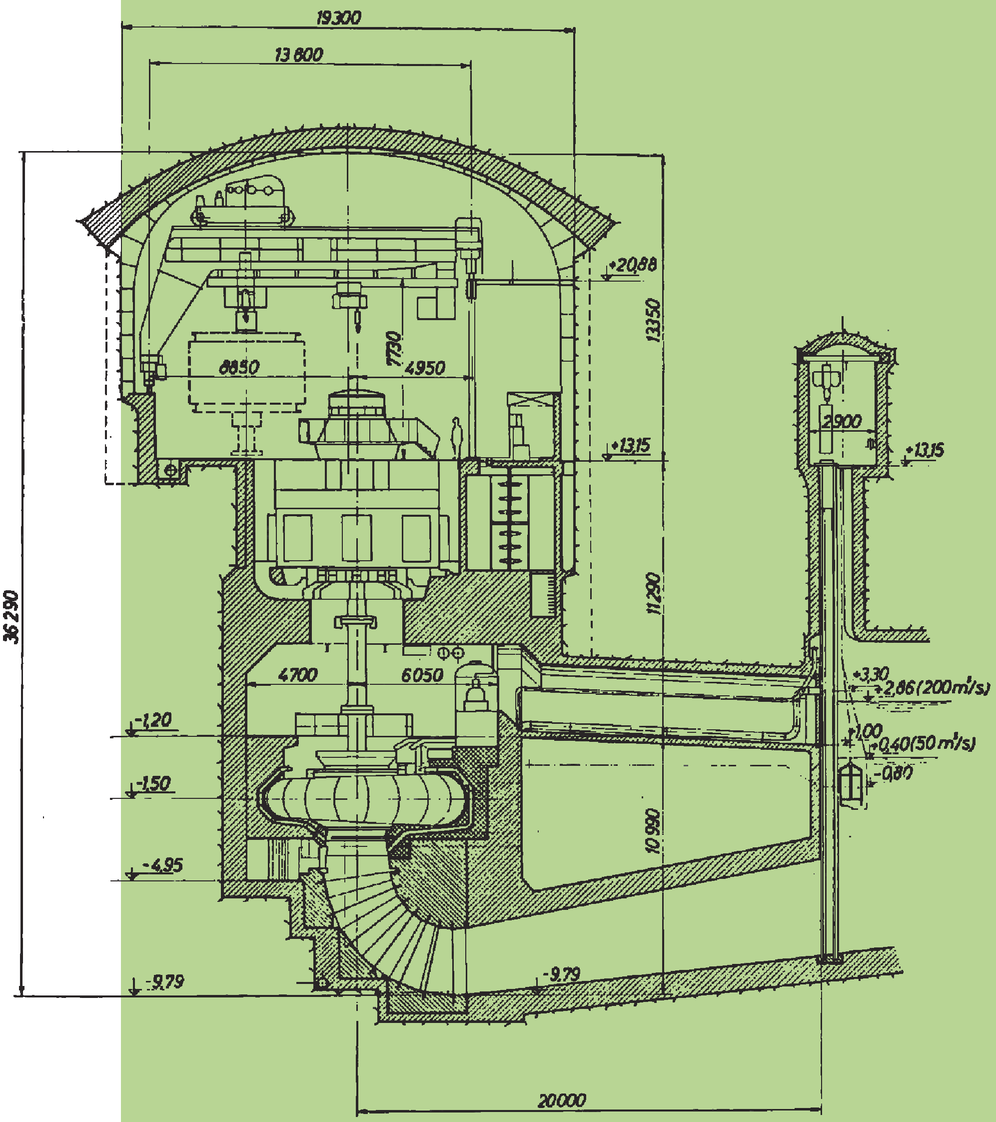

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Modeliranje sestavov kovine in elastomerov z uporabo postopka končnih elementov

Modelling Metal-Elastomer Composite Structures Using a Finite-Element-Method Approach

Sergio E. Floody[1] - Jorge P. Arenas[2] - José J. de Espíndola[3]
([1]Technical University of Chile; [2]Austral University of Chile; [3]Federal University of Santa Caterina, Brasil)

Sestavi kovine in elastomerov so pomembno orodje za zmanjšanje mehanskih nihanj. Pri upogibu nihajoči sestav lahko dušimo z dodatkom primerne plasti dušilnega materiala, na primer elastomera, kjer je plast izpostavljena ciklični deformaciji in na ta način tudi izgubi energije. Vendar pa prisotnost elastomera pomeni, da je sestav odvisen od frekvence, zaradi tega težko natančno napovedujemo, saj je težko izračunati rešitev ustreznega problema lastnih vrednosti. V prispevku je predstavljena metodologija za modeliranje sestavov kovine in elastomerov z uporabo metode končnih elementov. V nadaljevanju je obravnavana računska metoda določitve približne rešitve frekvenčno odvisnega problema lastnih vrednosti. Številčne rezultate vztrajnosti smo primerjali z rezultati preizkusa običajnega "sendvič" sestava grede. Metodo smo razširili na model in tako optimirali Stockbridgove dušilnike, ki so uporabljeni za dušenje zračnih nihanj dejanskega električnega daljnovoda. Namesto uglasitve dušilnika na neko določeno frekvenco, smo z uporabo genetskih algoritmov določili ciljno fukcijo in optimirali fizikalne izmere dušilnika. S takim postopkom smo analizirali celoten problem brez uporabe modalnega pristopa napetost-energija, kar pomeni, da ta tako modeliranje zadosti načelu vzorčnosti. Metoda je uporabna kot orodje za načrtovanje in modeliranje sestavov kovine in elastomerov.

(Ključne besede: kompoziti kovine - elastomeri, modeliranje strukture, metode končnih elementov, dušilniki vibracij)

Metal-elastomer composite structures are an important tool for the reduction of mechanical vibrations. A structure that vibrates in flexure can be damped by the appropriate addition of a layer of damping material, for example, an elastomer, where the layer undergoes cyclic strain and thereby dissipates energy. However, the presence of the elastomer means that the structure is frequency dependent, which is a difficult case for obtaining accurate predictions since the solution of the corresponding eigenvalue problem is hard to compute. In this paper a methodology for modelling metal-elastomer composite structures using a finite-element approach is presented. In addition, a calculation scheme to approximate the solution of the frequency-dependent eigenvalue problem is discussed. The numerical results for the inertness were compared with the experimental results for a classic composite sandwich beam. The method is extended to model and optimise Stockbridge absorbers used to suppress the aeolian vibrations of an actual electrical transmission line. Instead of tuning the absorber to some particular frequency, an objective function is defined and the physical dimensions of the absorber are optimised by means of a genetic algorithm. In this approach, the complete problem is analysed without using the modal strain-energy approach, implying that this modelling satisfies the causality principle. The method appears to be useful as a tool for designing and modelling metal-elastomer composite structures.

(Keywords: metal elastomer composite, structure modelling, finite element methods, Stockbridge dumpers)

0 INTRODUCTION

Metal-elastomer composite structures are an important tool for the reduction of mechanical vibrations. A structure that vibrates in flexure can be damped by the appropriate addition of a layer of damping material. As the whole system vibrates, the layer undergoes cyclic strain and thereby dissipates energy. Since the first successful modelling of a metal-elastomer composite presented by Ross et al. [1], considerable attention has been paid to the prediction of the dynamic behaviour of such structures. For many years, the finite element method has been used for modelling structures, and several of its applications have been shown to be quite accurate. Soni [2] has presented a finite element analysis of viscoelastically damped sandwich beams, which uses a combination of shell elements and three dimensional solids for the viscoelastic part. Another approach is to use shell elements with spring elements to model the elastomer [3]. This methodology has been shown to increase the speed of the calculations of the stiffness and mass matrices. Lumsdaine et al. [4] have reported a method using multi-layer elements, which has been proven to be very accurate. Although the modelling using three dimensional solid elements is the most complete alternative to solve this kind of problem, sometimes the computational cost of formulating and solving the equations can become prohibitive.

The viscoelastic materials of greatest practical interest for damping applications are plastics and elastomers. An elastomer is a soft substance that exhibits thermo-viscoelastic behaviour. Viscoelastic materials possess both elastic and viscous properties. For a purely elastic material, all the energy stored in a sample during loading is returned when the load is removed. Furthermore, the displacement of the sample responds immediately, and in-phase, to the cyclic load. Conversely, for a purely viscous material, no energy is returned after the load is removed. The input stress is lost to pure damping as the vibration energy is transferred to internal heat energy. All the materials that do not fall into one of the above extreme classifications are called viscoelastic materials. Some of the energy stored in a viscoelastic system is recovered upon removal of the load, and the remaining energy is dissipated by the material in the form of heat.

In a metal-viscoelastic-metal structure, the bending of the composite produces not only bending and extensional strains in all three layers, but also shears, primarily of the middle (viscoelastic) layer. The shear-strain energy storage tends to dominate the damping action of the constrained viscoelastic layers. Many practical applications operate on the principle of constrained layer damping. The shear forces in the constrained viscoelastic layer cause the energy of the vibration to be converted into heat.

Undamped metal structures normally have a very low loss factor, typically in the range 0.001 to 0.01. Using a viscoelastic layer can increase this loss factor. This means that the amplitude of the resonant vibration when the structure is subjected to structure-borne sound or vibration will be much lower than for an undamped structure. A reduced amplitude of vibration means less radiation of sound, and also a reduced risk of fatigue failure [5].

A characteristic of viscoelastic materials is that their Young's modulus is a complex quantity, having both a real and imaginary component. Furthermore, this complex modulus varies as a function of many parameters, the most important of which are the frequency and temperature of a given application. Consequently, this results in a corresponding eigenvalue problem in which the stiffness matrix depends on both the frequency and the temperature. The moduli typically take on relatively high values at low temperatures and/or high frequencies but take on comparatively small values at high temperatures and/or low frequencies. It is therefore necessary to establish an accurate understanding of the influence of these parameters in order to design effective damping treatments.

In general, the vibration analysis of a system that is frequency independent can be accurately achieved by classical techniques. It is much more difficult to obtain accurate predictions when the equations of motion are frequency dependent. This is because the solution of the corresponding eigenvalue problem is difficult to compute. Methods based on the modal strain energy have been used to approximate the solution of the problem [2]. However, they are not accurate when the frequency and temperature ranges are increased, and when they include the *transition region*, where the variations of the dissipation and the stiffness of the viscoelastic material are quite pronounced. The greatest loss factors occur in the transition region at intermediate frequencies and temperatures. On the other hand, some of the assumptions used by these methods do not fit the principle of causality for physical systems [6].

The final aim of this paper is to present a methodology to model metal-elastomer composite structures by using a finite-element approach. The method was experimentally tested for a classic composite sandwich beam. Then, an application to model and optimise a Stockbridge absorber used to suppress the aeolian vibrations of an electrical transmission line is presented.

1 THEORY

The theory of finite element methods has been clearly presented by several authors ([7] to [9]), so it will not be repeated here. However, a method to avoid inverting matrices of a large size will be discussed in this section, since it is quite useful to speed up the numerical solution.

As a result of the modelling using finite elements of a metal-elastomer structure, a frequency-dependent equation of motion is obtained. The equations of motion as a function of frequency for a forced multi-degree-of-freedom system and its associated eigenvalue problem can be written as:

$$\left[-\Omega^2\mathbf{M}+\mathbf{K}(\Omega,T)\right]\mathbf{q}(\Omega,T)=\mathbf{f}(\Omega) \qquad (1),$$

and

$$\mathbf{K}(\Omega,T)\boldsymbol{\varphi}(\Omega,T)=\sigma(\Omega,T)\mathbf{M}\boldsymbol{\varphi}(\Omega,T) \qquad (2),$$

where Ω is the angular frequency, T is a fixed temperature, $\mathbf{M}$ is the mass matrix, $\mathbf{K}(\Omega,T)$ is the stiffness matrix, $\mathbf{q}(\Omega,T)$ is the modal displacement vector, $\mathbf{f}(\Omega)$ is the vector of external forces, $\varphi(\Omega,T)$ is an eigenvector associated with the vibration modes, and $\sigma(\Omega,T)$ is an eigenvalue associated with a natural frequency.

In general, a direct solution of Eq. (2) will involve an expensive and inefficient method because of the large size of the matrices. Therefore, a proposed algorithm to simplify the task can be summarized as:

1) Solve the eigenvalue problem of order n for an arbitrary fixed frequency Ω_0, and for a value of temperature T, given by:

$$\mathbf{K}(\Omega_0,T)\boldsymbol{\varphi}(\Omega_0,T)=\sigma(\Omega_0,T)\mathbf{M}\boldsymbol{\varphi}(\Omega_0,T) \qquad (3).$$

Now, the modal matrix Φ_0 has the following properties:

$$\mathbf{\Phi}_0^T\mathbf{M}\mathbf{\Phi}_0=\mathbf{I}_n \qquad (4),$$

and

$$\mathbf{\Phi}_0^T\mathbf{K}(\Omega_0,T)\mathbf{\Phi}_0=\mathbf{\Sigma}_0 \qquad (5),$$

where the superscript T denotes the transpose, $\mathbf{I}_n$ is the $n\times n$ identity matrix, and $\Sigma_0=\text{diag}(\sigma_0)$ is a diagonal matrix of eigenvalues.

2) Let $\hat{\mathbf{\Phi}}_0$ be an $n\times\hat{n}$ truncated matrix of the $\hat{n}$ eigenvectors associated with the minor eigenvalues ($\hat{n}<n$). For a frequency $\Omega\neq\Omega_0$, the following product is calculated:

$$\hat{\mathbf{\Phi}}_0^T\mathbf{K}(\Omega,T)\hat{\mathbf{\Phi}}_0=\mathbf{\Sigma}(\Omega,T) \qquad (6),$$

where the matrix $\Sigma(\Omega,T)$ is not necessarily diagonal, but it is an $\hat{n}\times\hat{n}$ matrix. Then, the new eigenvalue problem can be stated as:

$$\mathbf{\Sigma}(\Omega,T)\boldsymbol{\psi}(\Omega,T)=\lambda(\Omega,T)\boldsymbol{\psi}(\Omega,T) \qquad (7),$$

$$\mathbf{\Psi}^T(\Omega,T)\mathbf{\Psi}(\Omega,T)=\mathbf{I}_{\hat{n}} \qquad (8),$$

and

$$\mathbf{\Psi}^T(\Omega,T)\mathbf{\Sigma}(\Omega,T)\mathbf{\Psi}(\Omega,T)=\mathbf{\Lambda}(\Omega,T) \qquad (9),$$

where $\lambda(\Omega,T)$ and $\psi(\Omega,T)$ are the eigenvalue and eigenvector, respectively, $\mathbf{I}_{\hat{n}}$ is the $\hat{n}\times\hat{n}$ identity matrix, $\Psi(\Omega,T)$ is a modal matrix, and $\Lambda(\Omega,T)=\text{tr}(\lambda_i(\Omega,T))$ is a trace matrix of eigenvalues. The new eigenvalue problem is still frequency dependent, but it is a problem of smaller size and consequently requires less computation time.

3) Consider the following transformation of coordinates:

$$\mathbf{q}(\Omega,T)=\hat{\mathbf{\Phi}}_0\mathbf{r}(\Omega,T) \qquad (10),$$

and

$$\mathbf{r}(\Omega,T)=\mathbf{\Psi}(\Omega,T)\mathbf{p}(\Omega,T) \qquad (11).$$

Substituting Eq. (10) and (11) into Eq. (1), and pre-multiplying by $\left[\hat{\mathbf{\Phi}}_0\mathbf{\Psi}(\Omega,T)\right]^T$ gives

$$\left[-\Omega^2\mathbf{I}_{\hat{n}}+\mathbf{\Lambda}(\Omega,T)\right]\mathbf{p}(\Omega,T)=\left[\hat{\mathbf{\Phi}}_0\mathbf{\Psi}(\Omega,T)\right]^T\mathbf{f}(\Omega) \qquad (12).$$

Thus, the nodal displacement vector is given by:

$$\mathbf{q}(\Omega,T)=\hat{\mathbf{\Phi}}_0\mathbf{\Psi}(\Omega,T)\left[-\Omega^2\mathbf{I}_{\hat{n}}+\mathbf{\Lambda}(\Omega,T)\right]^{-1}\left[\hat{\mathbf{\Phi}}_0\mathbf{\Psi}(\Omega,T)\right]^T\mathbf{f}(\Omega) \qquad (13).$$

Therefore, the receptance matrix is obtained from Eq. (13) as:

$$\boldsymbol{\alpha}(\Omega,T)=\hat{\mathbf{\Phi}}_0\mathbf{\Psi}(\Omega,T)\left[-\Omega^2\mathbf{I}_{\hat{n}}+\mathbf{\Lambda}(\Omega,T)\right]^{-1}\left[\hat{\mathbf{\Phi}}_0\mathbf{\Psi}(\Omega,T)\right]^T \qquad (14).$$

Defining the matrix product $\mathbf{S}(\Omega,T)=\hat{\mathbf{\Phi}}_0\mathbf{\Psi}(\Omega,T)$, Eq. (14) can be re-written as:

$$\boldsymbol{\alpha}(\Omega,T)=\mathbf{S}(\Omega,T)\left[-\Omega^2\mathbf{I}_{\hat{n}}+\mathbf{\Lambda}(\Omega,T)\right]^{-1}\mathbf{S}^T(\Omega,T) \qquad (15),$$

where $\Sigma(\Omega,T)=\Lambda(\Omega,T)$ for all Ω and T. Consequently, the inertness matrix is:

$$-\Omega^2\boldsymbol{\alpha}(\Omega,T)=-\Omega^2\mathbf{S}(\Omega,T)\left[-\Omega^2\mathbf{I}_{\hat{n}}+\mathbf{\Lambda}(\Omega,T)\right]^{-1}\mathbf{S}^T(\Omega,T) \qquad (16).$$

Then, the corresponding elements of the receptance matrix $\alpha(\Omega,T)$ are:

$$\alpha_{ij}(\Omega,T)=\sum_{k=1}^{\hat{n}}\frac{s_{ik}(\Omega,T)s_{jk}(\Omega,T)}{\lambda_k(\Omega,T)-\Omega^2} \qquad (17),$$

where s is an element of the matrix $\mathbf{S}(\Omega,T)$, and $\lambda_k(\Omega,T) \cong \sigma_k(\Omega,T)$.

Therefore, the $\hat{n}\times\hat{n}$ matrix $\Sigma(\Omega,T)$ can be assumed to be a projection of the stiffness matrix into an approximated subspace of the space formed by the real eigenvectors. So the quality of the approximation depends on the subspace, or $span\{\varphi_{01}...\ \varphi_{0h}\}$.

An important detail for stating the problem of Eq. (1) is the construction of the stiffness matrix $\mathbf{K}(\Omega,T)$. This construction can be done by using the finite element method for each frequency. If $\mathbf{K}(\Omega,T)$ is a matrix of large size, it can be computed for several frequencies by means of a Taylor series expansion in the neighbourhood of a transition frequency Ω_t as:

$$\mathbf{K}(\Omega,T)=\sum_{m=0}^{M}\frac{\mathbf{K}^{(m)}(\Omega_t,T)}{m!}(\Omega-\Omega_t)^m \qquad (18),$$

where

$$\mathbf{K}^{(m)}(\Omega,T)=\frac{\mathrm{d}^m\mathbf{K}(\Omega,T)}{\mathrm{d}\Omega^m} \qquad (19).$$

It is then relatively easy to compute the derivatives $\mathbf{K}^{(m)}(\Omega_t,T)$ since only the elementary stiffness matrices of the viscoelastic part are frequency dependent, while the derivatives of the stiffness matrices of the metal part are not. The use of M=3 for the series expansions shows that the results are quite exact for a narrow frequency band in the neighbourhood of a transition frequency.

2 RESULTS

2.1 Composite Sandwich-Beam

The first example of the application of the theory presented above is a simple clamped-free composite sandwich beam. This kind of structure is commonly used as a study object. The sandwich beam is made of two metal layers of steel 1020 and a viscoelastic core made of DYAD 601 material (Soundcoat Co.). The viscoelastic core was attached in between the metal layers by means of an epoxic-structural adhesive. The properties of this viscoelastic material were presented in reference [10]. The beam was 211.85 mm long and 11.97 mm wide. The thickness of each metal layer was 2.14 mm and the thickness of the viscoelastic core was 0.5 mm. All the dimensions of the sandwich composite beam are in accordance to the requirements of the ASTM E 756-98 standard [11].

The composite sandwich beam was divided into 114 two-dimensional Lagrangian solid elements on a plane state of stress. Along the beam 19 elements were selected at equal intervals and each layer was divided into two elements, resulting in a total of 507 nodes, having two degrees of freedom at each node, so n=1014 for this application. The above parameters of the structure were selected because they assured the determination of the first four modes and the modal damping produced by the shear deformation of the core.

An experimental set-up was devised to perform a dynamic test to measure the frequency response of the beam. The beam was excited using a magnetic actuator (B&K MM0002). The signal fed to the actuator was a chirp excitation between 0 to 1600 Hz, i.e., a sine wave of linearly increasing frequency, and amplified by a power amplifier (B&K 2706). The response of the beam was measured by a small accelerometer (B&K 4375). The signals were analysed using a two-channel FFT analyser (HP 3567A). The experimental set-up was placed inside a chamber in which the temperature could be controlled in the range between –30 and 60ºC. The precision of the chamber was ±1ºC. The excitation was applied at 59.64 mm from the clamped edge, which corresponds to node 143 in the finite element mesh, and the response was measured at 37.95 mm from the clamped edge, which corresponds to node 91 in the finite element mesh (see Fig. 1).

Computation of the inertness was developed for different temperatures ranging between –30 and 60ºC, and they were compared with the results obtained experimentally. In the computation $\hat{n}$=50 was used for the theory presented in Section 1. Figures 2

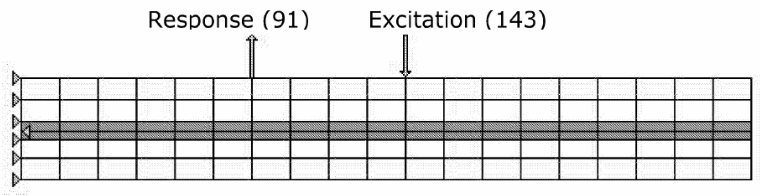

Fig. 1. *Finite element model for the clamped-free sandwich composite beam*

to 4 show the results of the inertness for three different temperatures.

From the results the effect on the natural frequencies caused by the increase in stiffness of the elastomer in the transition region ($-10^0C < T < 20^0C$) can be seen. In fact, in this region, the value of the fourth natural frequency increased so much that it fell out of the frequency range of the measurement. There is reasonable agreement between the numerical and experimental results for the inertness frequency responses presented in Figures 2 to 4, although it is observed that the numerical results seem to underpredict the natural frequencies when compared with those obtained from the experimental set-up. The differences are on average about 6%. Nevertheless, the differences between the numerical and experimental approaches can be due to imperfections in the experimental fixture, the small size of the structure under test, the contribution of the off-resonant modes, and the measurement uncertainty produced by the environment inside the chamber. The effect of the chamber should be more pronounced in the transition region, where small variations of temperature will cause large variations on the elastic properties of the elastomer. The value of the humidity inside the chamber was not accurately controlled during the experiment. This fact was reflected as noise in the measured inertness frequency-response curves, as seen in Figures 2 to 4.

2.2 Stockbridge Dynamic Vibration Absorber

In this section the theory will be applied to a more complicated case, i.e., a Stockbridge dynamic vibration absorber. The vibration absorber will be viscoelastically modified in order to increase the dissipation of vibrational energy.

A dynamic vibration absorber, also called a vibration neutralizer, is a device or structure (secondary system) that is attached to another device (primary system) to reduce vibration levels. It acts on the primary system by applying reaction forces and dissipating vibration energy. Vortex-induced or aeolian vibrations of overhead electrical transmission lines, also referred to as conductors, are very common and can lead to fatigue damage. These vibrations are usually caused by winds ranging in velocity from 1 to 7 m/s and can occur at frequencies from 3 to 150 Hz with peak-to-peak displacement amplitudes of up to one conductor diameter. In conventional transmission line systems, one or more Stockbridge absorbers may be attached to a conductor in an effort to suppress the aeolian vibrations ([12] and [13]).

The classic theory introduced by den Hartog [14] for a viscous vibration absorber, called MCK, and their extensions to a viscoelastic absorber, presented by Snowdon [15], are difficult to apply. This is because for complex mechanical systems many modes can contribute to the total response of the primary system. Interesting methods to optimise dynamic vibration absorbers have been presented by Brennan and co-workers ([16] to [19]). Kidner and Brennan [17] used a multi-degree-of-freedom beam neutralizer with piezoceramic patches as active elements, and they analysed the improvement on the performance of the absorber considering the rigid

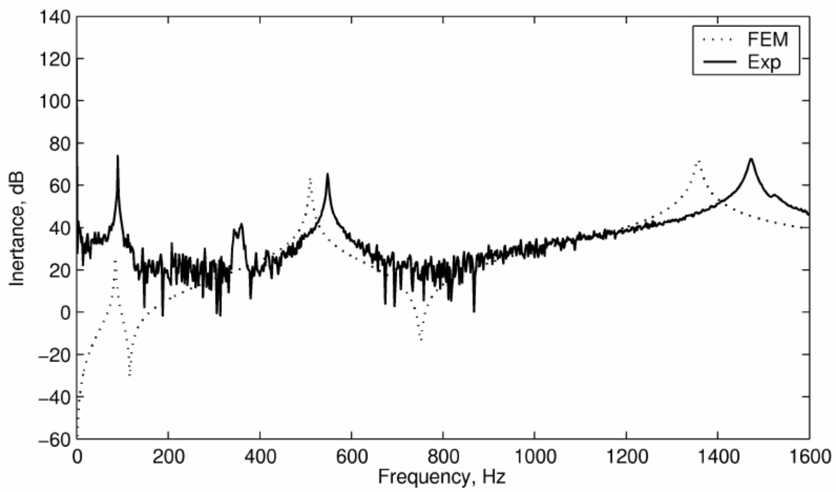

Fig. 2. *Comparison of the experimental and numerical results for the inertance frequency response of the beam at -30 °C*

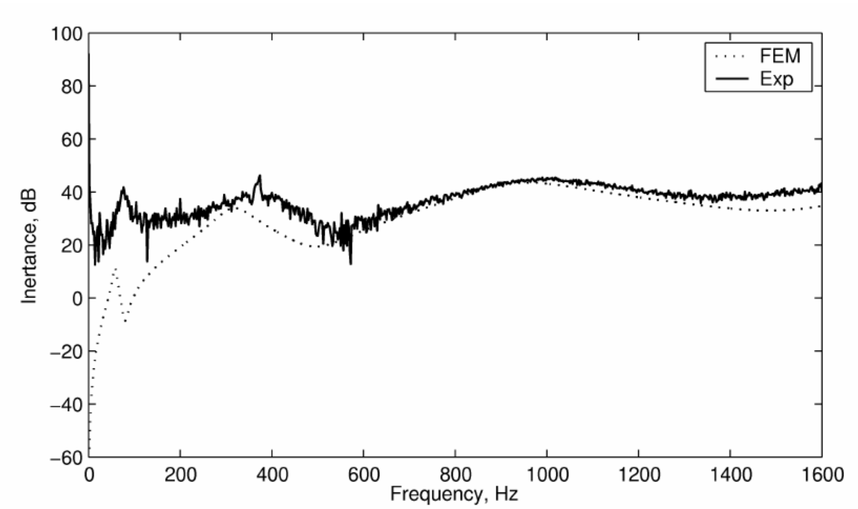

Fig. 3. *Comparison of the experimental and numerical results for the inertness frequency response of the beam at 10 °C*

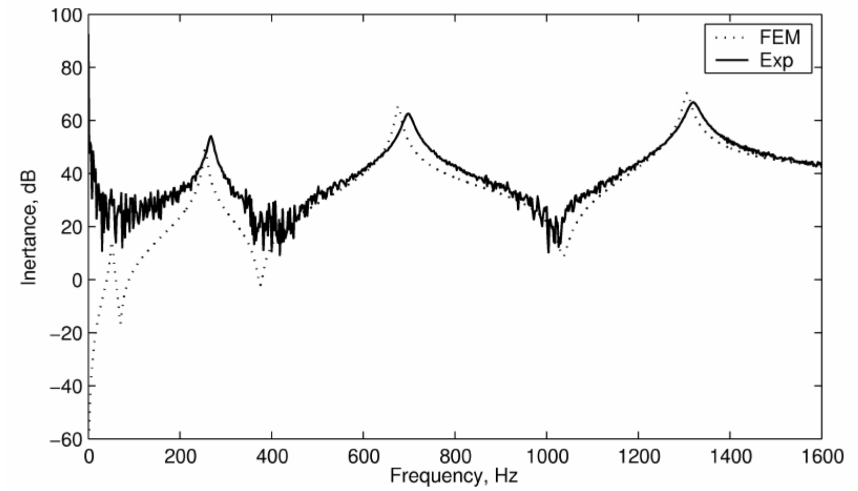

Fig. 4. *Comparison of the experimental and numerical results for the inertness frequency response of the beam at 60 °C*

body mode and the first mode of the beam in their analysis. Brennan and Dayou [18] used an equivalent damper to represent the dynamic stiffness of the absorber assuming a very low damping. Then, they were able to model the problem without adding degrees of freedom, but by using all the modes of the primary structure. More recently, an experimental verification of the optimum tuning method has been presented [19]. An interesting finding is that the absorber can be as effective as active control in reducing the global vibration of the structure. On the other hand, Espíndola and Silva [20] introduced the concept of generalized equivalent quantities. The basic idea of their technique is to transform the mechanical impedance of the absorber's coupling point to the primary system, into generalized quantities of mass and damping that are frequency dependent. Using the generalized quantities it is possible to formulate the compound equations of motion simply in terms of the generalized coordinates of the primary system. After the equations are written in the principal coordinates, and retaining those that correspond to the frequency band of interest (where the problem of high response residua), the computations are made in a modal subspace, which includes just a minimum number of equations.

2.3 Finite-Element Model for the Secondary System

In simple terms a Stockbridge absorber is composed of a mass at the centre, two attached sandwich (metal-elastomer-metal) beams, and two attached tuning masses, as shown in Figure 5. The mass at the centre is attached to the primary system. The finite element method is used to model the absorber's behaviour. The corresponding eigenvalue problem, which is frequency dependent, can be solved using the technique presented in Section 1. The finite element model of the absorber is shown in Figure 5. Now, for a fixed temperature the equations of motion for the secondary system are:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{K}(\Omega)\mathbf{u} = \mathbf{f}(t) \qquad (20).$$

After modification of the order of rows and columns in order to appropriately place the control node, as shown in Figure 5, we can define:

$$\mathbf{u} = \left[q_1, q_2, \cdots, q_{n-1}, y\right]^T = \left[\mathbf{q}, y\right]^T \qquad (21),$$

$$\mathbf{f}(t) = \left[0, 0, \cdots, 0, f(t)\right]^T = \left[\mathbf{0}, f(t)\right]^T \qquad (22),$$

and then Eq. (20) can be written in partitioned matrix form as:

$$\begin{bmatrix} \mathbf{M}_1 & \mathbf{M}_2 \\ \mathbf{M}_3 & \mathbf{M}_4 \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}} \\ \ddot{y} \end{bmatrix} + \begin{bmatrix} \mathbf{K}_1(\Omega) & \mathbf{K}_2(\Omega) \\ \mathbf{K}_3(\Omega) & \mathbf{K}_4(\Omega) \end{bmatrix} \begin{bmatrix} \mathbf{q} \\ y \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ f(t) \end{bmatrix} \qquad (23),$$

where $\mathbf{M}_1$ is an $n{-}1{\times}n{-}1$ mass submatrix, $\mathbf{M}_2$ is an $n{-}1{\times}1$ mass submatrix, $\mathbf{M}_3$ is an $1{\times}n{-}1$ mass submatrix, $\mathbf{M}_4$ is an $1{\times}1$ mass submatrix, $\mathbf{K}_1(\Omega)$ is an $n{-}1{\times}n{-}1$ stiffness submatrix, $\mathbf{K}_2(\Omega)$ is an $n{-}1{\times}1$ stiffness submatrix, $\mathbf{K}_3(\Omega)$ is an $1{\times}n{-}1$ stiffness submatrix, $\mathbf{K}_4(\Omega)$ is an $1{\times}1$ stiffness submatrix, $\mathbf{u}$ is the total displacement vector, $\mathbf{q}$ is the displacement vector without considering the control node, y is the displacement of the control node, and $f(t)$ is the force applied to the absorber by the primary system. Now, in the frequency domain, Eq. (23) can be expressed as the system of equations:

$$\left[-\Omega^2\mathbf{M}_1 + \mathbf{K}_1(\Omega)\right]\mathbf{Q}(\Omega) + \left[-\Omega^2\mathbf{M}_2 + \mathbf{K}_2(\Omega)\right]\mathbf{Y}(\Omega) = \mathbf{0}$$
$$\left[-\Omega^2\mathbf{M}_3 + \mathbf{K}_3(\Omega)\right]\mathbf{Q}(\Omega) + \left[-\Omega^2\mathbf{M}_4 + \mathbf{K}_4(\Omega)\right]\mathbf{Y}(\Omega) = \mathbf{F}(\Omega)$$
$$(24).$$

After solving Eq. (24), we obtain the dynamic stiffness of the system as:

$$K(\Omega) = \frac{F(\Omega)}{Y(\Omega)} = \mathbf{X}_4(\Omega) - \mathbf{X}_3(\Omega)\mathbf{X}_1^{-1}(\Omega)\mathbf{X}_2(\Omega) \qquad (25),$$

where:

$$\mathbf{X}_i(\Omega) = -\Omega^2\mathbf{M}_i + \mathbf{K}_i(\Omega), \text{ for i=1, ... , 4} \qquad (26).$$

Now, the inverse of $\mathbf{X}_1$ can be computed approximately by using Eq. (15), as:

$$\mathbf{X}_1^{-1}(\Omega) = \left[-\Omega^2\mathbf{M}_1 + \mathbf{K}_1(\Omega)\right]^{-1} \cong \mathbf{S}(\Omega)\left[-\Omega^2\mathbf{I}_{\hat{n}} + \mathbf{\Lambda}(\Omega)\right]^{-1}\mathbf{S}^T(\Omega)$$
$$(27).$$

From the dynamic stiffness we can obtain the dynamic impedance

$$Z(\Omega) = \frac{K(\Omega)}{j\Omega} \qquad (28),$$

where $j=\sqrt{-1}$, and the apparent mass

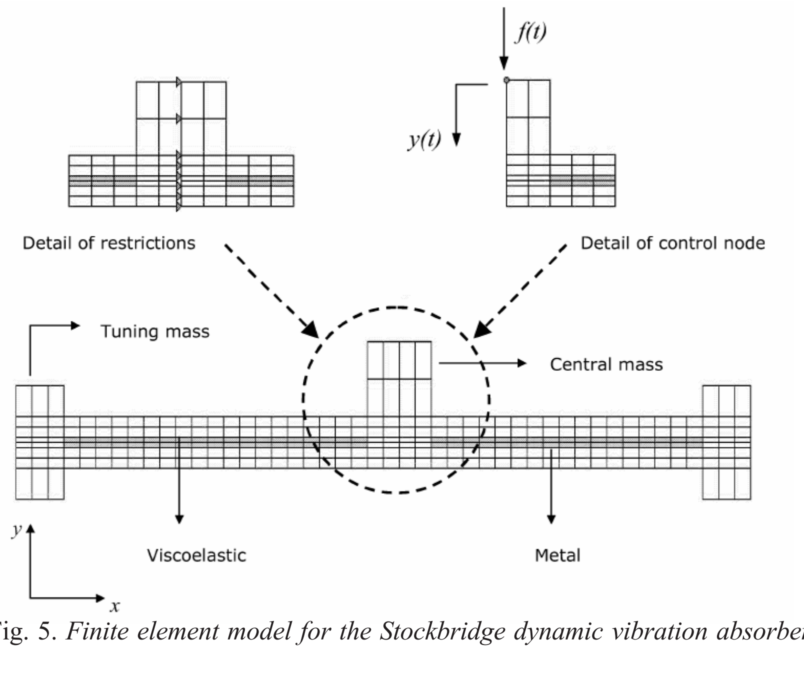

Fig. 5. *Finite element model for the Stockbridge dynamic vibration absorber*

$$M(\Omega) = \frac{K(\Omega)}{-\Omega^2} \quad (29).$$

Consequently, the equivalent damping and equivalent mass are

$$c_{eq}(\Omega) = \Re\{Z(\Omega)\} \quad (30),$$

and

$$m_{eq}(\Omega) = \Re\{M(\Omega)\} \quad (31),$$

respectively.

Then, the model of the absorber is replaced by an equivalent mechanical system composed of an equivalent mass connected to the primary system and an equivalent damper connected to the ground, where both are frequency dependent. In this way there are new physical degrees of freedom in the mechanical system, but there are no new degrees of freedom in the model. This formulation is equivalent to the simple model of a Stockbridge absorber, which makes use of the Euler-Lagrange equations.

2.4 Optimisation of the Stockbridge Absorber

Now, the secondary system (Stockbridge absorber) is attached to a primary system (electrical transmission line) resulting in a compound system. In order to optimise the physical dimensions of the absorber, an objective function has to be proposed. Here, the objective function will be defined from the maximum absolute values of the principal coordinate functions of the compound system. Assuming that the primary system has a very low and almost constant hysteretic damping, the equations of motion for the primary system in the frequency domain are:

$$\left[-\Omega^2 \mathbf{M}_{pr} + \mathbf{K}_{pr}\right]\mathbf{q}_{pr}(\Omega) = \mathbf{f}(\Omega) \quad (32),$$

where $\mathbf{M}_{pr}$ is the mass matrix of the primary system, $\mathbf{K}_{pr}$ is the complex stiffness matrix of the primary system, $\mathbf{q}_{pr}(\Omega)$ is the displacement vector of generalized coordinates, and $\mathbf{f}(\Omega)$ is the force vector. Using the theory of the equivalent generalized quantities [20], the compound system can be modelled as:

$$\left[-\Omega^2\left[\mathbf{M}_{pr} + \mathbf{M}_{eq}(\Omega)\right] + j\Omega\mathbf{C}_{eq}(\Omega) + \mathbf{K}_{pr}\right]\mathbf{q}_{pr}(\Omega) = \mathbf{f}(\Omega) \quad (33),$$

where $\mathbf{M}_{eq}(\Omega)$ is the equivalent mass matrix and $\mathbf{C}_{eq}(\Omega)$ is the equivalent damping matrix.

If p absorbers are attached to the primary system, at the generalized physical coordinates q_{k1}, q_{k2}, ... , q_{kp}, the equivalent generalized mass and damping matrices are:

$$\mathbf{M}_{eq}(\Omega) = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ 0 & m_{eq}(\Omega)_{k1} & \cdots & 0 & 0 \\ 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & \cdots & m_{eq}(\Omega)_{kp} & 0 \\ 0 & 0 & \cdots & 0 & 0 \end{bmatrix} \quad (34),$$

and

$$\mathbf{C}_{eq}(\Omega) = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ 0 & c_{eq}(\Omega)_{k1} & \cdots & 0 & 0 \\ 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & \cdots & c_{eq}(\Omega)_{kp} & 0 \\ 0 & 0 & \cdots & 0 & 0 \end{bmatrix} \quad (35),$$

respectively.

Using the transformation:

$$\mathbf{q}_{pr}(\Omega) = \mathbf{\Phi}_{pr}\hat{\mathbf{p}}_{pr}(\Omega) \quad (36),$$

where Φ_{pr} is the matrix of the eigenvectors associated with the eigenvalues of the primary system in the frequency band of interest, and $\hat{\mathbf{p}}_{pr}$ is the vector of the principal coordinates of the primary system, Eq. (33) can be written as:

$$\left[-\Omega^2\left[\mathbf{I} + \mathbf{M}_A(\Omega)\right] + j\Omega\mathbf{C}_A(\Omega) + \mathbf{\Sigma}_{pr}\right]\hat{\mathbf{p}}_{pr}(\Omega) = \mathbf{n}(\Omega) \quad (37),$$

where $\mathbf{M}_A(\Omega)=\Phi_{pr}^T\mathbf{M}_{eq}(\Omega)\Phi_{pr}$, $\mathbf{C}_A(\Omega)=\Phi_{pr}^T\mathbf{C}_{eq}(\Omega)\Phi_{pr}$, $\mathbf{n}(\Omega)=\Phi_{pr}^T\mathbf{f}(\Omega)$, and $\Sigma_{pr}=\Phi_{pr}^T\mathbf{K}_{pr}\Phi_{pr}=\mathrm{tr}(\sigma_i)$ is a trace matrix of eigenvalues of the primary system. Consequently:

$$\hat{\mathbf{p}}_{pr}(\Omega) = \left[-\Omega^2\left[\mathbf{I} + \mathbf{M}_A(\Omega)\right] + j\Omega\mathbf{C}_A(\Omega) + \mathbf{\Sigma}_{pr}\right]^{-1}\mathbf{n}(\Omega) \quad (38),$$

and the receptance matrix can be calculated by:

$$\boldsymbol{\alpha}(\Omega) = \mathbf{\Phi}_{pr}\left[-\Omega^2\left[\mathbf{I} + \mathbf{M}_A(\Omega)\right] + j\Omega\mathbf{C}_A(\Omega) + \mathbf{\Sigma}_{pr}\right]^{-1}\mathbf{\Phi}_{pr}^T \quad (39).$$

Then, in order to solve the optimisation problem it is possible to define an objective function $\bar{f}$ as the modulus of a vector formed by the maximum absolute values of the generalized principal coordinates of the primary system [20]. This can be expressed by the equation:

$$\bar{f}(\mathbf{x}) = \left\| \max_{\Omega_1 \le \Omega \le \Omega_2} \left|\hat{\mathbf{p}}_{pr}^i(\mathbf{x},\Omega)\right| \right\|^2 \quad (40),$$

where Ω_1 and Ω_2 are the lower and upper limits of the frequency band of interest, respectively, $\mathbf{x}$ is a design vector of project variables to optimise, and i=1,..., N, where N is the total number of degrees of freedom of the primary system.

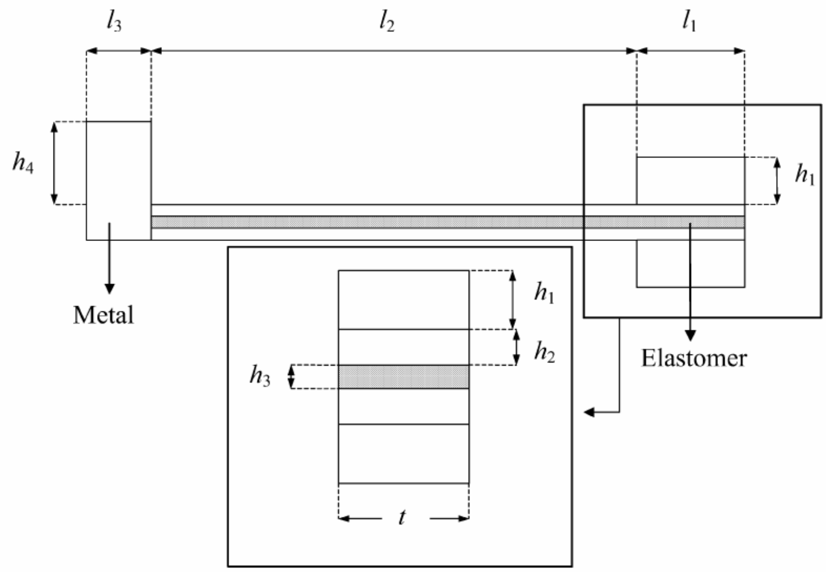

Fig. 6. *Definitions of the physical dimensions to optimise for the Stockbridge absorber*

The project variables to optimise are the physical dimensions of the absorber. Therefore, the design vector is defined as:

$$\mathbf{x} = \left[l_1, l_2, l_3, h_1, h_2, h_3, h_4, t\right]^T \quad (41),$$

where the elements of **x** are the physical dimensions shown in Fig. 6. The constraint functions are defined for each element of **x** as:

$$x_i^L \leq x_i \leq x_i^U \quad (42),$$

where x_i^L and x_i^U are the lower and upper limits for each element, respectively. For the force vector, a unit force at each excitation point of the primary system can be used, i.e., $\mathbf{f}=[1,1,\ldots,1,1]^T$.

A numerical example was performed for a real compound system. A total of four Stockbridge absorbers were attached to the primary system. In this example of a Stockbridge absorber the two sandwich beams are designed from two metal layers of steel 1020 and a viscoelastic core DYAD 601 (Soundcoat Co.). The finite element model of the absorber is shown in Fig. 5. The beams were divided into 114 elements. For the length and thickness of the core, 19 and 2 elements were used, respectively. This choice was found appropriate for both, representing efficiently the internal shear and determining the first four modes in the frequency band used. The mass at the centre was divided into 32 elements and the tuning masses were divided into 24 elements each. This choice is because the mechanical purposes of the masses do not require high discretization. All the elements are two-dimensional lagrangian and quadratic solids, of nine nodes, and they are in a plane state of stress. This gives a total of 308 elements, 1319 nodes, and a total of n=2638 degrees of freedom. For simplicity, the temperature is assumed to be a constant.

The primary system considered was an ACRS partridge cable, 30.2 m long, clamped at both extremes and subjected to a tension of 9000 N. The cable was divided into 81 equally spaced elements. The central masses of the absorbers were attached at nodes 5, 35, 46, and 76 of the cable. These positions were selected in order to be far from the nodes of the cable, allowing the absorbers to control a large number of modes of the primary structure. Figure 7 shows the physical model of the compound system and its corresponding generalized equivalent quantities model.

Since the finite elements were in a plane state of stress, t does not change a lot during the optimisation process, so it was fixed at a value of 10 mm. The lower and upper limits for each x_i were chosen such that: 1) the weight and size of the absorbers should not be excessive, and 2) the thickness of the elastomer should be small in order to have shear deformation from the vibration of the sandwich beams. The frequency range used to optimise the Stockbridge absorber was 40 to 60 Hz. The temperature was fixed at 10^{O}C. Because of its nature, the objective function has a large number of local minima so a genetic algorithm was used to perform the optimisation. The theory and applications of the genetic algorithms in optimisation problems

Table 1. *Results of the optimisation of the physical dimensions for the Stockbridge absorbers*

x_i	x_i^L mm	x_i^U mm	x_i optimised mm
l_1	0	200	10.321
l_2	0	1000	210.002
l_3	0	200	30.024
h_1	0	100	10.096
h_2	0	10	2.013
h_3	0	5	2.000
h_4	0	400	30.102
t	–	–	10.000

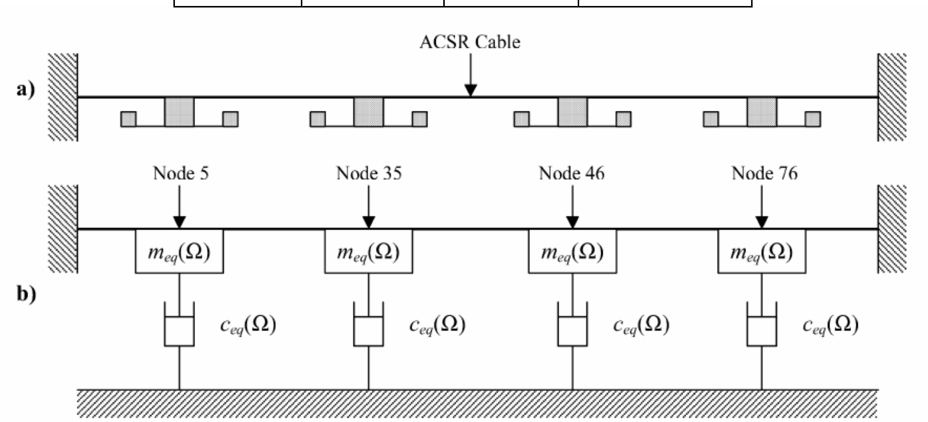

Fig. 7. *Diagram of the compound system (cable plus Stockbridge absorbers): a) the physical model and b) its generalized equivalent quantities model*

were explained in detail in the literature [21] to [23]. The numerical results of the optimisation process are presented in Table 1.

Figure 8 shows the results of the receptance at the mid point of the cable, when no absorber is attached, and when the absorbers are attached to the cable before and after the optimisation process. It can be seen that after their dimensions were optimised, the Stockbridge absorbers reduced the vibration level of the cable in a very effective way. Most of the peak values of the receptance frequency response were attenuated and for the peak value at around 60 Hz an attenuation of 30 dB was achieved after the optimisation.

3 CONCLUSIONS

The modelling of a metal-elastomer composite structure based on a finite element method has been presented. In addition, a methodology to reduce the computation time when dealing with frequency dependent matrices has proven to give good approximate results. It has to be noted that the precision of the approximation presented in Section 1 depends on the subspace. The factors that determine the behaviour of the algorithm are: a) the dimension $\hat{n}$ of the subspace (a larger value of the dimension will produce a better approximation), and b) the variation of the complex shear modulus of the viscoelastic material with both frequency and temperature. It can be expected that in the transition zone the errors will be increased. As a result, the distance between the subspace generated by the truncated modal matrix $\hat{\mathbf{\Phi}}_0$ and the space generated by the modal matrix Φ is increased. Obviously, this implies that the initial frequency Ω_0 plays an important role in the computations since the difference between $\mathbf{K}(\Omega_0,T)$ and $\mathbf{K}(\Omega,T)$ increases with the change of temperature. However, it can be concluded that the method used in this work seems to be quite efficient when compared to the subspace iteration method [8] and the Lanczos method [25], since these require the calculation of the inverse of the stiffness matrix for each iteration. In addition, a theory to determine the generalized equivalent quantities for a Stockbridge dynamic absorber has been presented. The use of these quantities does not add more degrees of freedom to the primary system and the

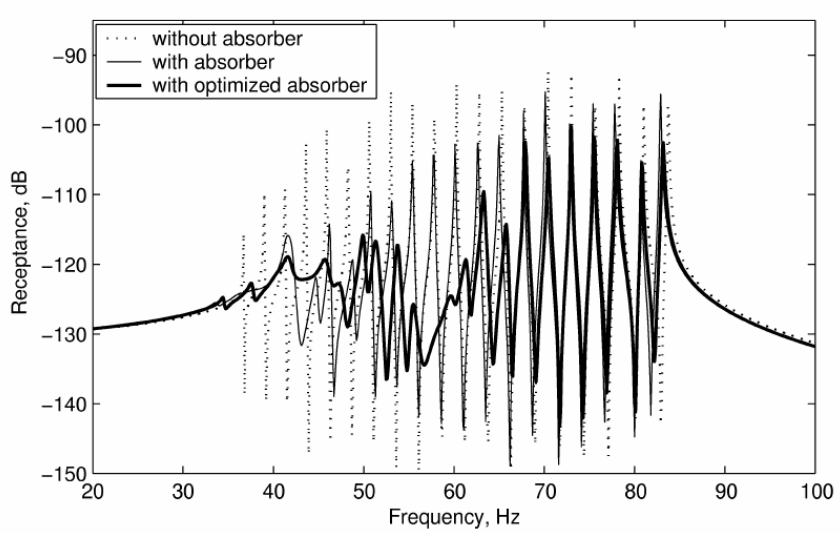

Fig. 8. *Comparison of receptance frequency responses at the mid point of the primary system, with and without an optimised Stockbridge absorber*

theory could be extended to other kinds of absorbers. Moreover, the use of generalized equivalent quantities allows one to define an objective function of the maximum absolute values of the principal coordinates of the primary structure. This objective function is independent of the geometry of the primary system and it is dependent on its modal parameters. The application of the method to Stockbridge absorbers used to suppress the aeolian vibrations of a real electrical transmission line shows that the reduction in the response of up to eleven modes is achieved after the dimensions of the absorbers are optimised using a genetic algorithm. The optimisation process can be quite slow when compared to other techniques reported in the literature [18] and [19]; however, the results presented in this work seem to be encouraging. Further work will be conducted regarding the computational costs and detuning of the absorber due to the presence of temperature changes in the elastomer layer.

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Authors' Addresses: Prof. Dr. Sergio E. Floody
Univ. Tecnológica de Chile
Brown Norte 290
Santiago, Chile
s.floody@utecnologica.cl

Prof. Dr. Jorge P. Arenas
Institute of Acoustics
Univ. Austral de Chile
PO Box 567, Valdivia, Chile
jparenas@uach.cl

Prof. Dr. José J. de Espíndola
Dept. Mechanical Engineering
Univ. Federal de Santa Caterina
Florianópolis, SC 80040-900, Brasil
espindol@mbox1.ufsc.br

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Ugotavljanje in vrednotenje potreb kupcev v postopku razvoja izdelka

Finding and Evaluating Customers' Needs in the Product-Development Process

Janez Kušar[1] - Jože Duhovnik[1] - Rok Tomaževič[2] - Marko Starbek[1]
([1]Fakulteta za strojništvo, Ljubljana; [2]CIMOS d.d., Koper)

Podjetja današnjih dni se soočajo z novimi izzivi. Imamo opravka z globalizacijo poslovanja in lokalizacijo delovanja, standardizacijo in individualizacijo izdelkov, zahtevnim kupcem in močno konkurenco. V prispevku so prikazane faze razvoja funkcij kakovosti (RFK - QFD) postopka sprejemanja izdelka in podano mesto pridobivanja, sestavljanja in vrednotenja potreb kupcev izdelka. Podrobno so opisani viri pridobivanja informacij o potrebah kupcev, predstavljene so metode pridobivanja, sestavljanja in vrednotenja podatkov o potrebah kupcev izdelka ter prikazan postopek razvoja izdelka. Podani so rezultati preizkusa predlagane metodologije upoštevanja glasu kupcev v postopku razvoja izdelka Vario Flow podjetja, ki se ukvarja s proizvodnjo in prodajo medicinske opreme za domači in tuji trg.

(Ključne besede: razvoj izdelka, razvoj funkcij kakvosti (RFK), potrebe kupcev, odločitveni postopki, hiša kakovosti)

Today's companies are facing new challenges: global business and local operation, the standardization and individualization of products, and demanding customers and fierce competition. This paper presents the phases of quality functions deployment (QFD) during a new-product development process along with the method for obtaining, structuring and evaluating customer needs. A full description of the information resources for obtaining the data on customer needs is given, and the methods for obtaining, structuring and evaluating the data on customer needs are presented. The QFD process of new-product development is described. We present the results of testing the proposed methodology, taking into account the voice of the customer, in the process of developing a new Vario Flow product in a company that produces and sells medical equipment on domestic and foreign markets.

(Keywords: product development, quality function deployment (QFD), customer needs, decision making, house of quality)

0 UVOD

Za današnjega kupca izdelkov lahko trdimo, da je “kralj”, saj je pripravljen kupiti le izdelke, ki zadovoljujejo njegove potrebe in zahteve. Podjetje želi doseči krajši čas razvoja izdelka, manjše stroške, vrhunsko kakovost izdelka ter končno zadovoljstvo kupcev izdelka. Da bi podjetje doseglo postavljene cilje, mora že med razvojem izdelka upoštevati potrebe in zahteve kupcev izdelka. Znano je, da se izdelek razvija v postopku, ki se prične z abstraktnim razmišljanjem in konča s končnim izdelkom. Izkušnje kažejo, da je treba v tem miselnem in stvarnem postopku razvoja izdelka upoštevati glas kupcev (potrebe in zahteve), če

0 INTRODUCTION

Today, we can maintain that the customer is “king” as he or she will only buy products that satisfy his or her needs and wants. Every company wants to achieve shorter product-development times, lower costs, higher quality of the product, and, finally, the satisfaction of its customers. In order to achieve the set goals, the company has to take into account the customers’ wants and needs during the new-product development process. It is well known that the new-product development process starts with an abstract idea and ends with the physical realization of the product. Experience has shown that in this mental and physical product-development process the voice želimo, da bo izdelek lahko tekmoval na globalnem tržišču.

Razvoj funkcij kakovosti ([1] do [3]) je edini, na kupca usmerjeni postopek razvoja izdelka, pri čemer je "glas kupca" izhodiščna točka vseh dejavnosti. RFK vpraša: "Kaj potrebuje in zahteva kupec" in spremeni njegova pričakovanja v značilke izdelka [4]. Razvoj funkcij kakovosti strmi za tem, da se izdelek tako definira, razvije, konstruira, izdela, dobavi in vgradi, da se ne izpolni le želja kupca, ampak da so želje celo več ko izpolnjene. Metoda razvoja funkcij kakovosti rabi za preoblikovanje potreb in zahtev kupcev v zmožnosti podjetja ter za vključitev vseh oddelkov oziroma služb podjetja za izpolnitev naročila.

Metoda RFK je igra vprašanj in odgovorov z dvema osnovnima vprašanjema:

- KAJ pričakujejo kupci izdelka,
- KAKO podjetje izpolni potrebe kupcev.

Metoda RFK spremlja postopek razvoja izdelka od faze razmišljanja pa do faze uporabe izdelka, pri tem pa je "hiša razvoja funkcij kakovosti izdelka" (sl. 1) namenjena dokumentiranju miselnih in načrtnih rezultatov.

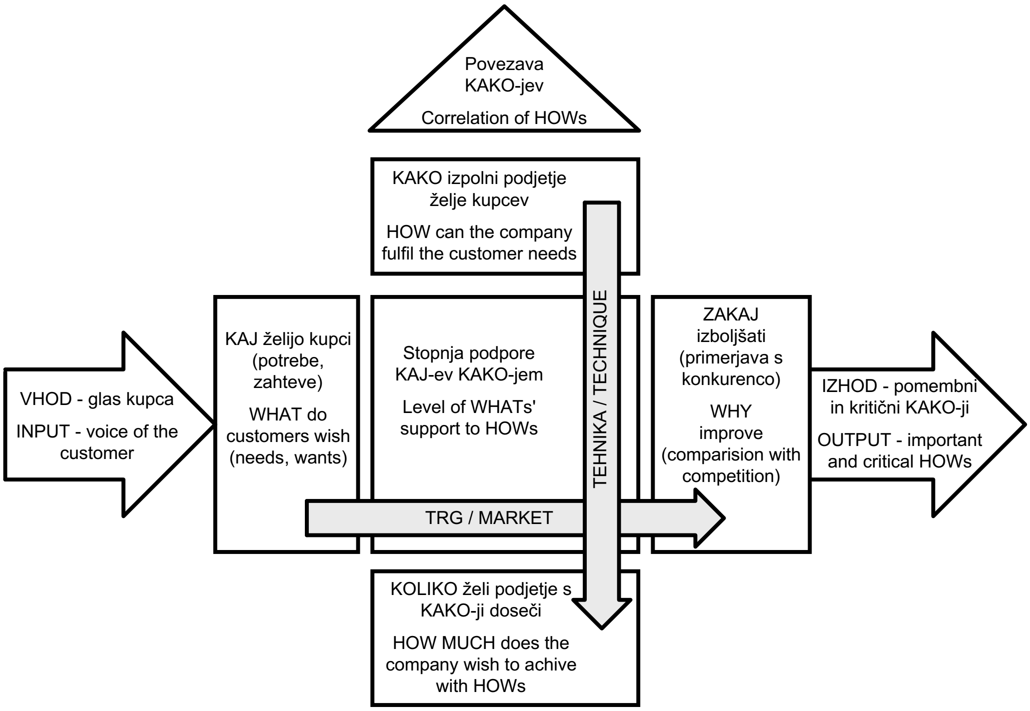
of the customer (his or her needs and wants) has to be taken into account in order to ensure that a globally competitive product will be produced.

Quality functions deployment (QFD) ([1] to [3]) is the only customer-oriented product-development method where the "voice of the customer" is the starting point of all activities. QFD starts with the question: "What does the customer need and want?" and transforms the customers' expectations into the product's features [4]. The goal of the QFD method is to define, develop, design, manufacture, supply and install the product in such a way that the customers' wishes are over-fulfilled rather than simply "just" fulfilled. The QFD method allows the transformation of the customers' needs and wants into the company's potentials and the engagement of all its departments to serve the customers.

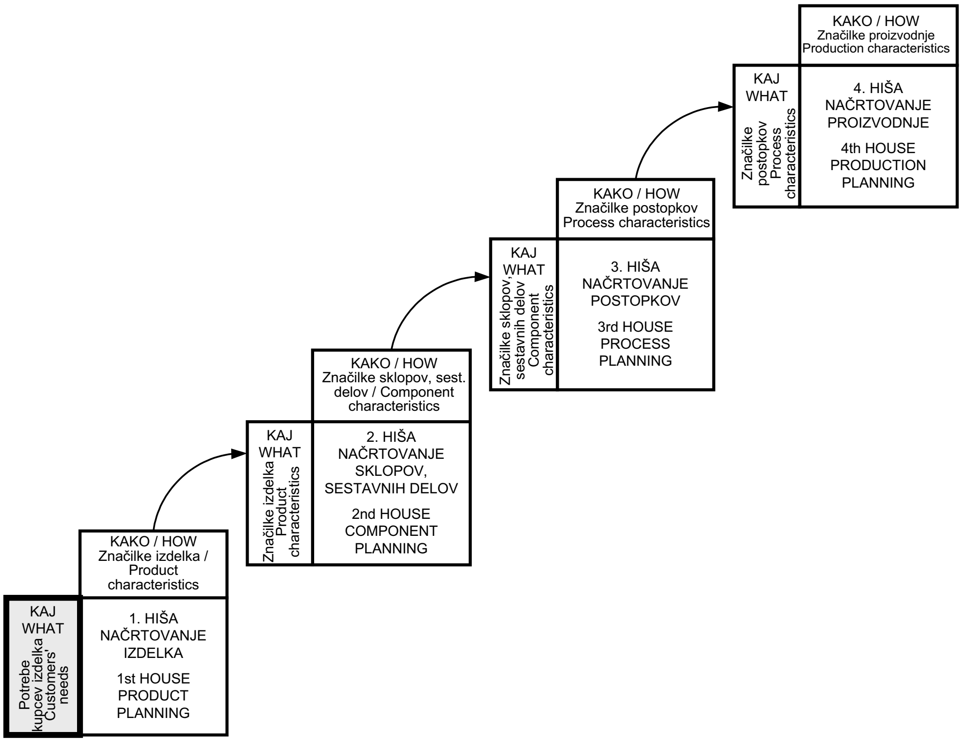
The QFD method is a game of questions and answers with two basic questions:

- WHAT do customers expect from the product?
- HOW can the producer fulfill the customer needs?

The QFD method is used throughout the product-development process: from the first abstract concept to the use of the product. The "product's quality-functions-deployment house" (Figure 1) is used to record the mental and planned results.



Sl. 1. *Hiša razvoja funkcij kakovosti izdelka*
Fig. 1. *Product's quality-functions-deployment house*



Sl. 2. *Postopek sprejemanja izdelka na osnovi RFK*
Fig. 2. *QFD process of new-product development*

Postopek razvoja izdelka na osnovi RFK poteka kaskadno in se opiše s štirimi hišami razvoja funkcij kakovosti (sl. 2) in to [4]:

- hišo razvoja funkcij kakovosti izdelka,
- hišo razvoja funkcij kakovosti sklopov oziroma sestavnih delov izdelka,
- hišo razvoja funkcij kakovosti postopka in
- hišo razvoja funkcij kakovosti proizvodnje.

Kakor prikazuje slika 2 se postopek razvoja izdelka na osnovi RFK prične s pridobivanjem, sestavljanjem in vrednotenjem potreb kupcev izdelka – rezultat je vektor ugotovljenih potreb kupcev izdelka, ki pomeni vhodni podatek hiše načrtovanja izdelka.

Da bi lahko pri sprejemanju izdelka upoštevali glas oz. potrebe kupcev, je le-te treba pridobiti in raziskati z namenom, da bi razumeli ter vedeli, kako bodo upoštevane.

Slika 3 prikazuje osnutek pridobivanja, sestavljanja in vrednotenja potreb kupcev izdelka.

V nadaljevanju bodo prikazani postopek in metode pridobivanja, sestavljanja in vrednotenja podatkov o potrebah kupcev, kar je temelj za uspešno izvedbo postopka razvoja izdelka oziroma za uspeh izdelka na trgu.

The QFD process of new-product development is carried out in cascades and can be described with four QFD houses (Fig. 2) [4]:

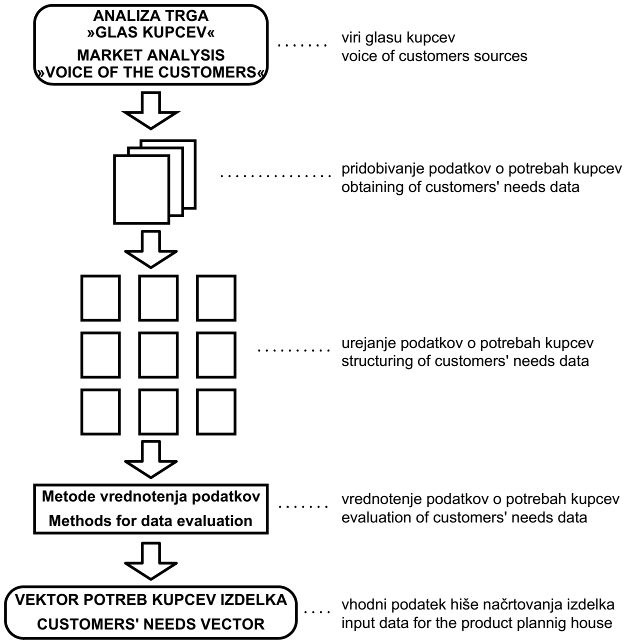
- the product's quality-functions-deployment house
- the product's component quality-functions-deployment house
- the process quality-functions-deployment house
- the manufacturing quality-functions-deployment house.

As presented in Figure 2, the QFD process of new-product development starts by obtaining, structuring and evaluating the customer needs, which represent the input data for the product planning house.

In order to take into account the customer needs during new-product development, they must be identified and analyzed beforehand, so that they can be properly understood and fulfilled.

Figure 3 presents the concept of obtaining, structuring and evaluating the data on customer needs.

In the text that follows, the procedure and methods for obtaining, structuring and evaluating customer needs are presented. These are the basis for the successful execution of the product-development process or for the success of the product on the market.



Sl. 3. *Osnutek zbiranja, urejanja in vrednotenja potreb kupcev izdelka*
Fig. 3. *The concept of obtaining, structuring and evaluating customer needs*

1 VIRI GLASU KUPCEV

Glas kupcev je pojem, s katerim se opišejo izrečene in neizrečene potrebe ter zahteve kupcev in je kot tak potreben za zagon postopka razvoja izdelka ([5] in [6]). Potreba kupca pomeni izjavo kupca o koristi, ki bi mu jo lahko prinesel izdelek ali storitev ([1] in [7]). Kupci želijo svoje potrebe in želje zadovoljiti z izbiro izdelkov ali storitev, ki to najbolje izpolnjujejo.

Kupci pa pogosto izražajo svoje potrebe z izjavami, ki govorijo o tem, kako bi lahko te potrebe zadovoljili, te izjave pa se imenujejo kupčeve zahteve [8], ki se prepoznajo kot nekaj zahtevanega, nekaj, o čemer se ne da pogajati.

Poznani so trije glavni viri pridobivanja informacij o glasu kupca, in to so ([3] in [9]):

- zunanji kupci,
- notranji kupci in
- podatki o izdelkih in postopkih.

1.1 Zunanji kupci

Zunanji kupci so kupci, ki so zunaj podjetja in govorijo drugačen jezik kakor proizvajalec izdelka. Po pregledu literature ([1], [3], [6] in [7]) lahko ugotovimo, da se zunanji kupci delijo v več kategorij in podkategorij, glede na to, od koga

1 SOURCES OF THE CUSTOMERS' VOICE

The voice of the customers is a concept that describes the uttered and unuttered customers' wants and needs; as such it must exist in order to start the new-product development process ([5] and [6]). A customer need is a description, in the customer's own words, of the benefit to be fulfilled by the product or service ([1] and [7]). Customers would like to satisfy their needs and wishes by selecting products or services that best fulfill them.

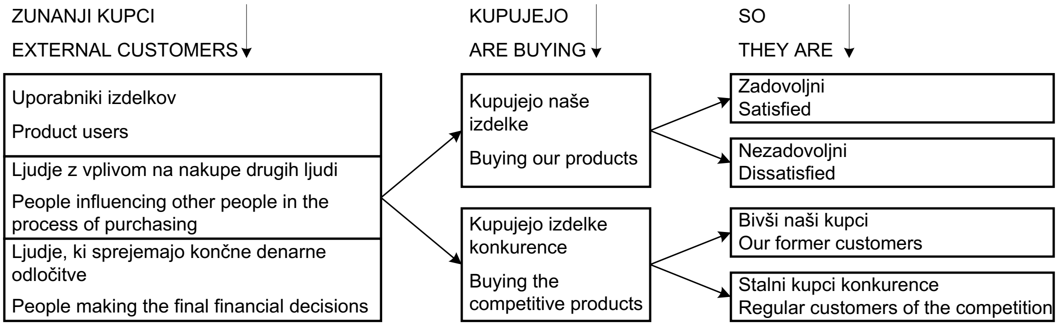
Customers often express their needs using statements that describe how these needs could be fulfilled and these statements are called "customer requirements" [8], which are considered as something required, something that is non-negotiable.

There are three major sources for obtaining information on the voice of the customer ([3] and [9]):

- external customers,
- internal customers,
- information on products and processes.

1.1 External customers

External customers are the customers outside the company. They speak a different language than the company that manufactures the product. A survey of the reference works ([1], [3], [6] and [7]) reveals that external customers fall into several categories and



Sl. 4. *Pregled zunanjih kupcev*
Fig. 4. *The overview of external customers*

kupujejo izdelke in kakšno vlogo imajo v oskrbovalni verigi. Slika 4 prikazuje delitev zunanjih kupcev.

1.2 Notranji kupci

Notranji kupci ([1], [3], [6] in [7]) so kupci, ki so v podjetju, njihov jezik se gotovo razlikuje od jezika zunanjih kupcev. Notranji kupci imajo svoje poglede na določene probleme v postopku razvoja izdelka, zato je treba ločevati njihov glas od glasu zunanjih kupcev. Glas notranjih kupcev lahko pomembno prispeva k izboljšanju postopka razvoja izdelka, saj je v njihovem interesu, da izboljšajo sam postopek razvoja izdelka, katerega del so, ter tako prispevajo k zadovoljevanju potreb zunanjih kupcev.
Slika 5 prinaša pregled notranjih kupcev.

1.3 Podatki o izdelkih in postopkih

Podatki o izdelkih in postopkih pomembno pomagajo pri ugotavljanju potreb kupcev, tako zunanjih kakor tudi notranjih.

Slika 6 prikazuje pregled podatkov o izdelkih in postopkih.

2 METODE PRIDOBIVANJA IN POSTOPEK UREJANJA PODATKOV O POTREBAH KUPCEV

Analizirane in ocenjene so bile različne metode pridobivanja in postopki sestavljanja podatkov o potrebah kupcev ([7] do [12]), rezultat tega dela je predlog za prakso najprimernejših metod pridobivanja in sestavljanja podatkov o potrebah kupcev.

sub-categories, depending on who they buy the products from and their role in the supply chain. Figure 4 presents the categories of external customers.

1.2 Internal customers

Internal customers ([1], [3], [6] and [7]) are customers who are from the company, and most certainly use a different language than the external customers. Internal customers have a unique perspective on specific problems in the product-and-process development, and that is why their voice must be distinguished from the voice of external customers. The voice of the internal customers can contribute significantly to the product-and-process development, as it is very important for them to improve the product development they are part of. In this way they contribute to satisfying the needs of external customers.
Figure 5 gives an overview of internal customers.

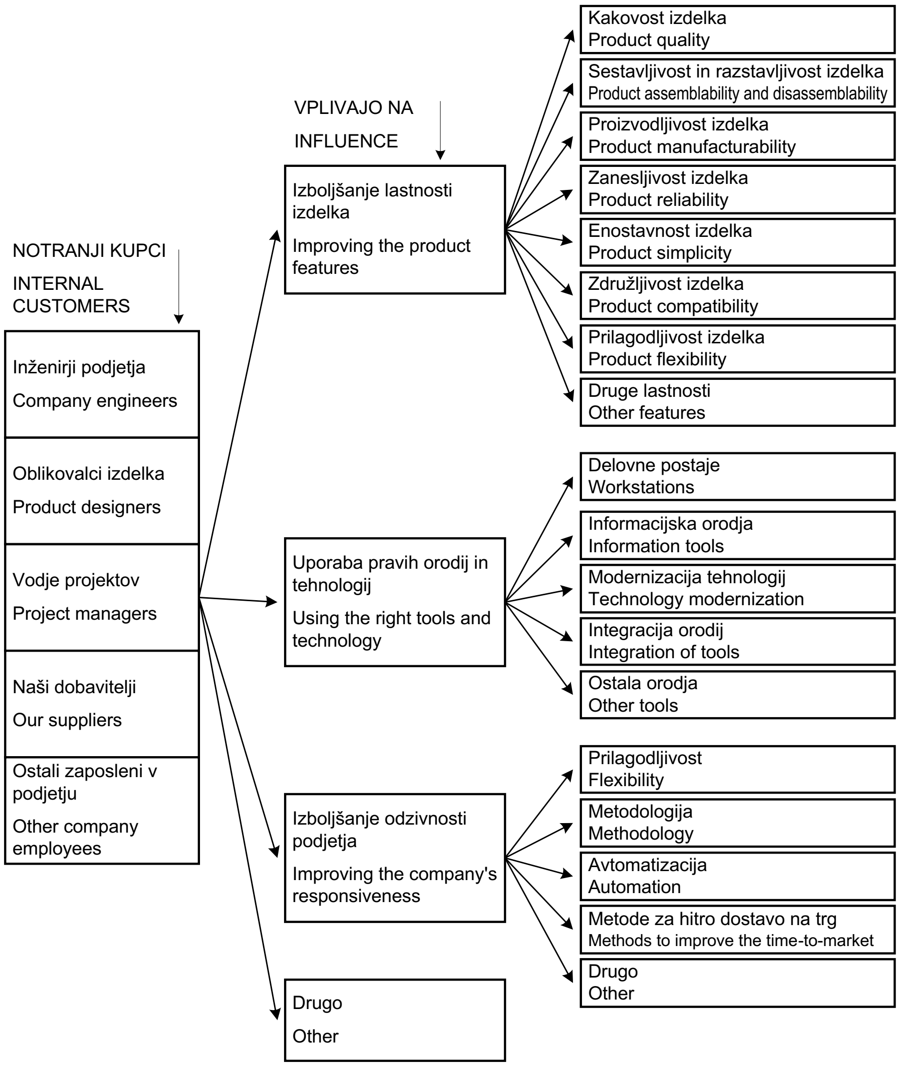
1.3 Information on products and processes

Information on products and processes is very helpful for discovering the needs of the customers, both the internal and external ones.

Figure 6 shows an overview of the information on products and processes.

2 METHODS FOR OBTAINING THE CUSTOMER NEEDS AND THE PROCEDURE FOR STRUCTURING THESE DATA

Several methods for obtaining customer needs and the procedures for structuring these data were analyzed and reviewed ([7] to [12]). The result is a suggestion for using the most suitable methods for obtaining and structuring the data on customer needs.



Sl. 5. *Pregled notranjih kupcev*
Fig. 5. *The overview of internal customers*

2.1 Metode pridobivanja podatkov o potrebah kupcev

Za pridobivanje podatkov o potrebah kupcev imajo prednost naslednje metode:
- metoda žariščne skupine,
- metoda izvedbe intervjuja,
- metoda pripomb in pritožb kupcev in
- metoda soočanja idej.

2.1.1 Metoda žariščne skupine

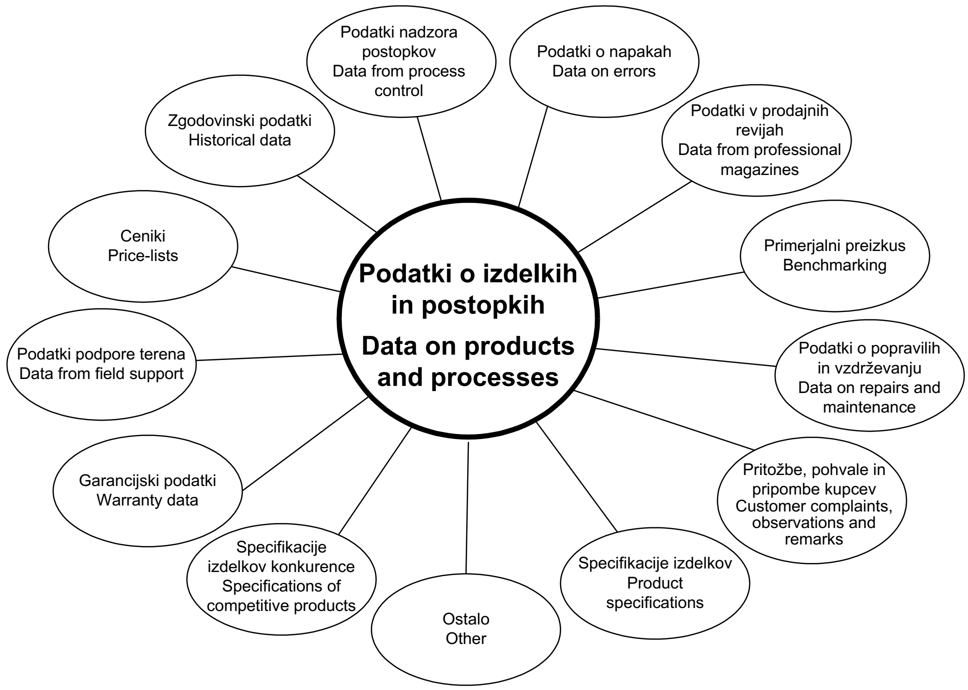
Metoda žariščne skupine je metoda, pri kateri izbrana skupina kupcev razpravlja o vprašanjih, ki jih poda moderator. Razprava nastane tako, da vsak član skupine poda svoje poglede na določen

2.1 Methods for obtaining the data on customer needs

When obtaining the data on customer needs preference is given to the following methods:
- the focus-group method,
- interviews,
- the customer-remarks-and-complaints method,
- brainstorming.

2.1.1 Focus-group method

The focus-group method uses a selected group of customers who discuss questions posed by a moderator. The discussion is initiated so that each group member first expresses his/her opinion on a particular



Sl. 6. *Podatki o izdelkih in postopkih*
Fig. 6. *Information on products and processes*

problem, sliši mnenja drugih in nanje tudi odgovarja. S takim načinom razprave metoda žariščne skupine priskrbi kakovostne poglede majhnega števila ljudi. Moderator lahko razišče razloge, ki povzročajo nezadovoljstvo in lahko razpravlja o mogočih rešitvah določenih problemov. Običajno je v žariščni skupini od 6 do12 ljudi, razprava pa traja dve do tri ure. Slika 7 prikazuje potek pridobivanja podatkov o potrebah kupcev po metodi žariščne skupine.

Da bi lahko s pomočjo žariščne skupine zagotovili ustvarjalno razpravo o določeni temi, je treba v skupino povabiti člane tima s podobnimi interesi in znanji. Izkušnje so pokazale, da je pri tem treba paziti, da člani tima niso v kakršnikoli ukazovalni hierarhiji.

Običajno se pri raziskovalnih projektih oblikuje več žariščnih skupin (zunanji in notranji kupci, razdeljeni po različnih delih), da se pridobijo različni pogledi na problem.

Razprava v žariščni skupini je sestavljena iz treh faz:

1. faza: uvodna predstavitev,
2. faza: razprava,
3. faza: sklep razprave.

Delo žariščne skupine vodi in usmerja moderator, ki prične z uvodno predstavitvijo, se

problem, then other participants comment on it and then further discussion of their opinions follows. In this way the discussion of the focus group provides a qualitative view of a small number of people. The moderator can search for reasons causing dissatisfaction and can discuss possible solutions for particular problems. Normally, there are 6 to 12 people in a discussion group, each discussion lasts for two to three hours. Figure 7 presents the course of obtaining the data on customer needs using the focus-group method.

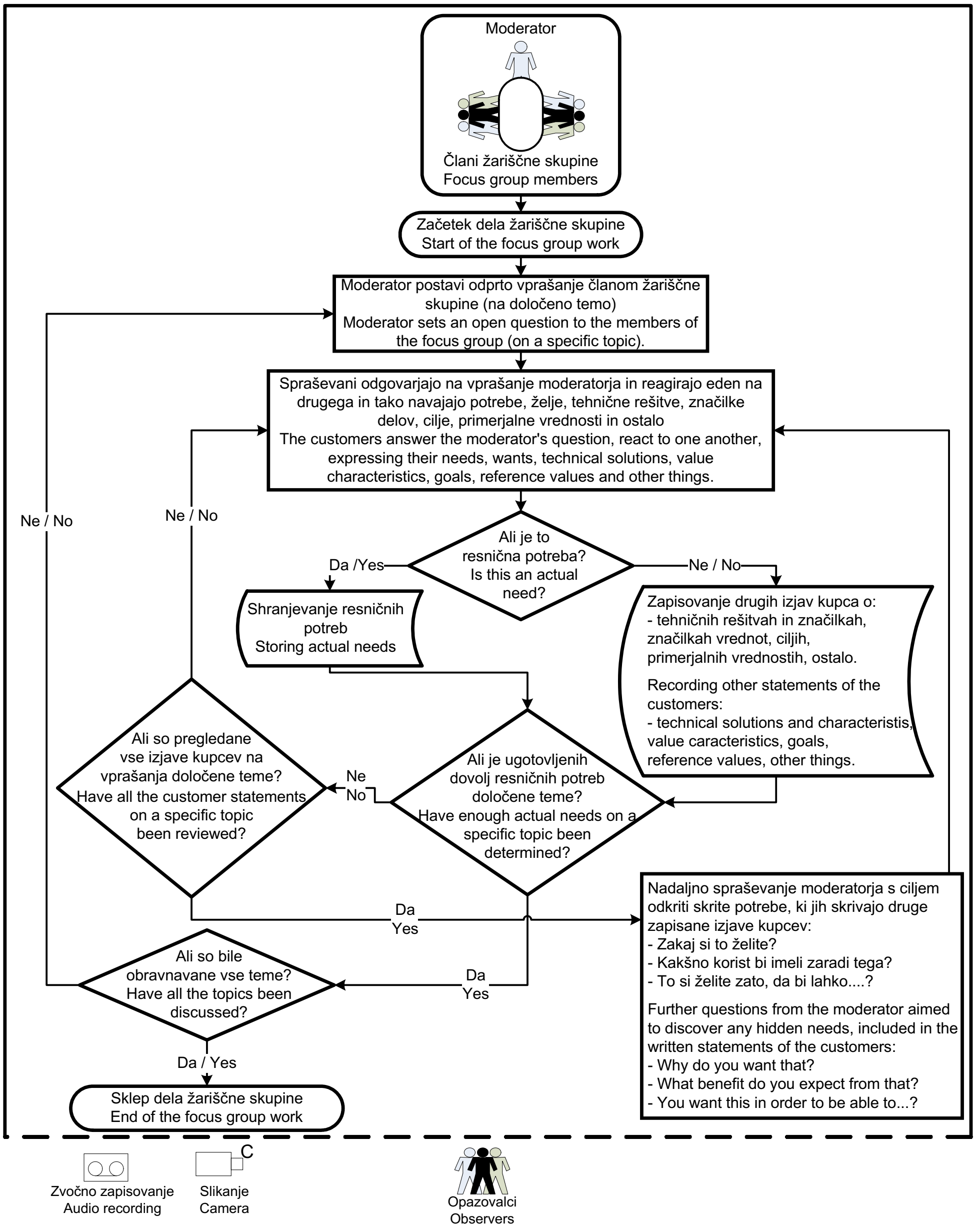
To be able to provide a productive discussion on a particular subject, discussion members with similar interests and knowledge must be selected. Experience shows that care must be taken that the members are neither in a superior nor in a subordinate relationship with each other.

Normally, there are several focus groups formed in the research project (external and internal customers are grouped by different segments) with the goal of gathering different opinions on a problem.

The focus-group discussion is carried out in three phases:

- phase 1: introduction,
- phase 2: discussion,
- phase 3: conclusion.

The focus-group work is directed by a moderator. He or she starts with an introduction by



Sl. 7. *Pridobivanje podatkov o potrebah kupcev z metodo žariščne skupine*
Fig. 7. *Obtaining the data on customer needs using the focus-group method*

predstavi in razloži namen žariščne skupine in vzrok za vabilo članom. Sledi seznanitev članov z osnovnimi pravili, nato pojasnitev namena zapisovanja in snemanja razgovorov ter zagotovitev zasebnosti sodelujočih.

Ko se člani tima predstavijo, moderator začne voditi razpravo tako, da uporablja osnutek vprašanj, namenjenih raziskavi različnih pogledov na obravnavano temo. Moderatorjevo osnovno delo je, da obdrži skupino osredotočeno. Po obravnavi

presenting the focus group, its purpose and the reason why the members have been invited. Then the members are acquainted with the basic rules and explained the purpose of recording the discussion, and the discretion of the participating members is ensured.

Then the members participating in the discussion are introduced and the moderator starts the discussion by asking the initial questions in order to gather different views relating to the topic of the discussion. The moderator's basic task is to keep the discussion group določenega vprašanja lahko moderator raziskuje naprej, da bi dobil več informacij in postavlja izzivalna vprašanja, da izvabi več razprave.

Običajno se zahteva, da je moderator izvedenec na področju, ki ga skupina obravnava, in da pozna cilje študije. Njegov cilj je pomagati skupini, da ustvarjalno razpravlja o temi. Kakovost podatkov v žariščnih skupinah je močno odvisna od tega, kako učinkovito moderator postavlja vprašanja in kako dobro vzdržuje razpravo, osredotočeno na predmetu raziskave. Moderator mora delovati kot pospeševalec, nadzirati mora sodelovanje med njim in člani skupine, kakor tudi med samimi člani skupine. Nekaj članov žariščne skupine je običajno bolj zgovornih, preostali pa so bolj zadržani, zato mora moderator najti način, da utiša preveč zgovorne, da lahko tihi spregovorijo. Ko so vprašanja izčrpana, moderator konča delo skupine.

Razprava žariščnih skupin se običajno izvede v posebni sobi, po možnosti je ta soba urejena tako, da ima na eni strani posebno steno, skozi katero se vidi v sobo, iz nje pa ne. Za to steno so slikovne in zvočne snemalne naprave ter ljudje, ki opazujejo intervju, vendar nanj nimajo vpliva.

2.1.2 Intervju

Intervju je metoda za pridobivanje kakovostnih informacij, pri katerih obstaja dialog med spraševalcem in vprašanim. Omogoča pridobivanje podrobnih informacij o potrebah kupcev in razpoznavo kakršnihkoli inovativnih rešitev. Kakovost intervjuja se meri s številom zapisanih potreb.

Odvisno od področja in obsega projekta je treba izbrati kupce, ki bodo intervjuvani, določiti, kje bodo intervjuji potekali, kdo jih bo vodil in kakšne vrste vprašanja bodo postavljena.

Intervju v konferenčni sobi

Najbolj običajna oblika intervjuja za pridobivanje potreb kupcev je intervju v konferenčni sobi (slika 8). Pri intervjuju v konferenčni sobi se je treba zanesti na zmožnost odgovarjajočega, da prikliče v spomin stvari, ki so mu bile ali mu niso bile všeč pri izdelku in da poskuša navesti tiste stvari, ki jih je pogrešal.

Spraševalec mora imeti nekakšen vodnik intervjuja, ki deluje kot opomnik, katere teme spraševati med intervjujem.

focused. After a question has been generally discussed, the moderator can search further to get more information by using additional teaser questions.

Normally, it is necessary that the moderator is an expert in the field discussed by the group and is acquainted with the subject of the study. It is his or her goal to help the group create a productive discussion on the specified topic. The quality of the data in the focus group mostly depends on how efficiently the moderator is asking questions and focusing the entire group on the topic. The moderator must work as a promoter, controlling the interaction between himself/herself and the members as well as between the members themselves. Some members of the focus group are usually more eloquent, while others are more reserved, so the moderator has to find a way to silence the too eloquent people in order to make the quiet ones start speaking as well. When all the issues have been discussed, the moderator concludes the work of the focus group.

The focus group discussion is normally carried out in a special room. The room can have a special one-way see-through wall, behind which there can be video- and audio-recording equipment, as well as additional observers.

2.1.2 Interview

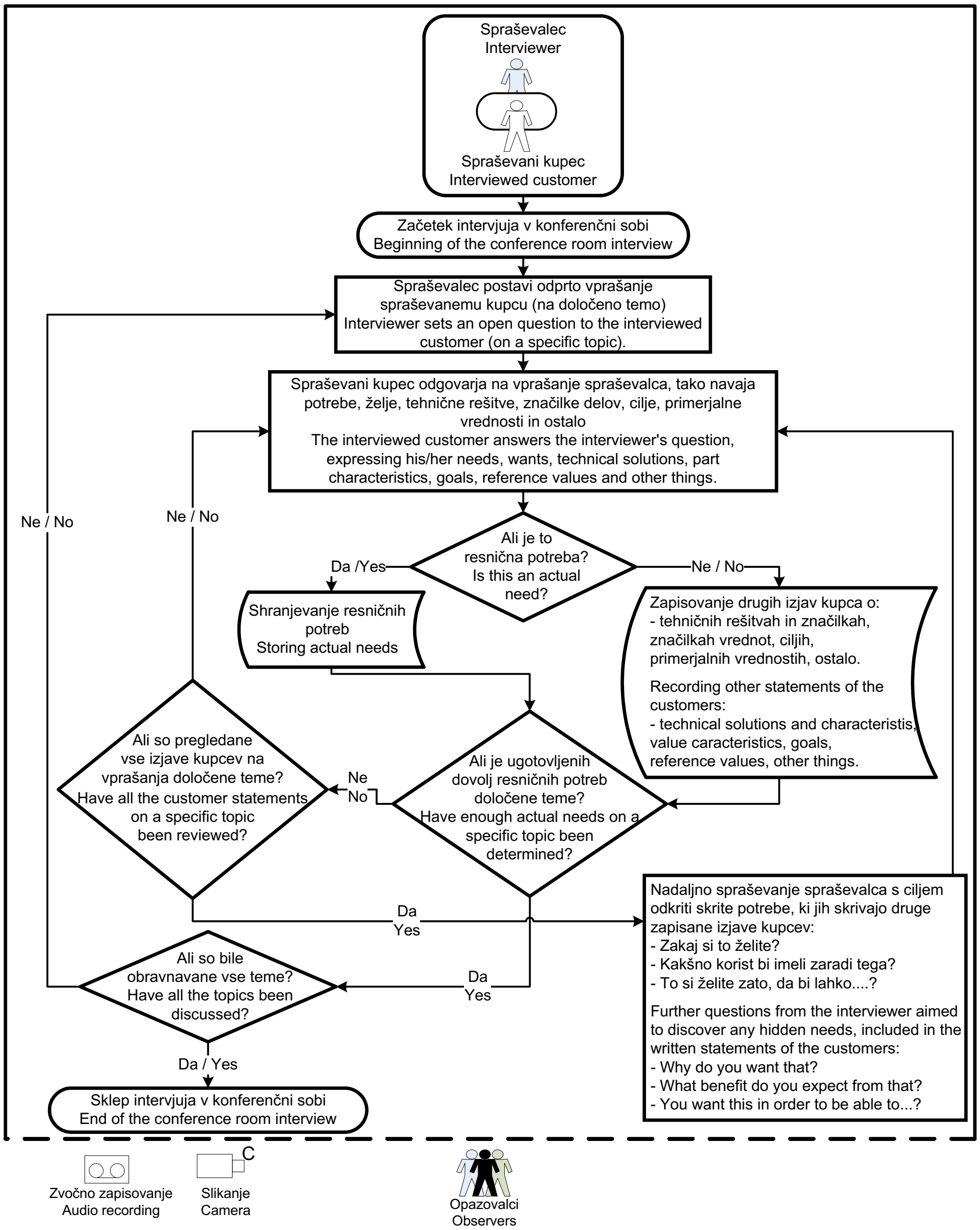
The interview is a method of gathering qualitative information through a dialog between the interviewer and the interviewee. It enables them to gather detailed information on customer needs and identify innovative solutions. The quality of the interview is measured by the number of recorded needs.

Depending on the area and the size of the project, the following must be selected: the customers to be interviewed, the locations where the interviews are to be carried out, the interviewers, and the type of questions asked.

Conference-room interview

The most common form of interview for obtaining customer needs is a conference-room interview (Figure 8). During a conference-room interview it is necessary to rely upon the ability of the interviewee to recall the things he or she liked or disliked about the product, and that he or she will try to mention the things he or she missed.

The interviewer has to have some sort of interview guide that serves as a checklist for the subjects to be asked about during the interview.



Sl. 8. *Intervju v konferenčni sobi*
Fig. 8. *Conference-room interview*

Intervjuji v konferenčnih sobah omogočajo dobro vodenje intervjujev in zato učinkovito izrabo časa.

Povezano poizvedovanje

Povezano poizvedovanje se izvaja na mestu uporabe izdelka (sl. 9). Omogoča spraševanje med opazovanjem dejanske uporabe izdelka.

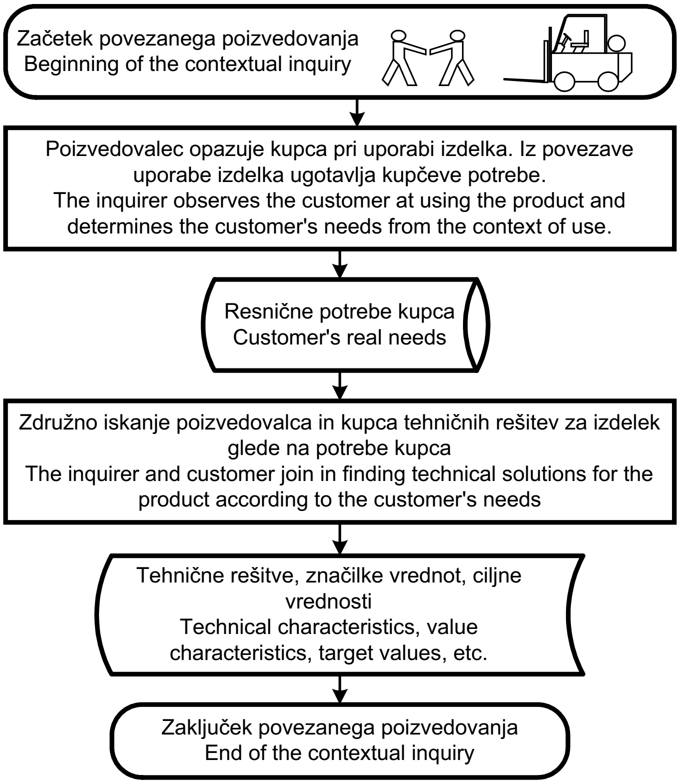
Povezano poizvedovanje se uporabi predvsem za boljše razumevanje okolja (vremenski

The conference-room interviews make possible good time-planning and the efficient use of time.

Contextual inquiry

A contextual inquiry is carried out at the location where the product is being used (Fig. 9). It allows the interview to be conducted during observation of the actual use of the product.

A contextual inquiry is used mostly for better understanding of the environment (weather, culture,



Sl. 9. *Povezano poizvedovanje*
Fig. 9. *Contextual inquiry*

vplivi, kultura okolja, vrednote), v katerem kupec uporablja izdelek. Povezano poizvedovanje pomeni partnerstvo kupca in spraševalca pri iskanju rešitev za ugotovljene potrebe kupca.

2.1.3 Pridobivanje potreb iz pritožb kupcev

Potrebe kupcev, ki se pridobijo iz baze podatkov o pritožbah kupcev so kakovostne informacije, ki se zaradi narave pridobivanja ne morejo posploševati na večjo populacijo. Pogosto se zgodi, da so ljudje, ki se pritožujejo, taki, da se pritožujejo iz navade, ali taki, ki so imeli posebej slabo izkušnjo, predvsem pa tisti, ki imajo čas, da se pritožujejo. Pritožbe kupcev pokažejo informacijo o vzrokih za nezadovoljstvo. Potrebe iz pritožb kupcev se uporabijo kot dopolnilo k potrebam kupcev, ki se pridobijo z intervjuji oz. žariščnimi skupinami.

Postopek ustvarjanja potreb kupcev iz pritožb kupcev obsega naslednje korake:
1. korak: Naključna izbira dogovorjenega števila pritožb iz baze podatkov.
2. korak: Pritožbe je treba prevesti v pozitivne izraze in osnutke, ki pomenijo skrite potrebe kupcev,

values) where the customer uses the product. A contextual inquiry is a partnership between the customer and the inquirer during their search for a solution to the identified customer needs.

2.1.3 Obtaining the needs from customer complaints

Customer requirements, obtained from the customer-complaint database are qualitative data that cannot be generalized to a wider population because of the way they were obtained. It often happens that certain people complain out of a habit, or those who have had an especially bad experience, and particularly those who have time to complain. Customer complaints reveal the causes of dissatisfaction. The needs obtained from customer complaints can be used in addition to the customer needs obtained by interviews and focus groups.

The procedure for obtaining the customer needs from customer complaints consists of the following steps:
Step 1: Random retrieval of a certain number of complaints from the database,
Step 2: Translation of the complaints into positive expressions and concepts, which represent the hidden

izražene s pritožbo.
3. korak: Prečistiti izraze potreb kupcev z odstranitvijo ponovitev.
4. korak: Označiti vsak izraz, dobljen iz pritožb kupcev.
5. korak: Spojiti izraze pritožb kupcev z izrazi, pridobljenimi z drugimi metodami.

2.1.4. Metoda soočanja idej pridobivanja podatkov o potrebah notranjih kupcev

Metoda soočanja idej je najbolj znana in najpogosteje uporabljena metoda ustvarjalnega pridobivanja podatkov o potrebah kupcev. Pri uporabi te metode je treba upoštevati štiri osnovna pravila:
1. pravilo: Vsaka kritika ali vrednotenje zamisli je strogo prepovedana, saj zavira ustvarjalno mišljenje.
2. pravilo: Zamisli drugih članov skupine so lahko prevzete in nadalje razvite.
3. pravilo: Člani skupine naj čim bolj prožijo svojo fantazijo pri reševanju problema.
4. pravilo: V kratkem času naj bo predlaganih čim več zamisli rešitve problema.

2.2 Postopek sestavljanja podatkov o potrebah kupcev

Sestavljanje podatkov o potrebah kupcev naj se izvede v naslednjem zaporedju korakov:

needs of the customers, expressed by the complaint,
Step 3: Removal of duplicates,
Step 4: Marking of each expression obtained from customer complaints,
Step 5: Combining customer complaints with the expressions obtained by other methods.

2.1.4 The brainstorming method for obtaining data on internal customer needs

The brainstorming method is the most popular and the most widely used creative method for obtaining data on customer needs. When using this method, four basic rules should be taken into account:
Rule 1: Any criticism or evaluation of ideas is strictly forbidden because it obstructs creative thinking.
Rule 2: The ideas of other team members can be used and developed further.
Rule 3: Team members should activate their imagination as much as possible during problem solving.
Rule 4: As many ideas as possible should be proposed in the shortest possible time.

2.2 Methods for structuring the data on customer needs

Structuring of the data on customer needs is carried out in the following sequence:

Tabela podatkov o izdelkih in postopkih / Table of products and processes data

ID Št./ ID No.	E/I	Demografija kupcev/ Customer demographics	Izjava kupca/ Customer statement	Uporaba / Usage						Analizirana izjava/ Analyzed statement	Potreba/ Značilka Need/ Characteristic	Vrsta potrebe/ značilke Type of need/ characteristic
				Kdo/ Who	Kaj/ What	Kdaj/ When	Kje/ Where	Zakaj/ Why	Kako/ How			

Tabela glasu notranjih kupcev / Table for the voice of the internal customers

ID Št./ ID No.	Demografija kupcev/ Customer demographics	Izjava kupca/ Customer statement	Uporaba / Usage						Analizirana izjava/ Analyzed statement	Potreba/ Značilka Need/ Characteristic	Vrsta potrebe/ značilke Type of need/ characteristic
			Kdo/ Who	Kaj/ What	Kdaj/ When	Kje/ Where	Zakaj/ Why	Kako/ How			

Tabela glasu zunanjih kupcev / Table for the voice of the external customers

ID Št./ ID No.	Demografija kupcev/ Customer demographics	Izjava kupca/ Customer statement	Uporaba / Usage						Analizirana izjava/ Analyzed statement	Potreba/ Značilka Need/ Characteristic	Vrsta potrebe/ značilke Type of need/ characteristic
			Kdo/ Who	Kaj/ What	Kdaj/ When	Kje/ Where	Zakaj/ Why	Kako/ How			

Sl. 10. *Izhodiščne preglednice glasu kupcev*
Fig. 10. *Initial tables for the voice of the customers*

1. korak: Oblikovanje izhodiščnih preglednic glasu kupcev,
2. korak: Oblikovanje sorodnostnega diagrama,
3. korak: Oblikovanje drevesnega diagrama.

1. korak: Oblikovanje izhodiščnih preglednic glasu kupcev

Z metodami za zbiranje podatkov se pridobijo najrazličnejše izjave kupcev, ki govorijo o njihovih problemih, priložnostih, zamislih, rešitvah, željah in potrebah.

Ločevanje resničnih potreb kupcev je prvi pogoj za sestavljanje potreb in ovrednotenje relativne pomembnosti potreb, ki naj se upoštevajo pri načrtovanju izdelka. Pri tem si tisti, ki analizirajo kakovostne podatke pomagajo z izhodiščnimi preglednicami glasu kupcev, v katere se vpišejo dobesedne izjave kupcev. Slika 10 prikazuje vsebino izhodiščnih preglednic glasu kupcev.

Stolpec z "razpoznavno številko" razpozna vir izjave kupca, npr. številka intervjuja, številka strani, številka vrstice ali datum intervjuja. Njegov namen je, da preskrbi povezavo nazaj do vira izjave za primer, ko želimo izvedeti nadaljnje informacije o izjavi.

Stolpec, ki obravnava "demografijo kupcev", vsebuje informacije, to so starost, prihodki, poklic ali lokacija osebe, ki je preskrbela podatke.

Razdelek "uporaba" vsebuje informacije, ki opisujejo povezavo uporabe izdelka.

V stolpcu "analizirana izjava" se označi, ali gre za resnične potrebe kupcev, in/ali pa za možne tehnične rešitve in cilje.

2. korak: Oblikovanje sorodnostnega diagrama

V izhodiščnih preglednicah glasu kupcev zbrane potrebe se nadalje razvrstijo z uporabo sorodnostnega diagrama, to je orodja za hierarhično organizacijo kakovostnih informacij. Slika 11

Step 1: Design of initial tables for the voices of the customers
Step 2: Design of the affinity diagram,
Step 3: Design of the tree diagram.

Step 1: Design of initial tables for the voices of the customers

Using data-acquisition methods various statements of the customers are obtained, related to their problems, opportunities, ideas, solutions, wishes and needs.

The separation of real customer needs from other expressions is a precondition for structuring the needs and evaluating the relative relevance of needs that are taken into account when planning the product. Those who analyze the quantitative data use the initial tables of the voice of the customers, which are filled out with literal customer statements. Figure 10 presents the contents of the initial voice-of-the-customer tables.

The "ID" column identifies the source of the customer statement, e.g., interview number, page number, number of the line or the date of the interview. It is used for back-referencing the statements in case further information is required about the source.

The "Customer demographics" column contains the age, income, occupation and location of the customer.

The "Use" section describes the context of use of the product in detail.

The "Analyzed statement" marks whether the statement is a real customer need and/or a possible technical solution or goal.

Step 2: Design of the affinity diagram

The needs, collected in the initial tables of the voice of the customers are further classified using the affinity diagram – this is a tool for the hierarchical organization of qualitative information.

Sl. 11. *Načelo gradnje sorodnostnega diagrama za vrednoto "kakovost izdelka"*
Fig. 11. *Principle of building the affinity diagram for the value of the quality*

prikazuje načelo oblikovanja sorodnostnega diagrama načrtovanja izdelka. Hierarhija se začne sestavljati od spodaj navzgor.

V vrednoti "kakovost izdelka" so vse potrebe, ki so jih izrazili zunanji kupci, to so predvsem potrebe, ki se nanašajo na varnost, delovanje in videz izdelka.

3. korak: Oblikovanje drevesnega diagrama

Drevesni diagram tako kakor sorodnostni diagram sestavlja potrebe hierarhično. V nasprotju s sorodnostnim diagramom je drevesni diagram grajen od zgoraj navzdol oz. z leve v desno. V drevesnemu diagramu so prikazane osnovne, drugotne in ostale potrebe kupcev. Terciarne potrebe predstavljajo vhod v "hišo kakovosti" načrtovanega izdelka. Slika 12 prikazuje načelo gradnje drevesnega diagrama za vrednoto "kakovost izdelka".

3 VREDNOTENJE PODATKOV O POTREBAH KUPCEV

Na podlagi podatkov o potrebah kupcev, sestavljenih v sorodnostnem oz. drevesnem diagramu, je treba izvesti še vrednotenje potreb, torej določiti pomembnost posameznih potreb kupcev.

Analiza in ocena razpoložljivih metod vrednotenja podatkov o potrebah kupcev ([5] in [13]) je pokazala, da je za vrednotenje podatkov najprimernejše "orodje" anketa, in to telefonska ali poštna.

Figure 11 presents the principle of affinity-diagram development for planning the product. The hierarchy is being built bottom-up.

"Quality of the product" contains all of the needs expressed by external customers, especially the needs related to the safety, functionality and aesthetics of the product.

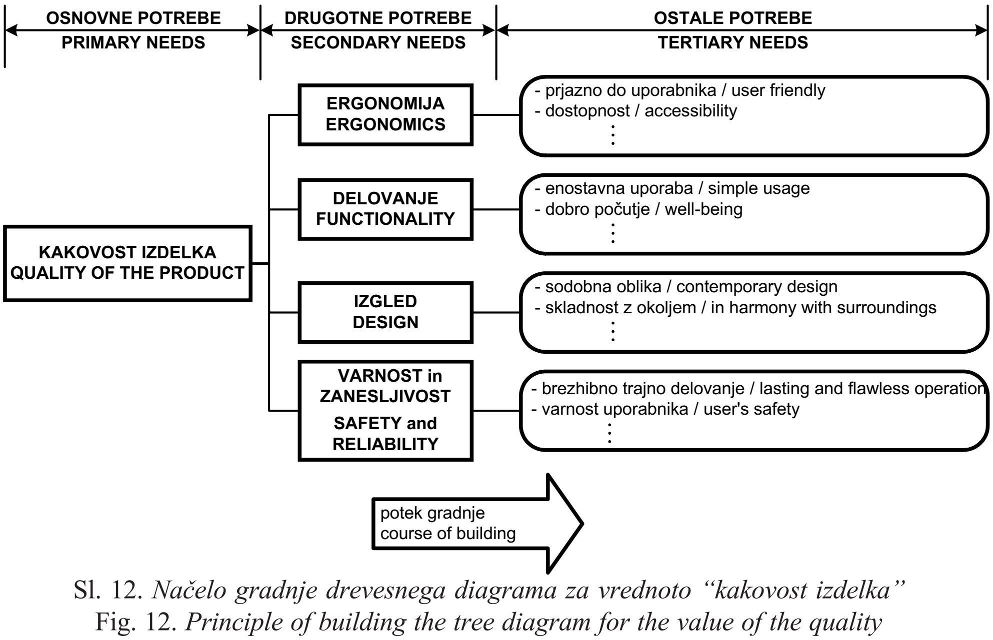
Step 3: Design of the tree diagram

In the tree diagram the needs are also structured in a hierarchical way. In contrast to the affinity diagram, the tree diagram is built from the top to the bottom (or from the left to the right). In the tree diagram the primary, secondary and tertiary customer needs are shown. Tertiary needs represent the entrance into the house of quality of the planned product. Figure 12 presents the principle of building the tree diagram for the value of the quality.

3 EVALUATION OF THE DATA ON CUSTOMER NEEDS

On the basis of the data on customer needs, stored in the affinity and tree diagrams, it is necessary to evaluate the needs, and therefore to define the relevance of each customer need.

The analysis and appraisal of the available methods for evaluating the data on customer needs ([5] and [13]) has revealed that in order to evaluate the data on customer needs the most suitable tool is a survey (conducted either by phone or mail).



Sl. 12. *Načelo gradnje drevesnega diagrama za vrednoto "kakovost izdelka"*
Fig. 12. *Principle of building the tree diagram for the value of the quality*

V anketi je treba vzorec izbrati naključno, tako da ima vsaka oseba v populaciji merljivo verjetnost izbire, s tem se rezultati ankete zanesljivo preslikajo iz vzorca na večjo populacijo. Anketa se lahko izvede v državi, regiji ali občini.

Telefonske ankete so drage, običajni vir za vzorčenje pa so telefonski imeniki.

Poštne ankete terjajo manjše stroške, so pa zelo učinkovite takrat, ko so naslovljene na uporabnike določene skupine izdelkov in preskrbijo merljive podatke, ki se lahko posplošijo na celotno populacijo. Naslovno pismo poštne ankete mora razložiti vzroke za anketo in izraziti zagotovila o zaupnosti.

Da zagotovimo veliko odgovorov, priporočamo pri poštni anketi priporoča upoštevanje naslednjih pravil:

1. pravilo: Večkratni stiki, ki obsegajo:
   - o pošiljanje predhodnega poštnega naznanila o anketi,
   - o pošiljanje ankete vsem odgovarjajočim ob istem času s spremnim besedilom,
   - o pošiljanje opomnika z informacijo, da lahko spraševani zahtevajo nadomestni vprašalnik,
   - o pošiljanje zadnjega nadomestnega vprašalnika s priporočeno pošto,
   - o pošiljanje potrdila ali priznanja za sodelovanje v anketi,

2. pravilo: Uporabiti natiskani papir in predstavniška pisma z logotipom in stično osebo,

3. pravilo: Vključitev ovojnice z znamko in naslovom za vrnitev ankete,

4. pravilo: Vključitev simboličnega darila s prvotnim ali naslednjim vprašalnikom kot spodbudo in znak spoštovanja.

Pri izvedbi ankete kupce zaprosimo, da posamezno potrebo ustrezno ovrednotijo. Za vrednotenje potreb kupcev je na voljo več metod ([14] in [15]), katerih značilnosti, prednosti in pomanjkljivosti so prikazane v preglednici 1.

Po opisani metodi pridobljene, sestavljene in vrednotene potrebe kupcev izdelka pomenijo vhodni podatek 1. hiše postopka razvoja izdelka z načinom RFK. Slika 13 prikazuje posplošeni model ugotavljanja in vrednotenja potreb kupcev.

4 PRIMER

Podjetje, ki izdeluje zdravstveno opremo, želi izboljšati konkurenčno zmožnost na domačem trgu in razširiti svojo ponudbo tudi na svetovni trg.

The sample for the survey should be selected randomly, so that each person in the population has a measurable probability of being selected and thus the survey results can be reliably extended to a larger population. The survey can be conducted in the state, region or municipality.

Phone surveys are expensive and the usual source for sampling is phone directories.

Mail surveys cost less; they are very effective when they are targeted to the users of a particular group of products and they provide measurable data that can be generalized to the whole population. The letter accompanying the mail survey should explain the reasons for the survey and give an assurance of confidentiality.

To ensure a high response rate, the following rules should be followed when conducting mail surveys:

Rule no. 1: Multiple contacts should be used, including:
- sending an announcement of the survey by mail,
- sending the survey with a cover letter to all interviewees at the same time,
- sending a reminder with contact details, enabling the interviewees to request a substitute survey,
- sending the last substitute survey with registered mail,
- sending a letter or certificate as a symbol of appreciation for the cooperation.

Rule no. 2: Use printed paper and memos with letter-heads and contact person details.

Rule no. 3: Use stamped envelopes with printed return addresses.

Rule no. 4: Enclose a symbolic gift with the first or subsequent surveys to recognize the efforts of the interviewees and to thank them,

When conducting a survey, the customers are requested to evaluate each individual need. There are several methods available to evaluate the customer needs ([14] and [15]). Their characteristics, advantages and drawbacks are presented in Table 1.

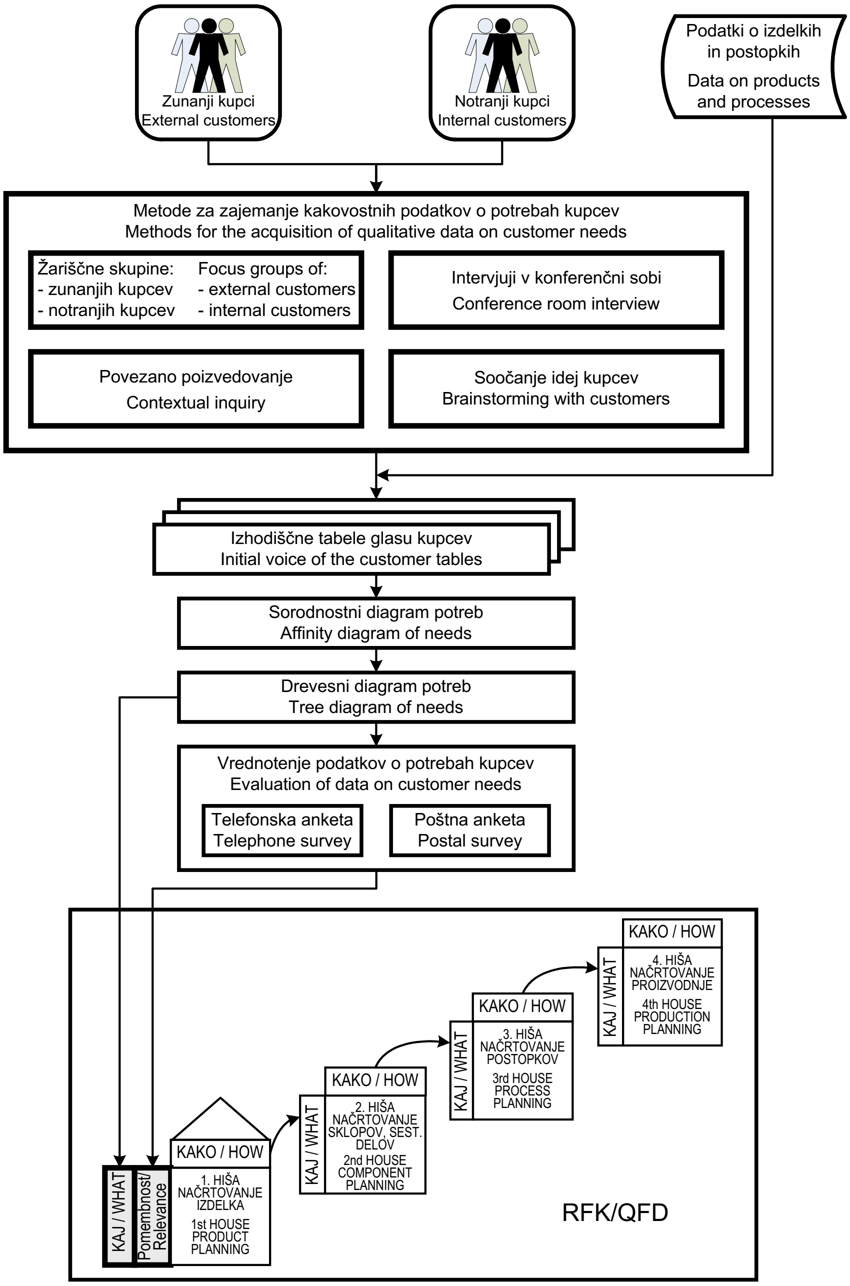
With the described methods obtained, structured and evaluated customer needs represent the input data for the 1st QFD house of new-product development. Figure 13 shows a general model for obtaining and evaluating customer needs.

4 CASE STUDY

A company that produces medical equipment wishes to improve its competitiveness on the domestic market and to offer its products to the global market.

Preglednica 1. *Metode vrednotenja podatkov o potrebah kupcev*
Table 1. *Methods for evaluating the data on customer needs*

METODA VREDNOTENJA / EVALUATION METHOD	OPIS METODE / DESCRIPTION OF THE METHOD	PREDNOSTI METODE / ADVANTAGES OF THE METHOD	SLABOSTI METODE / DISADVANTAGES OF THE METHOD
Neposredna ocenitev potreb kupcev / Direct evaluation of customer needs	Kupce se prosi, da ovrednotijo pomembnost vsake potrebe z lestvico, ki jo navaja anketa. Najbolj pomembne potrebe naj bi bile ocenjene z visokimi števili, medtem, ko naj bi bile potrebe z majhno pomembnostjo ocenjene z nizkimi števili. / The customers are asked to evaluate the relevance of every need on a scale, given by the survey. The most important needs should be marked with high scores while the less important needs should get lower scores.	Metoda je za kupce lahko razumljiva. / The method is easily comprehensible to the customers.	Kupci težijo k temu, da ocenijo vse potrebe kot zelo pomembne. To naredijo predvsem zato, ker jim ni potrebno primerjati potreb med seboj. / The customers tend to mark all needs as very important because they do not have to compare the needs with each other
Razvrstitev potreb kupcev po pomembnosti / Sorting customer needs by relevance	Kupce se naprosi, da razvrstijo potrebe iz seznama od najbolj pomembne do najmanj pomembne. / The customers are requested to sort the needs on the list from the most important need to the least important one.	Metoda je za kupce lahko razumljiva. Kupci morajo narediti tudi nekaj primerjalnih odločitev. / The method is easily comprehensible to the customers. They must also make some comparative decisions.	Metoda je težka za izvedbo, kadar je potrebno razvrstiti več kot deset potreb. / This method is difficult to carry out when more than ten needs have to be evaluated.
Kombinirana metoda razvrstitve pomembnosti in dodeljevanja točk potrebam kupcev / Combined method of sorting by relevance and assigning points to the needs	Pri tej metodi kupci potrebe najprej razvrstijo po padajočem vrstnem redu pomembnosti, nato tem potrebam dodajo števila s 100 številčne lestvice. Najvišje število dajo najpomembnejši potrebi in najmanjše število najmanj pomembni potrebi. / In this method the customers first sort the needs by relevance in descending order. Then they assign numbers from a 100 point scale to the needs, giving the highest number to the most important need and the smallest number to the least important need.	Metoda je lahko razumljiva. Kupci naredijo primerjalne odločitve že pri določanju vrstnega reda potreb, zato lažje dodajo različne vrednosti potrebam s 100 številčne lestvice./ The method is easily comprehensible to the customers. The customers already make comparative decisions when selecting the order of needs and can easily assign values from the 100 point scale to different needs.	Metoda je težka za izvedbo, kadar je potrebno razvrstiti več kot deset potreb. / This method is difficult to carry out when more than ten needs have to be evaluated.
Dodeljevanje 100 točk med vse potrebe kupcev / Assigning 100 points among all customer needs	Pri tej metodi je potrebno razdeliti 100 točk med potrebe kupcev iz seznama. / In this method, 100 points are distributed to the customer needs on the list.	Kupci morajo pri razdeljevanju točk sprejemati primerjalne odločitve in relativno primerjati potrebe med seboj. / The customers must make comparative decisions when assigning points and compare the needs relatively.	Ker se od odgovarjajočih zahteva velika pozornost, odgovarjajoči porabijo veliko časa za razdeljevanje točk med potrebe, posebej, če je teh potreb 10 ali več As the attention required from the interviewees is very high, a lot of time is necessary to assign the points to the needs, especially if there are more than ten needs.
Priorizacijski model 1-2-3 / Prioritization model 1-2-3	Priorizacijski model 1-2-3 je metoda, kjer kupci najprej določijo za njih najpomembnejšo potrebo, kasneje določijo druga mesta potrebam, za katere menijo, da so po pomembnosti za najpomembnejšo potrebo. Ostalim potrebam pripišejo tretja mesta. Analitiki kasneje pripišejo najpomembnejši potrebi za posameznega kupca 5 točk, potrebam, uvrščenim na drugo mesto, 3 točke in tretje uvrščenim potrebam 1 točko. Vsote točk za vsako potrebo so osnova za določanje relativne pomembnosti potreb. / The prioritization model 1-2-3 is a method where customers first determine the needs they find most important. Then they select the second most important needs. The remaining needs are considered as the third most important. The analysts assign 5 points to the most important need of the customer, 3 points to the second most important needs and 1 point to the third most important needs. The sum of points for each need is the basis for determining the relative relevance of the needs.	Metoda je lahka za razumevanje in hitra za izpolnjevanje. / The method is easy to comprehend and quick to fill in.	Kadar je potrebno obravnavati večje število potreb je metoda zamudna. / The method is slow when a large number of needs have to be dealt with.
Metoda primerjave parov potreb kupcev / Couple comparison method	Pri metodi primerjave parov se primerjata po dve potrebi, glede na direktno primerjavo se da prednost eni od obeh potreb. Potreba, ki je imela največkrat prednost glede na ostale potrebe, je po rangu najvišje, to pomeni, da je najpomembnejša. Potrebe se uredijo v obliki matrike, ugotovitve primerjave parov pa se vnašajo v odgovarjajoča polja matrike. / In the couple comparison method, two needs are directly compared in order to determine the more important one. The need which was selected in favor of others most of the times, is ranked the highest, i.e., the most important need. The needs are sorted in matrix form and the results of comparisons are entered in the appropriate fields of the matrix.	Možnost pridobitve relativnih pomembnosti potreb. / The possibility to acquire relative relevance of needs.	Možnost nedoslednih sodb. Kadar je potrebno obravnavati večje število potreb je metoda zamudna. / The possibility of inconsistent judgments. Time-consuming when a lot of needs have to be evaluated.
Analitični hierarhični pristop / Analytical hierarchic approach	Analitični hierarhični pristop uporablja primerjavo parov potreb samo med sorodnimi potrebami v drevesu in tako ustvarja lestvico razmerij pomembnosti. Najprej se ugotovijo pomembnosti potreb na višjih nivojih, nato pa pomembnosti potreb po posameznih skupinah na nižjih nivojih. Pare primerjamo z ocenami od 1 do 9. / The analytical hierarchic approach uses the couple comparison of needs only among related needs in the tree, creating a scale of relevance relations. Firstly, the relevance of needs on higher levels is determined, followed by the relevance of needs by individual groups on lower levels. The couples are compared by using marks from 1 to 9.	Možnost pridobitve relativnih pomembnosti potreb. Najbolj natančna metoda. / The possibility to acquire relative relevance of needs. The most accurate method.	Kadar je potrebno obravnavati večje število potreb je metoda zamudna. / The method is slow when a large number of needs must be dealt with.



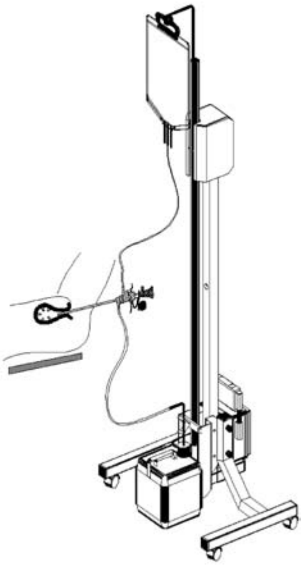
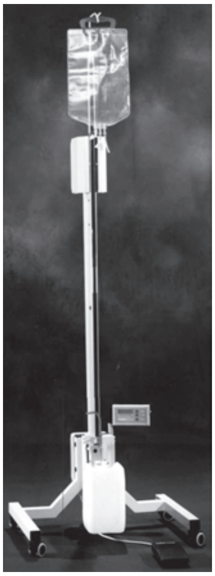
Sl. 13. *Posplošeni model ugotavljanja in vrednotenja potreb kupcev*
Fig. 13. A *general model for obtaining and evaluating customer needs*

Vodstvo podjetja se je odločilo, da za izdelek Vario Flow (sl. 14), ki se uporablja v zdravstvu kot pripomoček pri posegih, ugotovi potrebe kupcev in kasneje z uporabo metodologije RFK te potrebe v kar največji meri upošteva pri sprejemanju nove različice izdelka ([16] in [17]).

V nadaljevanju je prikazan postopek pridobivanja, sestavljanja in vrednotenja potreb

The company management has decided that it will establish the customer needs for the Vario Flow product (Fig. 14 – it is used in medicine as an aid in surgery), and later on, using the QFD methodology, consider these needs in the development of a new version of the product ([16] and [17]).

In the text that follows, the procedure for obtaining, structuring and evaluating the needs of

Sl. 14. *Vario Flow*
Fig. 14. *Vario Flow*

kupcev izdelka Vario Flow ter oblikovanja vhodnega vektorja KAJ hiše razvoja funkcij kakovosti izdelka.

Za izvedbo naloge je vodstvo podjetja izbralo projektni način in imenovalo projektni tim v sestavi:

- Moderator: Inženir načrtovanja kakovosti, ker dobro pozna metodologijo RFK in izdelek Vario Flow,
- Člani tima:
  - o razvojni inženir, ker pozna konstrukcijske zahteve izdelka,
  - o zdravnik, ker uporablja izdelek pri posegih,
  - o oblikovalec, ker je odgovoren za obliko izdelka,
  - o član vodstva, ker je odgovoren za povezovanje projektne skupine z vodstvom podjetja in pozna kupce,
  - o inženir načrtovalec proizvodnih postopkov, ker pozna tehnološke postopke izdelave izdelka,
  - o proizvodni inženir, ker pozna možnosti in omejitve izdelave v podjetju.

Vario Flow customers and the establishment of the input WHAT vector for the house of QFD of the product is presented.

In order to accomplish the task, the company management selected the project approach and appointed a project team consisting of:

- Moderator: quality-planning engineer – because he knows well the QFD methodology and the Vario Flow product,
- Team members:
  - o development engineer – because he knows the design requirements of the product,
  - o physician – because he uses the product in surgical procedures,
  - o designer – because he is responsible for the design of the product,
  - o managing board member – because he is responsible for connecting the project team with the company management and he knows the customers,
  - o production process planning engineer – because he knows the production processes,
  - o production engineer – because he knows the possibilities and limitations of manufacturing in the company.

4.1 Viri glasu kupcev za izdelek Vario Flow

Projektna skupina je ugotovila, da so za izdelek Vario Flow na voljo naslednji viri glasu kupcev:

4.1 Sources of the customers' voice for the Vario Flow product

The project team established that the following sources for the customers' voice for the Vario Flow product are available:

- Zunanji kupci (zdravniki, ki opravljajo endoskopske posege; inštrumentarke, ki sodelujejo pri posegih, ter zastopniki vodstva podjetja).
- Notranji kupci (inženirji, odgovorni za razvoj izdelka, postopkov, kakovosti; dobavitelji sestavnih delov in materialov; vzdrževalci, ki skrbijo za nemoteno delovanje izdelka).
- Podatki o izdelkih in postopkih (podatki o opravljenih vzdrževalnih posegih, pripombah in pritožbah kupcev).

4.2 Pridobivanje podatkov o potrebah kupcev izdelka Vario Flow

Za pridobitev podatkov o potrebah kupcev je projektna skupina izbrala metodo intervjujev, in to v obliki:

- intervjujev v konferenčni sobi in
- povezanega poizvedovanja.

Za prvo obliko intervjujev se je projektna skupina odločila zaradi lažjega časovnega usklajevanja udeležencev intervjuja. Intervjuja se je udeležilo 10 oseb različnih profilov: zdravniki, inštrumentarke, inženirji, vzdrževalci, predstavniki vodstev podjetij. Udeleženci so vnaprej dobili okvirna vprašanja, da so se lahko ustrezno pripravili.

S pomočjo intervjuja je bilo zbranih 35 potreb kupcev, in sicer:

- posebne zahteve za laparaskopijo, artroskopijo...
- stabilnost sistema
- nadzor kakovosti
- majhni proizvodni stroški
- majhni garancijski stroški
- majhni stroški posegov
- zahteva za prave dobavitelje in kooperante
- oblika za dobro mobilnost sistema
- primernost videza za zdravstveno okolje
- neodvisnost od vira energije
- varnost za bolnika
- varnost naprave
- zanesljivo delovanje
- vzdržljivost naprave
- varnost delovanja
- varnost izdelka in odgovornost za posledice
- izboljšanje napak človeškega dejavnika
- varnost za uporabnika in odgovornost za posledice
- hiter prenos
- varen prenos
- preprosto vzdrževanje
- preprosta in hitra montaža/demontaža

- External customers (physicians who perform endoscopies, scrub nurses who participate in surgery and representatives of the company management).
- Internal customers (engineers responsible for the development of the product, the processes, the quality; the suppliers of components and materials; the maintenance crew that is responsible for normal operation of the product).
- Product and process data (data on performed maintenance works, customer remarks and complaints).

4.2 Obtaining the data on customer needs for the Vario Flow product

In order to obtain the data on customer needs the project team selected the following forms of interviews:

- conference-room interviews
- contextual inquiry.

The project team selected the first form of interview because of the easier time management of the interviewees. The interviewees were 10 people of various profiles: physicians, scrub nurses, engineers, maintenance personnel and company management representatives. The participants were given general questions in advance so that they could prepare properly.

35 customer needs were identified by the interview:

- Special requirements for laparoscopy, arthroscopy, etc.
- Stability of the system
- Quality control
- Low production costs
- Low warranty costs
- Low operating costs
- Requirement for suitable suppliers and cooperators
- Good system mobility design
- Aesthetical suitability for medical environment
- Independence of energy source
- Patient's safety
- Device's safety
- Reliable operation
- Durability of the device
- Safety of operation
- Safety of the product and responsibility for consequences
- Improvement of human-factor errors
- Safety for the user and responsibility for the consequences
- Fast transport
- Safe transport
- Simple maintenance
- Simple and quick assembly/disassembly

- lahka izvedljivost
- pravočasnost (JIT)
- prilagodljivost delovnega okolja
- metodologija načrtovanja
- avtomatizacija
- vrednostni sistem
- izboljšanje organizacije/vodenja
- izobraževanje in izpopolnjevanje zaposlenih
- delovna postaja
- informacijsko vodenje
- zahteve skupin
- integracija
- orodje za odzivnost

Povezano poizvedovanje je bilo namenjeno spoznavanju postopka uporabe izdelka v kirurški dvorani.

V razgovoru z uporabniki je bilo oblikovanih še nadaljnjih 14 potreb kupcev, in sicer:

- dobra vidljivost v polju posegov
- nastavitev tlaka kirurgu in/ali inštrumentarki
- dobra vidnost informacije o stanju tlaka v sistemu
- dobra vidnost informacije o stanju pomanjkanja v sistemu
- hitra menjava tekočine
- večja ločljivost prikazovalnika
- omogoča dostop v notranjost telesa
- zvezna nastavitev tlaka
- segrevanje vode
- po menjavi vode upoštevanje prejšnjega stanja tlaka
- prednastavljanje vrednosti tlaka
- nadzor količine vode v sistemu
- opozorila stanja zbiralnika
- opozorila o kritičnih stanjih sistema

Skupno je bilo torej oblikovanih 49 zahtev kupcev.

4.3 Sestavljanje podatkov o potrebah kupcev izdelka Vario Flow

Projektna skupina je izvedla sestavljanje podatkov o potrebah kupcev v treh korakih:

1. korak: Oblikovanje izhodiščnih preglednic glasu kupcev

Izhodiščne preglednice glasu kupcev izdelka Vario Flow (sl. 15) so bile oblikovane posebej za zunanje in notranje kupce ter glede na podatke o izdelkih in postopkih.

V preglednici zunanjih kupcev je navedenih 21 potreb, v preglednici notranjih kupcev 26 in v preglednici podatkov o izdelkih in postopkih dve

- Simple manufacturability
- JIT (just in time)
- Flexibility of the operating environment
- Planning methodology
- Automation
- Value system
- Improvement of organization/management
- Training of employees
- Workstation
- IT management
- Requirements of teams
- Integration
- Tool for response

The purpose of the contextual inquiry was to get acquainted with the use of the product in the operating theater.

Another 14 customer needs were identified during the discussions with users:

- Good visibility in the surgical field
- Operator and/or scrub nurse can set the pressure
- System pressure is clearly visible
- System deficit is clearly visible
- Quick exchange of fluid
- Higher display resolution
- Interior of the body should be accessible
- Continuous set of pressure
- Heating of water
- Following water change, the previous pressure is taken into account
- Pressure can be pre-set
- Control of amount of water in the system
- Battery status warnings
- Critical system state warnings

Altogether there were 49 customer requirements formed.

4.3 Structuring the data on customer needs for the Vario Flow product

The project team carried out the structuring of data on customer needs in three steps:

Step 1: Forming the initial tables of the voice of the customers

Initial tables of the voice of the customers of the Vario Flow product (Figure 15) were formed especially for external and internal customers and according to the data on products and processes.

The table of external customers contains 21 needs, the table of internal customers contains 26 needs, and the table on the product and process

PREGLEDNICA GLASU ZUNANJIH KUPCEV / TABLE FOR THE VOICE OF THE EXTERNAL CUSTOMERS

Id. št./ ID No.	Demografija kupcev Customer demography	Izjava kupca Customer statement	UPORABA / USE Kdo Who	Kaj What	Kdaj When	Kje Where	Zakaj Why	Kako How	Analizirana izjava Analyzed statement	Potreba/ značilka Need/feature	Vrsta potrebe/ značilke Type of need/ feature
1.	Zdravniki Physicians	Omogoča dostop v notranjost telesa Interior of the body is accessible	Kirurg Surgeon		Med celotnim posegom During entire surgery	Operacijska dvorana Operation theatre	Za nemoteno delo For uninterrupted work		Omogočen dostop v notranjost telesa med posegom Interior of the body is accessible	Kakovost Quality	Delovanje Functionality
2.	Zdravniki Physicians	Dobra vidljivost v polju posega Good visibility in the surgical field	Kirurg Surgeon		Med celotnim posegom During entire surgery	Operacijska dvorana Operation theatre	Za nemoteno delo For uninterrupted work	Z endoskopom With endoscope	Dobra vidljivost v polju posega Good visibility in the surgical field	Kakovost Quality	Delovanje Functionality
3.	Zdravniki Physicians	Zvezna nastavitev tlaka Continuous set of pressure	Kirurg Surgeon	Dobra vidljivost Good visibility	Med celotnim posegom During entire surgery	Operacijska dvorana Operation theatre	Za nemoteno delo For uninterrupted work		Nastavitev tlaka mora biti zvezna Pressure should be set continuously	Kakovost Quality	Delovanje Functionality
4.	Zdravniki, inštrumentarke Physicians, scrub nurses	Nadzor količine vode v sistemu Control of water amount in the system	Kirurg in inštrum. Surgeon and scrub nurse	Prava količina vode The right amount of water	Med celotnim posegom During entire surgery	Operacijska dvorana Operation theatre	Varnost bolnika Safety of the patient	Kontrolna naprava Control device	Kontrola količine vode v napravi Control of water amount in the device	Kakovost Quality	Varnost Safety
:											
21.											

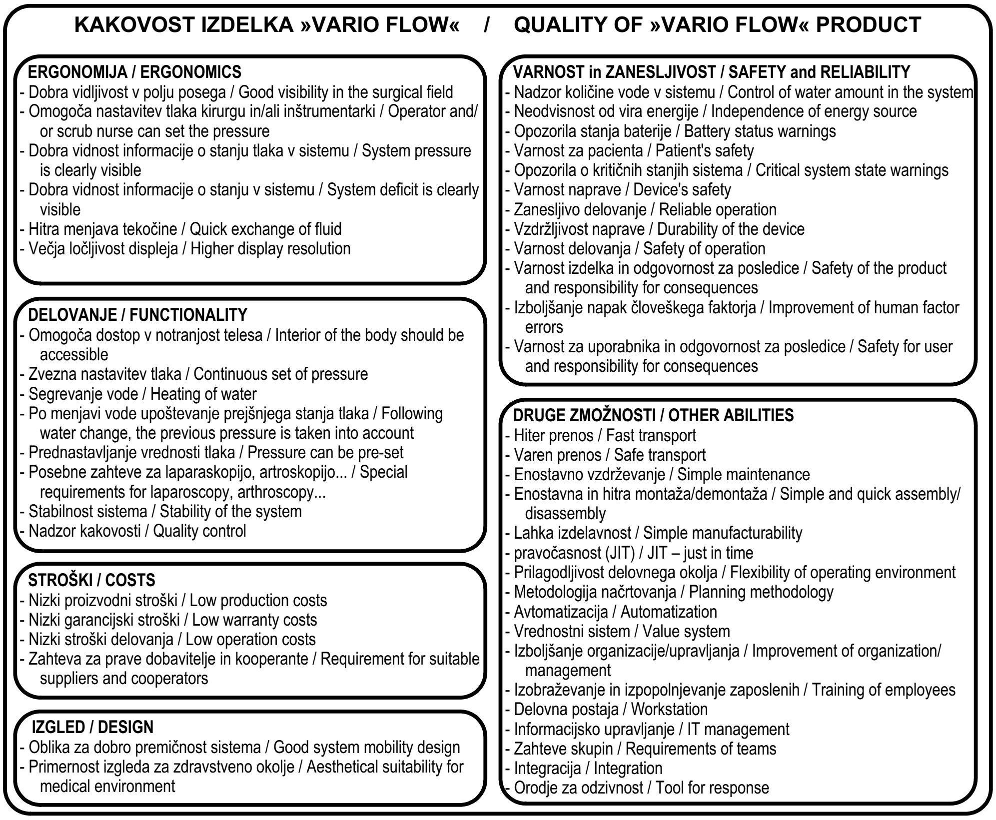
PREGLEDNICA GLASU NOTRANJIH KUPCEV / TABLE FOR THE VOICE OF THE INTERNAL CUSTOMERS

Id. št./ ID No.	Demografija kupcev Customer demography	Izjava kupca Customer statement	UPORABA / USE Kdo Who	Kaj What	Kdaj When	Kje Where	Zakaj Why	Kako How	Analizirana izjava Analyzed statement	Potreba/ značilka Need/feature	Vrsta potrebe/ značilke Type of need/ feature
22.	Nadzorni inženirji Inspection engineers	Varnost za bolnika Safety of the patient		Preprečit. poškodb Prevention of injuries	Med posegom During surgery	Op. dvorana Operation theatre		Varnost. sistem Safety system	Zagotovljena varnost pacienta Ensured safety of the patient	Kakovost Quality	Varnost Safety
23.	Razvojni inženir Development engineer	Zanesljivo delovanje Reliable operation		Preprečitev zastojev Prevention of deadlocks	Med posegom During surgery	Operacijska dvorana Operation theatre	Nemoteno delovanje Undisturbed operation	Konstrukcijska rešitev Design solution	Izboljšanje konstrukcijske rešitve Design solution improvement	Kakovost Quality	Zanesljivost Reliability
24.	Razvojni inženir Development engineer	Vzdržljivost naprave Device durability			Vsaj dve leti At least 2 years		Brezhibno delovanje Perfect operation	Konstrukcijska rešitev Design solution	Vzdržljivost naprave Device durability		Zanesljivost Reliability
25.	Razvojni inženir Development engineer	Varnost delovanja Safety of operation		Preprečitev zastojev Prevention of deadlocks	Med posegom During surgery	Operacijska dvorana Operation theatre	Da ne pride do poškodb To prevent injuries	Konstrukcijska rešitev Design solution	Varnost delovanja izdelka in odgovornost za posledice Safety of operation and responsibility for consequences	Kakovost Quality	Zanesljivost Reliability
:											
47.											

PODATKI O IZDELKIH IN PROCESIH / PRODUCT AND PROCESS DATA

Id. št./ ID No.	Demografija kupcev Customer demography	Izjava kupca Customer statement	UPORABA / USE Kdo Who	Kaj What	Kdaj When	Kje Where	Zakaj Why	Kako How	Analizirana izjava Analyzed statement	Potreba/ značilka Need/feature	Vrsta potrebe/ značilke Type of need/ feature
1.	Vzdrževalna služba Maintenance service	Hitra menjava tekočine Quick exchange of fluid	Inštrumentarka Scrub nurse		Pred in med posegom Before and during surgery	Na izdelku On the product	Nemotena oskrba s tekočino Uninterrupted fluid supply	Ročno Manual	Enostavna menjava tekočine Simple exchange of fluid	Kakovost Quality	Delovanje Functionality
2.	Zdravniki Physicians	Premajhen prikazovalnik Too small a display	Zdravnik Physician	Premajhna ločljivost Insufficient resolution	Med posegom During surgery	Na izdelku On the product	Da ne pride do napak To prevent errors		Zagotoviti večjo ločljivost prikazovalnika To ensure higher display resolution	Kakovost Quality	Delovanje Functionality

Sl. 15. *Izhodiščne preglednice glasu kupcev izdeleka Vario Flow*
Fig. 15. *Initial tables of the voice of the customers for the Vario Flow product*



Sl. 16. *Sorodnostni diagram za vrednoto kakovost izdelka Vario Flow*
Fig. 16. *Affinity diagram for the value of the quality of the Vario Flow product*

potrebi. Za vsako potrebo so v preglednicah navedeni podatki: prepoznavna številka potrebe, demografija kupca, izjava kupca, uporaba potrebe (kdo, kaj, kdaj, kje, zakaj, kako), analiza izjave ter vrsta potrebe oz. značilke.

2. korak: Oblikovanje sorodnostnega diagrama izdelka Vario Flow

Na podlagi podatkov, zbranih v izhodiščnih preglednicah kupcev, je projektna skupina lahko oblikovala sorodnostni diagram za vrednoto kakovost izdelka Vario Flow. Zahteve kupcev je razdelila na šest skupin in vsaki potrebi, zapisani v izhodiščni preglednici glasu kupcev, priredil pripadnost v eno skupino potreb. Sorodnostni diagram za vrednoto kakovost izdelka Vario Flow je prikazan na sliki 16.

3. korak: Oblikovanje drevesnega diagrama izdelka Vario Flow

V drevesnem diagramu za vrednoto kakovost je projektna skupina, podobno kot v sorodnostnem diagramu potrebe kupcev uredila hierarhično,

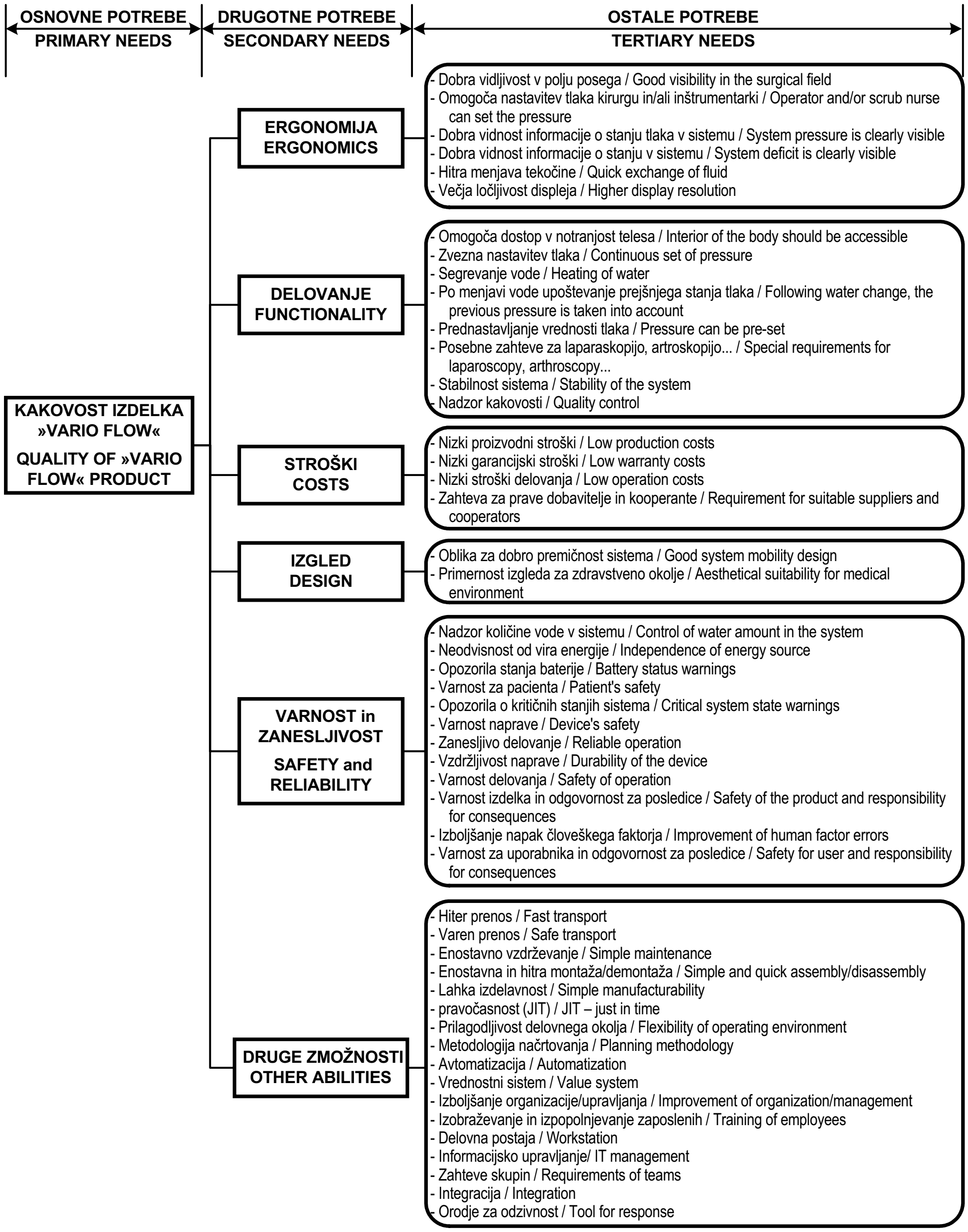
data contains 2 needs. For each need the table contains the following data: ID number of the need, customer demography, customer statement, use of the need (who, what, when, where, why, how), analyzed statement and the type of need or characteristics.

Step 2: Forming the affinity diagram for the Vario Flow product

On the basis of the data collected in the source tables of customers the project team formed the affinity diagram for the value of quality of the Vario Flow product. Customer needs were divided into six groups and each need, written in the source table for the voice of the customers, was assigned to one group of needs. The affinity diagram for the value of quality of the Vario Flow product is presented in Figure 16.

Step 3: Forming the tree diagram for the Vario Flow product

In the tree diagram for the value of quality the customer needs are arranged hierarchically (similar to the affinity diagram), divided into primary,



Sl. 17. *Drevesni diagram za vrednoto kakovost izdelka Vario Flow*
Fig. 17. *Tree diagram for the value of quality of the Vario Flow product*

razdeljene na osnovne, drugotne in ostale potrebe. Drevesni diagram za vrednoto "kakovost izdelka" Vario Flow je prikazan na sliki 17.

4.4 Vrednotenje podatkov o potrebah kupcev izdelka Vario Flow

Skupina se je odločila za izvedbo poštne ankete. Izdelan je bil anketni list, v katerem so bile

secondary and tertiary needs. The tree diagram for the value of quality of the Vario Flow product is shown in Figure 17.

4.4 Evaluation of the data on customer needs for the Vario Flow product

The team decided to use the postal survey. A survey form was composed where the primary, secnavedene osnovne, drugotne in ostale potrebe kupcev, in poslan v ocenitev 50-tim naključno izbranim možnim kupcem izdelka Vario Flow.

V predpisanem roku je prispelo 38 izpolnjenih anketnih listov, v katerih so kupci izdelka Vario Flow določili za njih najpomembnejšo potrebo, manj pomembne in končno zelo malo pomembne potrebe. Projektna skupina je kasneje z uporabo PREDNOSTNEGA MODELA 1-2-3 najpomembnejši potrebi posameznega kupca (prvo mesto) pripisala 5 točk, malo pomembnim potrebam, uvrščenim na drugo mesto, 3 točke in potrebam, uvrščenim na tretje mesto, 1 točko.

S seštevanjem točk pomembnosti potreb, navedenih v vseh 38 izpolnjenih anketnih listih, je projektna skupina končno prišla do rezultatov o absolutni in relativni pomembnosti posamezne potrebe, kar prikazuje preglednica 2.

V preglednici 2 pridobljene, sestavljene in vrednotene potrebe kupcev predstavljajo vhodni podatek 1. hiše (načrtovanje izdelka) – postopka sprejemanja izdelka. Slika 18 prikazuje model ugotavljanja in vrednotenja potreb kupcev izdelka Vario Flow.

5 SKLEPI

Podjetje ne more priti do konkurenčnega izdelka, če že v fazo sprejemanja izdelka ne vključi tistega osebka, ki bo izdelek uporabljal oziroma imel od njega korist, torej kupca izdelka.

Pravočasno vključevanje kupcev v postopek sprejemanja izdelka daje kupcu možnost, da z

ondary and tertiary customer needs were stated and it was sent for evaluation to 50 randomly selected potential customers of the Vario Flow product.

Up to the due date, 38 survey responses were received; in these, Vario Flow customers stated what in their opinion were the most important, less important and least important needs. After that the project team, using the "PRORITY MODEL 1-2-3", assigned 5 points to the most important feature of a particular need, less important needs were assigned 3 points and the least important features were assigned 1 point.

By summing up the points obtained from all 38 surveys the project team finally obtained the results on the absolute and relative relevance of a particular need, as presented in Table 2.

The customer needs, obtained, structured and evaluated in Table 2, are the input data for the first – product planning house – the development process. Figure 18 shows a model for obtaining and evaluating the customer needs of the Vario Flow product.

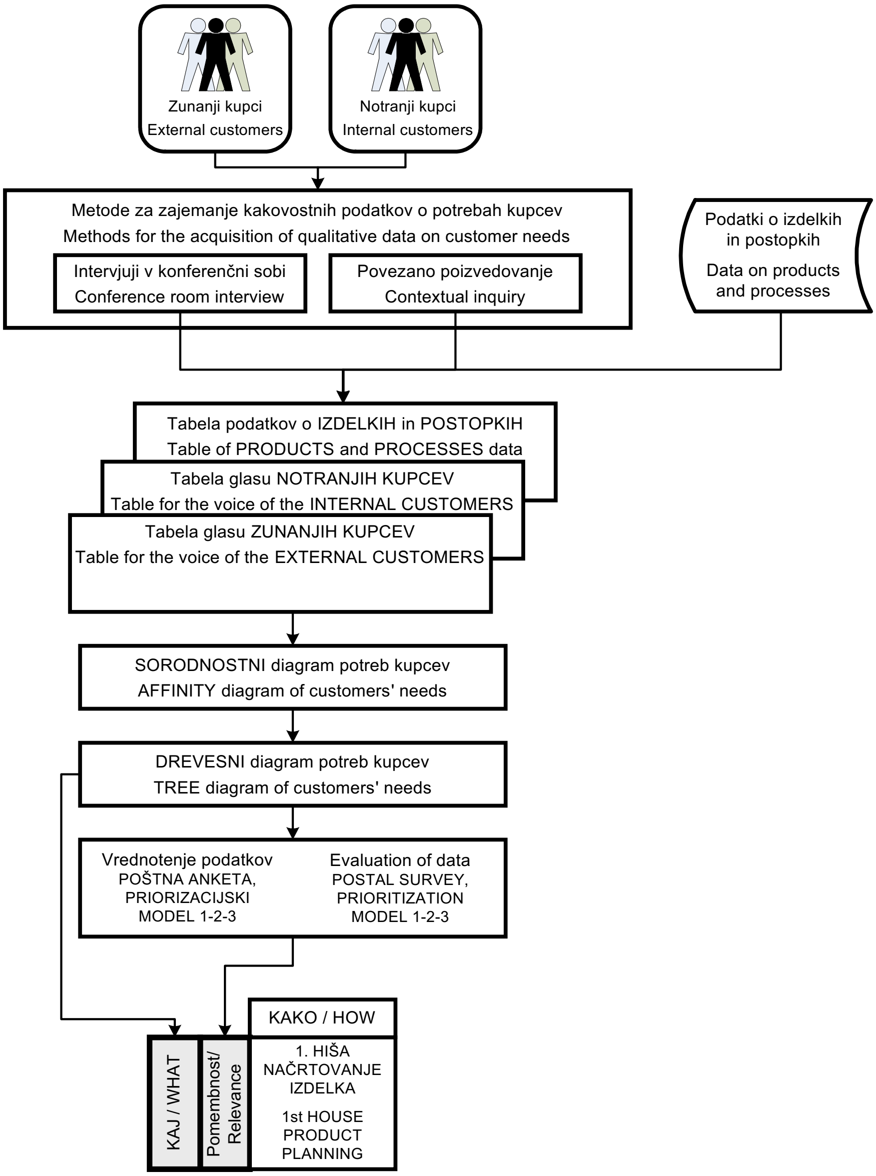
5 CONCLUSIONS

A company cannot produce a competitive product unless the client (end user) takes part in the development process.

If the clients take part in the new-product development process early enough, then the client (by expressing his or her needs) can influence the

Preglednica 2. *Absolutna in relativna pomembnost dela potreb kupcev izdelka Vario Flow*
Table 2. *Absolute and relative relevance of customer needs for the Vario Flow product*

ID ŠT. / ID NO.	POTREBE KUPCEV / CUSTOMERS' NEEDS	Absolutna pomembnost (število točk) / Absolute relevance (number of points)	Relativna pomembnost / Relative relevance [%]
1.	Dobra vidljivost v polju posega / Good visibility in the surgical field	149	2,8
2.	Omogoča nastavitev tlaka kirurgu in/ali inštrumentarki / Surgeon and/or scrub nurse can set the pressure	190	3,5
3.	Dobra vidnost informacije o stanju tlaka v sistemu / System pressure is clearly visible	143	2,7
4.	Dobra vidnost informacije o stanju v sistemu / System deficit is clearly visible	135	2,5
5.	Hitra menjava tekočine / Quick exchange of fluid	151	2,8
⋮	⋮	⋮	⋮
48.	Integracija / Integration	69	1,3
49.	Orodje za odzivnost / Tool for response	63	1,2
	VSOTA / TOTAL	5370	100,0



Sl. 18. *Model ugotavljanja in vrednotenja potreb kupcev izdelka Vario Flow*
Fig. 18. *Model for obtaining and evaluating the customer needs of the Vario Flow product*

izražanjem svojih potreb vpliva na definiranje izdelka in celotni postopek sprejemanja izdelka.

Dosedanje raziskave upoštevanja potreb oziroma zahtev kupcev izdelka v postopku sprejemanja izdelka so se nanašale na oblikovanje modela ugotavljanja, sestavljanja in vrednotenja potreb oziroma zahtev kupcev izdelka glede na kakovost izdelka. V primeru izdelka Vario Flow je bilo prepoznanih 21 potreb zunanjih kupcev, 26 potreb notranjih kupcev in 2 potrebi o izdelku in

concept of the product and the whole product-development process.

Past researches that analyzed the customers' needs or demands in the new-product development process were related only to the development of the model for obtaining, structuring and evaluating the customers needs as to the quality of the product. In the case of the Vario Flow product, there were identified 21 needs of external customers, 26 needs of internal customers and 2 needs on product and propostopkih, torej skupaj 49 potreb oziroma zahtev kupcev, ki pomenijo izhodiščni podatek za razvoj delovanja kakovosti izdelka na sonovi RFK ([3] in [16]). Pri ugotavljanju pomembnosti potreb izdelka Vario Flow z ABC analizo [18] se je izkazalo, da je nadpovprečno pomembnih 12 potreb, povprečno pomembnih 16 in manj pomembnih 21 potreb. V postopku razvoja izdelka, bo torej treba posebej paziti na izpolnitev nadpovprečno pomembnih zahtev in med njimi najbolj na izpolnitev zahteve o "možni nastavitvi tlaka".

Nadaljnje raziskave upoštevanja glasu kupcev bodo usmerjene na ugotavljanje potreb za izboljšanje ne samo kakovosti temveč tudi drugih lastnosti in vrednot izdelka, npr. preprostost, sestavljivost, možnost ponovne uporabe , odzivnost, stroški itn., ki jih izražajo predvsem notranji kupci in so izhodiščni podatek za sočasni razvoj funkcij kakovosti [12].

cesses. There are 49 needs or customer demands together, which represent the source data for the quality functions deployment (QFD) process [3, 16]. The obtaining of the importance of the needs of the Vario Flow product with ABC analysis [18] shows that there are 12 needs with high importance, 16 with average importance and 21 less important needs. Special attention should be given to fulfilling the high-importance needs in the process of product development, and from these needs, in particular for "Possible pressure setting".

Further research on the influence of the voice of the customers will be focused on establishing the needs for the improvement of not only the quality but other features as well, such as simplicity, ease of assembly, recyclability, responsibility, costs, etc., which are expressed mostly by internal customers and which represent the source data for concurrent functions deployment [12].

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Naslova avtorjev: doc. dr. Janez Kušar
prof. dr. Jože Duhovnik
prof. dr. Marko Starbek
Univerza v Ljubljani
Fakulteta za strojništvo
Aškerčeva 6
1000 Ljubljana
janez.kusar@fs.uni-lj.si
joze.duhovnik@fs.uni-lj.si
marko.starbek@fs.uni-lj.si

Rok Tomaževič
CIMOS d.d.
Marežganskega upora 2
6000 Koper

Authors' Addresses: Doc. Dr. Janez Kušar
Prof. Dr. Jože Duhovnik
Prof. Dr. Marko Starbek
University of Ljubljana
Faculty of Mechanical Eng.
Aškerčeva 6
1000 Ljubljana, Slovenia
janez.kusar@fs.uni-lj.si
joze.duhovnik@fs.uni-lj.si
marko.starbek@fs.uni-lj.si

Rok Tomaževič
CIMOS d.d.
Marežganskega upora 2
6000 Koper, Slovenia

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Vpliv pravokotnosti mreže na konvergenco programa SIMPLE za reševanje Navier-Stokes-ovih enačb

The Influence of Grid Orthogonality on the Convergence of the SIMPLE Algorithm for Solving Navier-Stokes Equations

Ivo Džijan - Zdravko Virag - Hrvoje Kozmar
(University of Zagreb, Croatia)

Razvili smo metodo končnih volumnov za reševanje Navier-Stokesovih enačb na lokalno pravokotni nestrukturirani mreži z uporabo algoritma SIMPLE. Razvito metodo smo primerjali s podobno metodo na strukturirani, ne nujno pravokotni mreži, v členih pretekle konvergence in obsegu pod-relaksacijskih faktorjev, pri katerih se metodi približujeta. Kadar je strukturirana mreža pravokotna, sta stopnji približevanja obeh metod podobni. V primerih, kadar strukturirana mreža ni pravokotna, se pokaže prednost predlagane metode pri lokalno pravokotni mreži v razmerah pretekle konvergence. V teh primerih je obseg pod-relaksacijskih faktorjev, pri katerih je predlagana metoda zadovoljivo konvergentna, mnogo večji kot pri metodi na nepravokotni mreži.

(Ključne besede: Navier-Stokesove enačbe, metode končnih volumnov, algoritmi SIMPLE, nestrukturirane mreže)

A finite-volume method for solving the Navier-Stokes equations on a locally orthogonal unstructured grid using the SIMPLE algorithm has been developed. The developed method was compared with a similar method on a structured, not necessarily orthogonal grid, in terms of convergence history and the range of under-relaxation factors in which the methods converge. When the structured grid is orthogonal, the convergence rates of the two methods are similar. For the cases when the structured grid is non-orthogonal, the superiority of the proposed method on the locally orthogonal grid is demonstrated in terms of convergence history. In these cases, the range of under-relaxation factors in which the proposed method shows satisfactory convergence is much wider than for the method on the non-orthogonal grid.

(Keywords: Navier-Stokes equations, finite volume methods, SIMPLE algorithm, unstructured grid)

0 INTRODUCTION

The rapid development of computers has brought about rapid developments in the field of computational fluid dynamics. Calculation domains are now more complex, which increases the need to use an unstructured grid for their discretization. Finite volume methods are widely applied for solving fluid flow problems. Initially, these methods were used on structured staggered grids. Nowadays they are used on unstructured collocated grids, on which segregate algorithms with the pressure-based approach are applied for incompressible flows. The most popular algorithm based on pressure correction is the SIMPLE (Semi-Implicit Method for the Pressure-Linked Equation) algorithm, Caretto et al. [1] and Patankar and Spalding [2]. In the pressure-velocity correction relation the effects coming from velocity corrections in neighboring nodes on the pressure correction in the central node are neglected. The consequence of this neglecting is the overestimation of the pressure correction, which can cause the divergence of the numerical process. To ensure the stability of the numerical process, the under-relaxation factor for the pressure is introduced. The optimal value of this factor cannot be estimated in advance since it depends on the grid's characteristics and the nature of the problem.

The SIMPLE algorithm is originally defined on a staggered grid where the pressure is calculated in the cell centre and the velocity components are calculated on the cell faces. On a collocated grid, the pressure field and velocity components are calculated in the cell centre. The application of the SIMPLE algorithm on a collocated grid started with Rhie and Chow [3].

The grid non-orthogonality is one of the factors that increases the number of iterations of the SIMPLE algorithm. If the connecting line of two neighboring nodes is not perpendicular to the cell face, some terms that appear due to non-orthogonality are usually neglected. This is the case with the CAFFA public-domain computer code [4]. It is believed that this neglecting slows down the rate of convergence of the numerical method. Therefore, the modification of the finite volume method on an unstructured locally orthogonal grid is proposed. The rate of convergence of the SIMPLE algorithm on that grid will be compared with the rate of convergence on a structured, not necessarily orthogonal grid.

1 MATHEMATICAL MODEL AND NUMERICAL PROCEDURE

The mathematical model of steady, laminar, incompressible fluid flow with constant viscosity and without mass forces is adopted. The model is described with the following Navier-Stokes equations:

$$\frac{\partial}{\partial x_j}\left(\rho v_j\right)=0 \quad (1)$$

$$\frac{\partial}{\partial x_j}\left(\rho v_j v_i\right)=-\frac{\partial p}{\partial x_i}+\mu\frac{\partial^2 v_i}{\partial x_j \partial x_j} \quad (2)$$

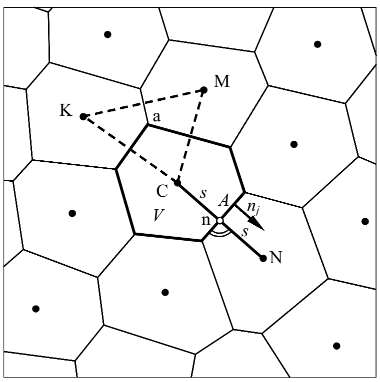


Fig. 1. *A part of calculation domain and a typical cell of locally-orthogonal unstructured grid*

where ρ, v_j, p, μ and x_j are the fluid density, velocity, pressure, viscosity and coordinates, respectively. These equations will be numerically solved on an unstructured locally orthogonal grid. A part of such a computational grid is shown in Fig. 1.

The main nodes, C and N, at which the velocity and pressure fields are calculated, are placed within their respective cells. The connecting line CN is perpendicular to the cell face and the nodes C and N are at an equal distance from an auxiliary node n, which enables a simple formulation of the high-order interpolation. It is clear that such a grid is possible in every 2D case, because the cell vertex a in Fig. 1 is the circumcenter of the triangle formed by the nodes C, M and K. Such a grid generator is described by Džijan [5], which includes a grid-smoothing procedure that forces the main nodes to be close to the cell centroids and the auxiliary nodes to be close to the cell-face centroids.

Discretization of the equations starts with integrating over the cell volume V, according to Fig. 1. By using the Gauss theorem and the mean-value theorem, the integrated governing equations take the form:

$$\sum_{k=1}^{m}\left[F\right]^k=0 \quad (3)$$

$$\sum_{k=1}^{m}\left[F\,v_i\big|_\mathrm{n}-\mu A\frac{\partial v_i}{\partial x_j}\bigg|_\mathrm{n} n_j\right]^k=-V\frac{\partial p}{\partial x_i}\bigg|_\mathrm{C}+\sum_{k=1}^{m}\left[\mu A\frac{\partial v_j}{\partial x_i}\bigg|_\mathrm{n} n_j\right]^k \quad (4)$$

where $F=\rho A v_j\big|_\mathrm{n} n_j=\rho A v_n$ is the mass flow through the cell face and $J_i=F\,v_i\big|_\mathrm{n}-\mu A(\partial v_i/\partial x_j)\big|_\mathrm{n} n_j$ is the momentum flux through the cell face. A and n_j are the cell-face area and its outward normal vector, V is the cell volume, while k denotes the cell-face index and m is the number of cell faces on the considered volume. The scope of the differencing schemes is to define the velocity $v_i\big|_\mathrm{n}$ and its normal derivatives at the auxiliary node n in terms of velocity values at the main nodes. Since the adopted grid is locally orthogonal, these values are defined by using only the values at nodes C and N. A blending scheme of the central differencing scheme (CDS) and of the first-order upwind differencing scheme (UDS) is used in the CAFFA computer code. Therefore, the same scheme will also be used in the proposed method. In the case of the locally orthogonal grid, the diffusion part of the flux vector is modeled with the following equation:

$$J_i^\mathrm{d}=-\mu A\frac{\partial v_i}{\partial x_j}\bigg|_\mathrm{n} n_j=-\mu A\frac{\partial v_i}{\partial n}\bigg|_\mathrm{n}=-\mu A\frac{v_i\big|_\mathrm{N}-v_i\big|_\mathrm{C}}{2s} \quad (5).$$

In the case of a non-orthogonal grid, an additional term appears. In the CAFFA computer code this term is implemented by using the deferred correction approach, i.e., by using the velocity values from the previous iteration.

In the first-order UDS, the convective flux is modelled by:

$$J_i^{\mathrm{UDS}} = F\, v_i\big|_{\mathrm{n}} = \begin{cases} F\, v_i\big|_{\mathrm{C}} & \text{for } F>0 \\ F\, v_i\big|_{\mathrm{N}} & \text{for } F<0 \end{cases} \qquad (6),$$

and in the CDS (for the case when the node n lies in the middle of the CN connection line) by:

$$J_i^{\mathrm{CDS}} = \frac{1}{2} F\left(v_i\big|_{\mathrm{C}} + v_i\big|_{\mathrm{N}} \right) \qquad (7).$$

By introducing the mixing factor γ, the final expression for the momentum flux is:

$$J_i = (1-\gamma)\, J_i^{\mathrm{UDS}} + \gamma J_i^{\mathrm{CDS}} + J_i^{\mathrm{d}} \qquad (8)$$

where, for $\gamma = 0$ the result is the UDS, and for $\gamma = 1$ the CDS.

Introducing the expressions for the fluxes into (4) results in:

$$a_{\mathrm{C}}\, v_i\big|_{\mathrm{C}} - \sum_{k=1}^{m} \left[a_{\mathrm{N}}\, v_i\big|_{\mathrm{N}} \right]^k = -V \left.\frac{\partial p}{\partial x_i}\right|_{\mathrm{C}} + b_i \qquad (9)$$

where:

$$a_{\mathrm{N}} = \left[\max(-F,0) + \frac{\mu A}{2s} \right] \qquad (10),$$

$$a_{\mathrm{C}} = \sum_{k=1}^{m} \left[a_{\mathrm{N}} \right]^k \qquad (11)$$

and

$$b_i = \gamma \left\{ \sum_{k=1}^{m} \left[\frac{1}{2} F\, v_i\big|_{\mathrm{N}} \right]^k - \sum_{k=1}^{m} \left[\max(-F,0) \right]^k v_i\big|_{\mathrm{C}} + \sum_{k=1}^{m} \left[\max(-F,0)\, v_i\big|_{\mathrm{N}} \right]^k \right\} \qquad (12).$$

It is obvious that all the terms coming from the CDS are treated as a deferred correction, the same as in the CAFFA code.

To reduce the possibility that the numerical process diverges, this equation is under-relaxed in the following form:

$$\left(1 + \frac{1}{\alpha_{uv}} \right) a_{\mathrm{C}}\, v_i\big|_{\mathrm{C}} - \sum_{k=1}^{m} \left[a_{\mathrm{N}}\, v_i\big|_{\mathrm{N}} \right]^k = -V \left.\frac{\partial p}{\partial x_i}\right|_{\mathrm{C}} + b_i + \frac{a_{\mathrm{C}}\, v_i\big|_{\mathrm{C}}}{\alpha_{uv}} \qquad (13)$$

which was proposed by Patankar [6]. The last term on the right-hand side is calculated from the previous iteration, and α_{uv} is the under-relaxation factor for the velocity.

According to Rhie and Chow [3], the mass flow through the cell face is defined as follows:

$$F = \rho A v_n = \rho A \overline{(v_n)} - \rho A \overline{\left(\frac{V_{\mathrm{n}}}{a_{\mathrm{n}}} \right)} \left[\left.\frac{\partial p}{\partial n}\right|_{\mathrm{n}} - \overline{\left(\left.\frac{\partial p}{\partial n}\right|_{\mathrm{n}} \right)} \right] \qquad (14)$$

where the line above a symbol indicates the linear interpolation between the values at nodes C and N, as follows:

$$\overline{(v_n)} = \frac{1}{2}\left(v_j\big|_{\mathrm{C}} + v_j\big|_{\mathrm{N}} \right) n_j \qquad (15),$$

$$\overline{\left(\left.\frac{\partial p}{\partial n}\right|_{\mathrm{n}} \right)} = \frac{1}{2}\left(\left.\frac{\partial p}{\partial n}\right|_{\mathrm{C}} + \left.\frac{\partial p}{\partial n}\right|_{\mathrm{N}} \right) \qquad (16)$$

and

$$\overline{\left(\frac{V_{\mathrm{n}}}{a_{\mathrm{n}}} \right)} = \frac{1}{2}\left(\frac{V_{\mathrm{C}}}{(a_{\mathrm{C}})\big|_{\mathrm{C}}} + \frac{V_{\mathrm{N}}}{(a_{\mathrm{C}})\big|_{\mathrm{N}}} \right) \qquad (17).$$

In the case of a locally orthogonal grid, the normal derivative of the pressure is defined by using the CDS, as follows:

$$\left.\frac{\partial p}{\partial n}\right|_{\mathrm{n}} = \frac{p_{\mathrm{N}} - p_{\mathrm{C}}}{2s} \qquad (18).$$

In the CAFFA code, where the grid is non-orthogonal, additional terms emerge and are treated explicitly by using the values from the previous iteration.

Solving the momentum equation with a given pressure field p^* results in the velocity field v_i^*, and the mass flow F^*, which does not necessarily satisfy the continuity equation. For that reason, the velocity corrections v_i' and the corresponding F' and pressure correction p' are searched, so that the corrected velocity field $v_i = v_i^* + v_i'$ and corrected mass flow $F = F^* + F'$ satisfy the continuity equation. According to Equation (14), the corrected mass flow is approximated as follows:

$$F = F^* - \frac{\rho A}{2s} \overline{\left(\frac{V_{\mathrm{n}}}{a_{\mathrm{n}}} \right)} \left(p'_{\mathrm{N}} - p'_{\mathrm{C}} \right) = F^* - a_{\mathrm{N}}^{p'} \left(p'_{\mathrm{N}} - p'_{\mathrm{C}} \right) \qquad (19).$$

Introducing the corrected mass flows in the continuity equation (3) results in the following equation for the pressure correction:

$$a_{\mathrm{C}}^{p'} p'_{\mathrm{C}} - \sum_{k=1}^{m} \left[a_{\mathrm{N}}^{p'} p'_{\mathrm{N}} \right]^k = b^{p'} \qquad (20)$$

where

$$a_{\mathrm{C}}^{p'} = \sum_{k=1}^{m} \left[a_{\mathrm{N}}^{p'} \right]^k \qquad (21)$$

and

$$b^{p'} = -\sum_{k=1}^{m} \left[F^* \right]^k \qquad (22).$$

The solving of this equation results in the pressure-correction field. Therefore, the pressure field is corrected using the following equation:

$$p_C = p_C^* + \alpha_p p'_C \tag{23}$$

where α_p is the under-relaxation factor for the pressure. The velocities in the main nodes are corrected as follows:

$$v_i\big|_C = v_i^*\big|_C - \frac{V}{a_C}\frac{\partial p'}{\partial x_i}\bigg|_C \tag{24}.$$

The gradients of the physical values in the main nodes are calculated using the Gauss formula as follows:

$$\frac{\partial \phi}{\partial x_i}\bigg|_C = \frac{1}{V}\sum_{k=1}^{m}\left[\phi_n n_i A\right]^k = \frac{1}{2V}\sum_{k=1}^{m}\left[\phi_N n_i A\right]^k \tag{25}$$

where ϕ can stand for v_i, p or p'.

The steps in the SIMPLE algorithm for solving the Navier-Stokes equations can be summarized as follows:

1. Guess the pressure field p^* and the velocity field v_i.
2. Solve the momentum equation (13) to obtain v_i^*.
3. Solve the p' equation (20). Correct the pressure according to (23), correct the velocity according to (24) and the mass flow according to (19).
4. Treat the corrected pressure as p^* and return to Step 2. Repeat the whole procedure until a converged solution is obtained.

The converged solution is obtained when the normalized residuals for the continuity and momentum equations become smaller than some small number, ε. In this paper $\varepsilon = 10^{-6}$ was used. The residual for the continuity equation is:

$$R_m = \sum_{l=1}^{M}\left[\left|b^{p'}\right|\right]^l \tag{26}$$

and the residual for the momentum is:

$$R_{v_i} = \sum_{l=1}^{M}\left[\left|a_C\, v_i\big|_C - \sum_{k=1}^{m}\left[a_N\, v_i\big|_N\right]^k + V\frac{\partial p}{\partial x_i}\bigg|_C - b_i\right|\right]^l \tag{27}.$$

In the above expressions, l denotes the cell index and M the total number of cells. The values of the variables in the above formula are from the current iteration, and the coefficients are prepared for the next iteration. The following residuals are usually normalized: the mass residuals with the inlet mass-flow rate and the residuals for the momentum equation with the inlet momentum flow rate.

2 RESULTS

The described numerical method is implemented in the FVM computer code. In this code the residuals are defined and normalized in the same way as in the CAFFA code. The rate of convergence of the described method and of the method used in the CAFFA code will be compared by varying the grid's non-orthogonality and the differencing scheme. Also, the range of under-relaxation factors in which the numerical procedure converges will be analyzed.

2.1 Laminar flow in a lid-driven cavity with inclined side walls

In this test the 2D laminar fluid flow is calculated in a closed cavity whose lid is moving in a tangential direction with velocity v_t Perić [7]. The Reynolds number based on the side length a is $\mathrm{Re} = \rho . v_t . a/\mu = 1000$. The calculation is performed for different inclination angles of the side walls, $\beta = 90°$, 67.5° and 45°. In this problem the residuals defined by (26) and (27) are not normalized.

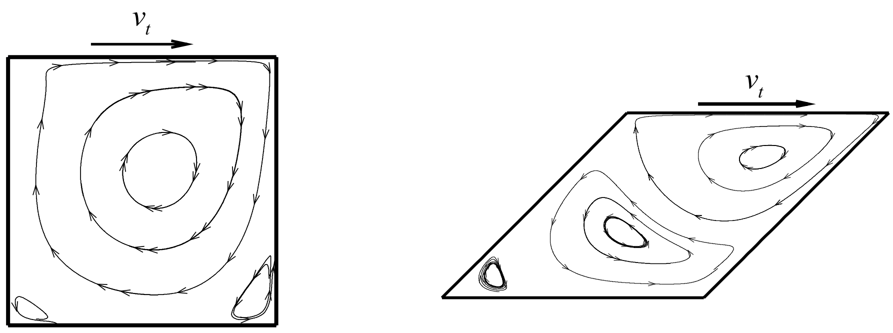
Fig. 2 shows the qualitative picture of the streamlines for $\beta = 90°$ and 45°. It is obvious that the initially assumed constant-velocity field will be very different from the final solution.

The problem is solved using the CAFFA numerical code on structured grids of size 40x40 cells, and with the FVM code on unstructured grids with approximately 1600 cells. Fig. 3 a shows a part of the unstructured grid for $\beta = 45°$ that is used in the FVM code. The borders of the finite volumes are presented, and the main nodes are marked. Fig. 3 b shows a part of the geometric grid for the same case, which is used in the CAFFA code. The displayed lines connect the main nodes at which the pressure and velocity fields are calculated.

In the SIMPLE algorithm, two under-relaxation factors should be given. The rate of convergence depends on the values of these two factors. Their optimal values are not known in advance, so that the described problem will be solved for a range of under-relaxation factors by varying α_{uv} from 0.5 to 0.95 with a step of 0.025, and α_p from 0.1 to 0.6 with a step of 0.1. The comparison criteria will be the number of iterations needed for the residuals to fall below $\varepsilon = 10^{-6}$.

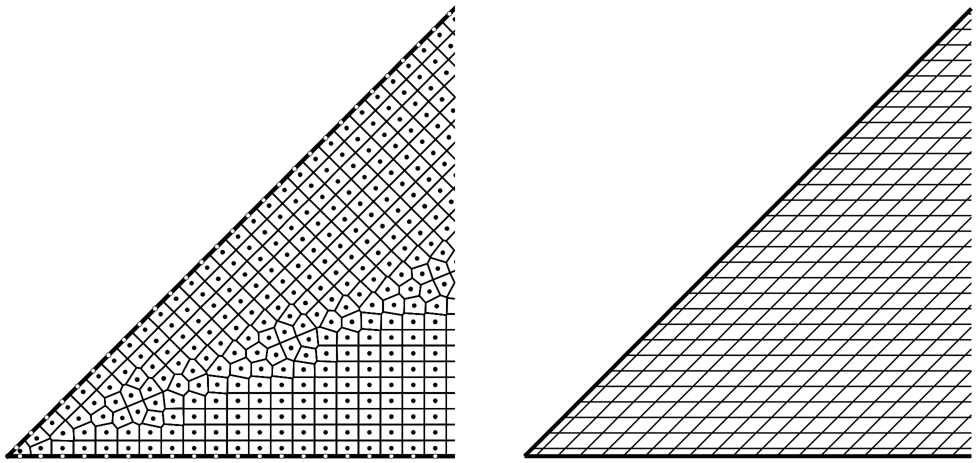
In the CAFFA and FVM codes different solvers for linear algebraic equations are used. For this reason, a sufficient number of inner iterations is given at every iterative step to be sure that the systems are solved equally well in both codes.

Fig. 4 shows the numbers of outer iterations N_ε required to reduce the residual levels to ε as a function of the under-relaxation factors α_{uv} and α_p,



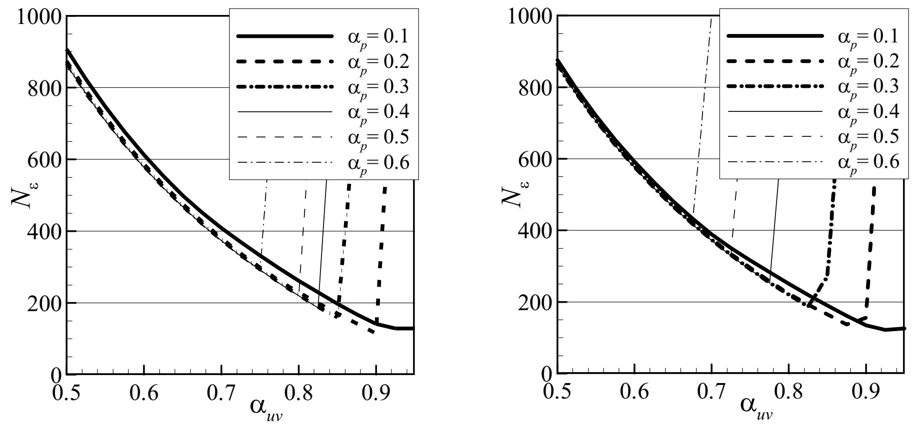
a) b)

Fig. 2. *Streamlines in laminar flow in a lid-driven cavity a) β = 90°, b) β = 45°*



a) b)

Fig. 3. *A part of the grid for the lid-driven cavity problem for β = 45° a) FVM, b) CAFFA*



a) b)

Fig. 4. *Required number of outer iterations to reduce residual levels to $\varepsilon = 10^{-6}$ for the lid-driven cavity problem for β = 90° (UDS) a) FVM, b) CAFFA*

for β = 90°. In this case, the grids for both codes are orthogonal, and the achieved results are almost identical. This confirms the equivalent implementation of the SIMPLE algorithm in both codes.

Fig. 5 shows N_ε for two algorithms for β = 45°. The SIMPLE algorithm in the CAFFA code converges in that situation only in the case that $\alpha_p = 0.1$, and only for small $\alpha_{uv} \leq 0.7$. N_ε is considerably

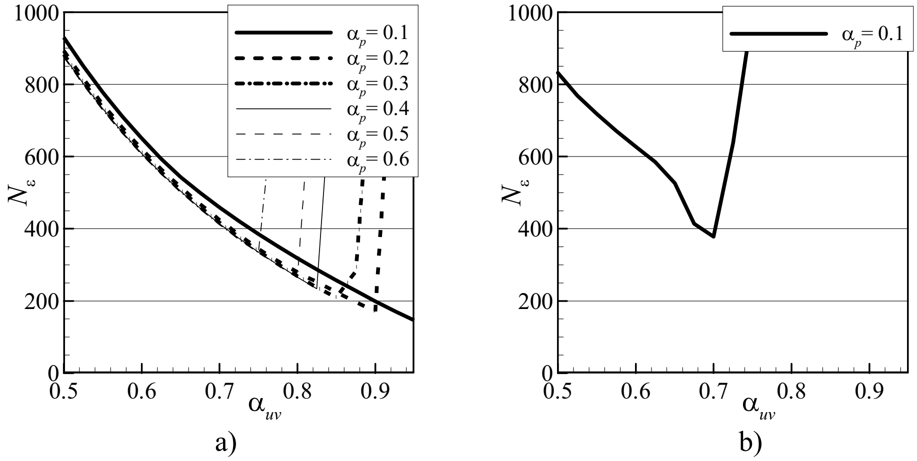


Fig. 5. *Number of outer iterations required to reduce the residual levels to $\varepsilon = 10^{-6}$ for the lid-driven cavity problem for $\beta = 45°$ (UDS) a) FVM, b) CAFFA*

larger than for the FVM code, which is a consequence of the grid's non-orthogonality.

Fig. 6 shows N_ε for two algorithms for β= 67.5°. In the FVM code, the necessary number of iterations has not significantly changed compared with the two previous cases. In the CAFFA code, the range of under-relaxation factors in which the algorithm converges is narrower than for β = 90°, and wider than for β= 45°. For the same combination of under-relaxation factors, N_ε increases with the increase of the grid's non-orthogonality.

Fig. 7 a shows the convergence histories (the greatest of three residuals versus the number of iterations N_{it}) of two methods for β = 90°, 67.5° and 45°, at a corresponding optimum combination of under-relaxation factors and by using the UDS. It is obvious that the convergence history on a locally orthogonal grid is unaffected by β, unlike the case of a non-orthogonal grid. It is worth noting that this comparison is valid for optimum values of under-relaxation factors that are unknown prior to the calculation. The clear advantage of the locally orthogonal grid over the non-orthogonal one can be read from Figs 4 to 6, from which one can conclude that the convergence history on this grid is slightly changed by a relatively large deviation from the optimum combination of under-relaxation factors, which is not the case for the non-orthogonal grid.

Fig. 7 b shows the convergence histories of two methods for β= 90° and 45°, at a corresponding optimum combination of under-relaxation factors and by using the CDS. The optimum values of the under-relaxation factors are the same as for the UDS. The rate of convergence slows down by switching from

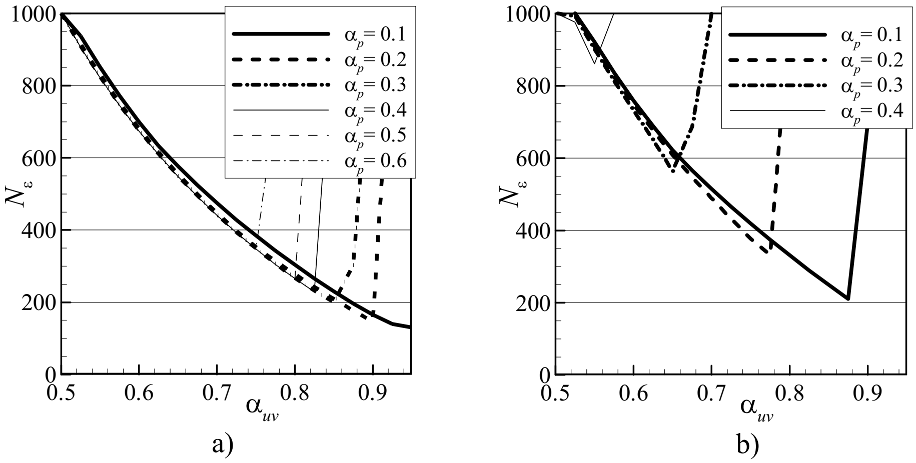
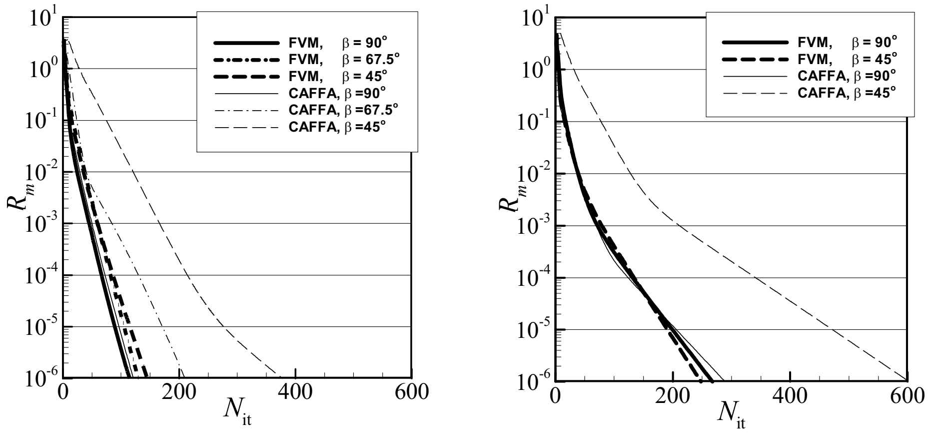


Fig. 6. *Number of outer iterations required to reduce the residual levels to $\varepsilon = 10^{-6}$ for the lid-driven cavity problem for $\beta = 67.5°$ (UDS) a) FVM, b) CAFFA*



a) b)

Fig. 7. *Convergence histories for the SIMPLE algorithm in the FVM and CAFFA codes for the lid-driven cavity problems a) UDS, b) CDS scheme*

the UDS to the CDS, which can be explained with the implementation of the CDS by using the deferred correction approach. Again, for $\beta = 90°$ the convergence history of the two methods is practically the same. For $\beta = 45°$ the convergence history of the method on a non-orthogonal grid is considerably slowed down due to the addition of the deferred correction on the non-orthogonality effects.

2.2 Laminar flow in a curved channel

The example of laminar flow in a curved channel where the grid is in some parts orthogonal and in some parts non-orthogonal is chosen. This is the usual case in practical applications of this method.

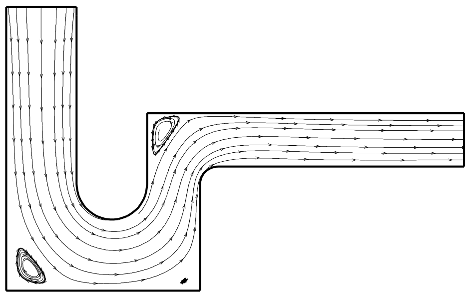
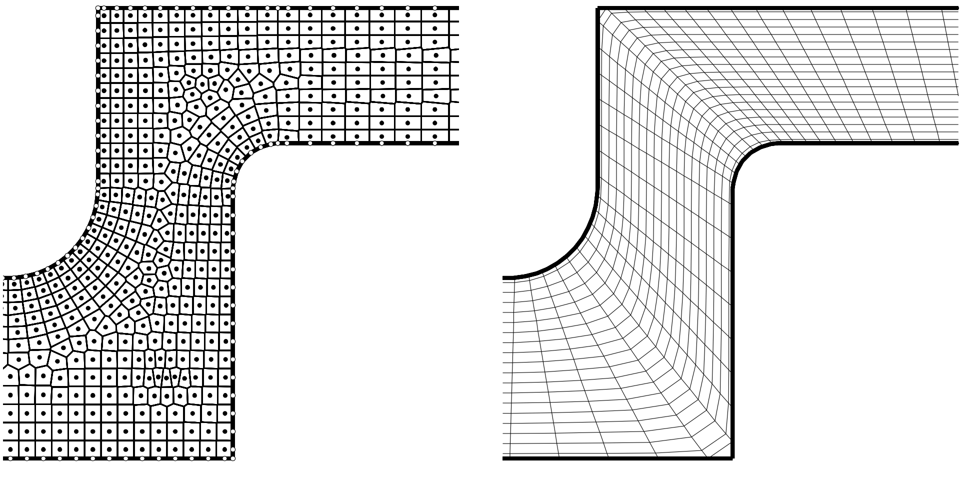


Fig. 8. *Streamlines for laminar flow in a curved channel*



a) b)

Fig. 9. *A part of the computational grid for the curved-channel problem a) FVM, b) CAFFA*

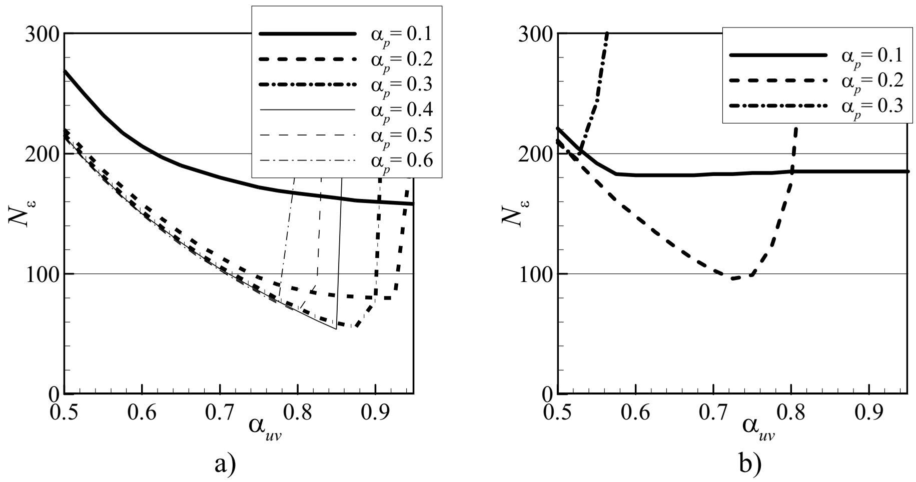


Fig. 10. *Number of outer iterations required to reduce the residual levels to $\varepsilon = 10^{-6}$ for the curved-channel problem (UDS) a) FVM, b) CAFFA*

Fig. 8 shows the calculation domain and the streamlines for this problem. Obviously, the final flow pattern is significantly different from the one that can be reasonably guessed at the beginning of the calculation.

Fig. 9 shows the part of the calculation area discretized with a locally orthogonal grid for the FVM and a structured grid for the CAFFA codes. The grid for the CAFFA code is non-orthogonal, and partially smoothed in the corners. In the straight parts of the channel this grid is orthogonal. The grid for the FVM code has 1180 finite volumes and the grid dimensions for the CAFFA code are 20×60 finite volumes. The uniform profile of the normal velocity v_n is given at the inlet. At the outlet boundary, the standard assumption of a zero velocity gradient is applied. The other boundaries are impermeable walls. The Reynolds number based on the normal velocity v_n and the inlet width a is $\mathrm{Re} = \rho v_n \cdot a/\mu = 200$.

Fig. 10 shows N_ε for the SIMPLE algorithm on a locally orthogonal grid. The range of good values of the under-relaxation factors is wider than in the case of the non-orthogonal grid. For the non-orthogonal grid, N_ε increases considerably for small changes of the under-relaxation factors with respect to their optimum values.

Fig. 11 shows the convergence histories for two methods for a corresponding optimum combination of under-relaxation factors by using the UDS and the CDS. The advantage of the method on the locally orthogonal grid is obvious. The effects of the deferred correction approach in the CDS are superimposed on the effects of the grid's non-orthogonality.

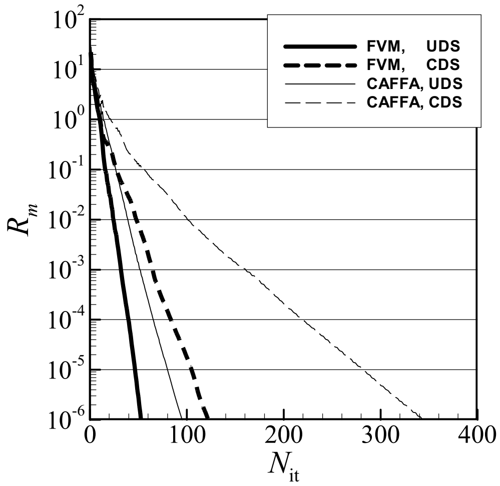


Fig. 11. *Convergence histories for the SIMPLE algorithm in the FVM and CAFFA codes for the curved-channel problem (UDS and CDS)*

3 CONCLUSIONS

From the comparison of the two methods in the selected test problems, the following conclusions can be drawn:

1) The results obtained by the FVM and CAFFA codes are nearly the same when both grids are orthogonal.
2) The method on a locally orthogonal grid implemented in the FVM code requires a smaller number of iterations than the method on a non-orthogonal grid implemented in the CAFFA code, when using corresponding optimum combinations of under-relaxation factors.

3) The range of under-relaxation factors for which the method converges is narrowing with the increase of the grid's non-orthogonality. This is a serious drawback, if we know that the optimum values of the under-relaxation factors are not known in advance, and that they take different values from problem to problem.
4) The application of the CDS based on the deferred correction approach increases the required number of iterations. This effect is superimposed on the effects of the grid's non-orthogonality.

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Authors' Addresses:
Doc. Dr. Ivo Džijan
Prof. Dr. Zdravko Virag
Dr. Hrvoje Kozmar
University of Zagreb
Faculty of Mechanical Engineering and Naval Architecture
I. Lučića 5
HR-10000 Zagreb, Croatia
ivo.dzijan@fsb.hr
zdravko.virag@fsb.hr
hrvoje.kozmar@fsb.hr

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Matematični modeli dinamike helikopterskega letenja

Mathematical Models of Helicopter Flight Dynamics

Dragan Cvetković[1] - Duško Radaković[2]
([1]University "Union", Serbia; [2]Federal Bureau for Measures and Precious Metals, Serbia)

Helikopter se razlikuje od drugih prometno transportnih sredstev, ne le po svoji sestavi temveč tudi po možnostih svojega gibanja. Helikopter se lahko premika navpično, lahko lebdi v zraku, lahko se vrti na istem mestu, lahko se premika naprej in v stran, a lahko tudi kombinira vse te premike. Zaradi tega sta modeliranje in testiranje dinamike helikopterja zelo zapleten problem. Trenutno se problemi dinamike helikopterskega letenja v glavnem rešujejo z uporabo sodobnih računalnikov. Čeprav so za mnoge zahtevne probleme računalniki neizogibni, ne omogočajo razumevanja fizikalne plati problema. Na srečo je veliko problemov v zvezi s helikopterji mogoče analizirati brez preveč zapletenih izračunov in navadno je mogoče priti do preproste formule. Čeprav niso ustrezne za preračune, te formule, pri konstrukciji helikopterja, omogočajo zadovoljivo interpretacijo potrebnih aerodinamičnih in dinamičnih pojavov. Helikopter spada v skupino zračnih sistemov in njegovo tradicionalno modeliranje se deli na: a) prostorsko geometrijo in kinematiko in na b) dinamiko togega telesa in dinamiko zraka, skozi katerega se giblje. V zadnjem času, so se razvili naslednji modeli: c) elastični model, odvisen od aerodinamičnih sil, d) model pogonskega sistema, e) model hidravličnih in drugih izvršilnikov za aerodinamično krmiljenje, f) model obnašanja pilota, g) model sistema navigacije in h) model problema vodenja. Matematični model, opisan v tem prispevku, se nanaša na a) in b).

(Ključne besede: helikopterji, dinamika letenja, matematični modeli)

The helicopter is a specific form of traffic-transportation, not just in terms of its structure but also in terms of its possibilities for motion. The helicopter can move vertically, hover in the air, turn around, move forward and move laterally, and it can also perform combinations of these movements. As a result, modeling and testing helicopter dynamics is a very complex problem. The problems in helicopter flight dynamics are mostly solved with the aid of modern computers. Though inevitably, with many complex problems, computers do not make it possible to understand the physical nature of the problem. Fortunately, many problems related to helicopters can be analyzed without overly complex calculus, and usually it is possible to obtain simple formulae. Though not suitable for calculus, these formulae, when designing the helicopter, enable a satisfactory interpretation of the required aerodynamic and dynamic phenomena. The helicopter belongs to the group of aerospace systems and its traditional modeling may be divided into: a) three-dimensional (space) geometry and kinematics, and b) rigid-body dynamics and the fluid dynamics through which it moves. Recently, the following models were developed: c) the elasticity model in intersubordinance with a fluid, d) the propulsion system model, e) the hydraulic model and other actuators that achieve aerodynamic control, f) the pilot-behavior model, g) the navigation-system model, and h) the beacon-problem model. The mathematical model described in this paper is related to a) and b).

(Keywords: helicopters, flight dynamics, mathematical models)

1 GIBANJE ROTORSKIH KRAKOV

Da bi razumeli dinamiko letenja helikopterja in določili dinamične momente in sile, ki delujejo na helikopter, je nujno potrebno najprej raziskati

1 MOTION OF ROTOR BLADES

To understand the flight dynamics of helicopters and determine the dynamic moments and forces that act upon the helicopter, it is a necessity to pre-investigate gibanje nosilnih krakov rotorja. Iz velikega števila različnih helikopterjev smo izbrali helikopter z enim rotorjem, katerega kraki so povezani na glavo rotorja s členkom, okoli katerega se prosto gibljejo. Treba je povedati, da so kraki trdno povezani z glavo rotorja.

the motion of the supporting rotor blades. From a vast number of different types of helicopters, we chose the single-rotor helicopter that has its blades coupled with the main rotor by a hinge about which they can move freely. It should be noted that there are also rotors that have the blade connected in a fixed manner to the hub.

1.1 Enačbe mahanja kraka

Krake rotorja vzamemo kot togo telo. Vodoravni členek je na razdalji *eR* od osi vrtenja. Kotna hitrost gredi je Ω=konst, a krak maha s kotno hitrostjo d*β*/d*t*. Vzdolžna os kraka je vzporedna vztrajnostni osi kraka in gre skozi členek(sl. 1).

Na sliki 1 je *R* dolžina kraka, kot *β* je položaj kraka. Po zapletenih preračunih, dobimo enačbe gibanja krakov:

1.1 Equations of blade flapping

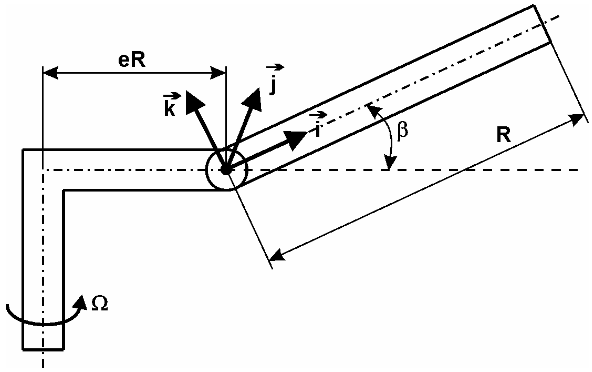
Rotor blades are regarded as a rigid body. The horizontal hinge is placed at a length *eR* from the rotation axis. The shaft rotates at an angular speed Ω=const, and the blade flappers at an angular speed of d*β*/d*t*. The axis that passes through the blade is parallel to the axis of inertia of the blade and passes through the hinge (Fig. 1).

In Figure 1, *R* represents the length of the blade, *β* represents the flapping angle of the blade. Following some complex calculus, the equations for blade flapping are obtained:

$$\ddot{\beta} + \Omega^2 \left(1+\varepsilon\right) \beta = M_{Ay}/\mathrm{J_y} \tag{1}$$

$$\mathrm{J_x}\ \dot{\beta}\ \Omega\ \cos\beta + J_x \left(-\dot{\beta}\right) \Omega\ \sin\beta = 0 \tag{2}$$

$$-2\ J_y\ \Omega\ \dot{\beta}\ \sin\beta = M_z \tag{3}$$



Sl. 1. *Prikaz mahanja kraka*
Fig. 1. *Explanatory drawing for blade flapping*

1.2 Enačbe zaostajanja kraka

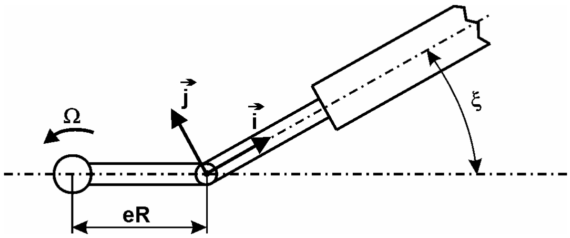
Predpostavimo, da je *β*=0 in da se krak giblje naprej glede na navpični členek za kot zaostajanja *ξ*. Navpični členek je na razdalji *eR* od osi vretena. Koordinatni sistem postavimo enako kot v prejšnjem primeru. Slika 2 prikazuje poenostavljeno skico za določanje zaostajanja kraka.

Iz tega izhaja enačba zaostajanja kraka:

1.2 Equations of blade throwback

It is assumed that *β*=0 and that the blade is moving forward in relation to the vertical hinge by the throwback angle amount *ξ*. The vertical hinge is placed at a distance *eR* from the shaft axis. The coordinate system is positioned as in the previous case. Figure 2 presents a simplified scheme for determining the blade throwback.

From this the equation for blade throwback follows:



Sl. 2. *Prikaz zaostajanja kraka*
Fig. 2. *Explanatory scheme for blade throwback*

$$\ddot{\xi} + \Omega^2 \varepsilon\ \xi - 2\ \Omega\ \beta\ \dot{\beta} = M_z / J_z \tag{4}$$

Če je kot med položajem kraka in smerjo letenja $\psi=\Omega t$, sledi:

If the azimuth angle is described as $\psi=\Omega t$, then it follows that:

$$\frac{d^2\xi}{d\psi^2} + \varepsilon\ \xi - 2\ \beta \frac{d\beta}{d\psi} = \frac{M_z}{J_z \Omega^2} \tag{5}$$

1.3 Enačba vzpenjanja kraka

Vzemimo, da sta kota mahanja in zaostajanja enaka nič. Korak kraka je kot med tetivo profila kraka in ravnino glave rotorja, označen kot θ_k. Na sliki 3 vidimo koordinatni sistem, povezan s krakom.

Enačbe gibanja kraka okoli vzdolžne osi so:

1.3 Equation of blade climb

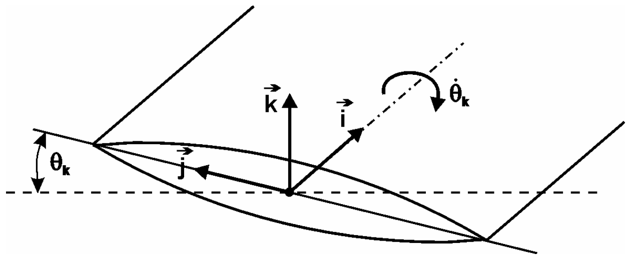
It is assumed that the flapping and the throwback angles are equal to zero. The blade step is the angle between the blade cross-section chord and the plane of the hub, designated as θ_k. Figure 3 shows the coordinate system attached to the blade.

The equations of blade motion about the longitudinal axis are:

$$\ddot{\theta}_k + \Omega^2\ \theta_k = M_x / J_x \tag{6}$$

$$-2\ J_z\ \Omega\ \ \dot{\theta}_k \sin\theta_k = M_z \tag{7}$$

$$J_y\ \Omega\ \ \dot{\theta}_k \cos\theta_k - J_y\ \ \dot{\theta}_k \cos\theta_k = 0 \tag{8}$$



Sl. 3. *Koordinatni sistem na profilu kraka*
Fig. 3. *Coordinate system at the blade cross-section*

2 ROTORSKE SILE

Za projekcijo sil lahko uporabimo naslednje osi: os v smeri vlečne sile rotorja, os rotorskega diska, ki je pravokotna na ravnino rotorja, to je na ravnino, kjer ležijo konci krakov in os gredi.

Ko izberemo eno izmed teh osi, bosta preostali dve osi v koordinatnem sistemu pravokotni nanjo, usmerjeni bočno, oziroma proti repu helikopterja. Običajno se komponenta sile v smeri izbrane osi

2 ROTOR FORCES

To project the forces the following axes may be used: the control axis, the rotor disc axis (which is normal to the rotor plane, i.e., to the plane on which the blade tips reside), and the shaft axis.

Once the axis is chosen, the remaining axes of the coordinate system will be normal to it and pointed laterally, i.e., to the tail of the helicopter. The force component along the chosen axis is normally referred imenuje **vlečna sila**, komponenta sile proti repu se imenuje **sila *H***, a komponenta sile, usmerjena bočno, se imenuje **sila *Y***. Če komponente sile označimo brez indeksiranja, menimo da se nanašajo na os v smeri včene sile. Indekse "*D*" in "*S*" uporabljamo, če se komponente nanašajo na os rotorja oziroma na os pogonske gredi.

Ker sta kota mahanja in zaostajanja ponavadi majhna (do 10°), lahko napišemo:

to as the **tow force**, the force component pointed towards the tail is called the ***H* force**, and the force component pointed laterally is said to be the ***Y* force**. If the force components are designated without subscripts, it is assumed that they are determined relative to the control axis, whereas the subscripts "*D*" and "S" are used when they relate to the rotor axis, i.e., the shaft axis.

Since the flutter and mount angles are usually small (to 10°), a relation between these components can be obtained:

$$T \approx T_D \approx T_S$$
$$H \approx H_D + T_D\ a_1 \cong H_S + T_S\ B_1$$

2.1 Vzdolžno ravnotežje sil

2.1 Longitudinal equilibrium of forces

Kot B_1 je vzdolžna amplituda ciklične spremembe koraka kraka; kot a_{1s} je kot med gredjo in osjo rotorskega diska. Po obsežnih izračunih dobimo izraz za vzdolžno amplitudo ciklične spremembe koraka kraka:

Angle B_1 is the longitudinal amplitude of a cyclic change in the blade step; angle a_{1s} is the angle between the shaft and the axis of the rotor disc. After extensive calculus the expression for the longitudinal amplitude of cyclic change in the blade step is obtained:

$$B_1 = \frac{M_f - G \cdot fR + H \cdot hR + M_S \cdot a_1}{T \cdot hR + M_S} \tag{9}$$

Za e=0, lahko vzamemo da je M_s=0 in M_f=0. Ker je T=G, sledi:

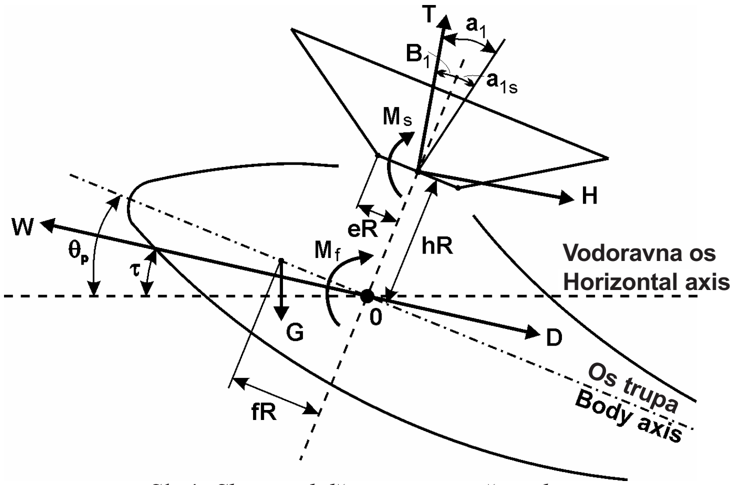
For e=0, we can say that M_s=0 and M_f=0, and since T=G, it follows that:

$$B_1 = -\frac{f}{h} + \frac{H}{G} \tag{10}$$

$$\theta_p = -\frac{D}{G}\cos\tau - \frac{f}{h} + \frac{M_f}{G \cdot hR} \tag{11}$$

Za enačbo (10) imamo preprosto fizikalno pojasnilo: amplituda vzdolžnega cikličnega krmiljenja krakov mora imeti tako vrednost, da postavi smer rezultirajoče sile rotorja skozi masno središče.

Equation (10) has a simple physical interpretation: the amplitude of the longitudinal cyclic control must have such a value in order to position the direction of the resultant rotor force through the center of mass.



Sl. 4. *Skica vzdolžnega ravnotežja sil*
Fig. 4. *Drawing for determining the longitudinal equilibrium of forces*

2.2 Prečno ravnotežje sil

Kot A_1 pomeni amplitudo prečne ciklične spremembe koraka kraka rotorja:

2.2 Lateral equilibrium of forces

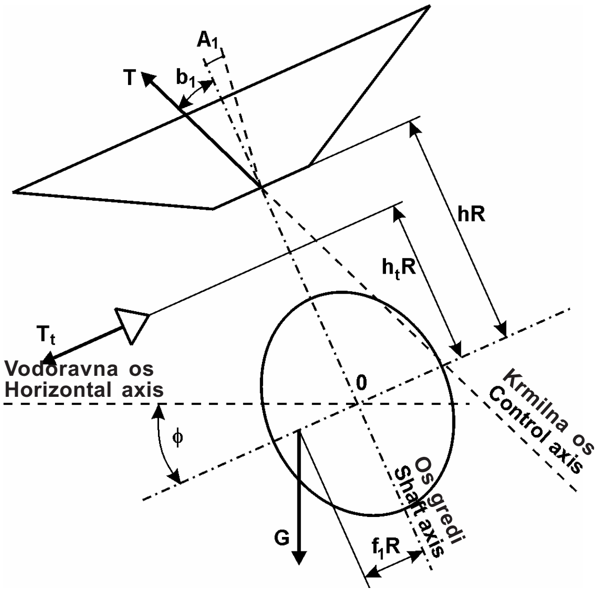
Angle A_1 represents the amplitude of lateral cyclic change in the blade step of the supporting helicopter rotor:

$$A_1 = -\frac{G \cdot f_1 R + M_S \cdot b_1 + T_t \cdot h_t R}{G \cdot hR + M_S} \tag{12}$$

Če vrednost A_1 uvrstimo v ustrezne enačbe, dobimo vrednost kota ϕ, ki določa lego trupa.

By replacing the value A_1 in the corresponding equations, we obtain the value of angle ϕ, which determines the position of the fuselage.

$$\phi = -\frac{T_t}{G} + \frac{G \cdot f_1 R + M_S \cdot b_1 + T_t \cdot h_t R}{G \cdot hR + M_S} \tag{13}$$



Sl. 5. *Skica prečnega ravnotežja sil*

Fig. 5. *Drawing for determining the lateral equilibrium of forces*

Če je M_S=0 in h_t=h, kar pogosto lahko vzamemo, sledi:

If M_S=0 and h_t=h, which can often be assumed, it follows that:

$$\phi \approx \frac{f_1}{h},$$

kar pomeni, da je glava rotorja navpično nad masnim središčem. Vse vrednosti izračunanih kotov so tako imenovane *uravnovešene vrednosti*.

which means the rotor hub is positioned vertically above the center of mass. All the values of these determined angles are the so-called *trimmed values*.

3 NELINEARNI MATEMATIČNI MODEL DINAMIKE LETENJA

Matematično modeliranje helikopterskega gibanja je izredno zahtevna naloga in zato je nujno privzeti številne predpostavke in približke. Za analizo dinamičnih značilnosti helikopterja ni nujno treba, razen v izjemnih primerih, poznati gibanja

3 NON-LINEAR MATHEMATICAL MODEL OF THE FLIGHT DYNAMICS

Mathematical modeling of a helicopter's motion is a very complex task and, therefore, it is necessary to introduce a series of assumptions and approximations. Knowledge of the motion of the individual helicopter blades is not necessary for investigating the dynamic posameznih krakov. Za definiranje sil in momentov pri motenem letu je dovolj opazovati rotor kot celoto. Zaradi velikega števila različnih helikopterjev, v tem prispevku analiziramo helikopter z enim samim rotorjem, katerega kraki so s členki pritrjeni na glavo rotorja. Kakor je že bilo rečeno, je helikopter zmožen različnih gibanj in bi zato bilo zelo težko narediti matematični model za kombinacijo vseh gibanj. Vzeli bomo, da je helikopter vzletel in da leti premočrtno. Komponente hitrosti helikopterja pri nominalni vrednosti in premočrtnem letenju so: W_x, W_y in W_z. Koti spremembe smeri ψ, nagiba ϕ in vzpenjanja θ, veljajo dokler so velikosti motenj v dovoljenih mejah. Na sliki 6 je predstavljena shema helikopterja s premičnim koordinatnim sistemom, vezanim na njegovo masno središče, a na sliki 7 je blokovni diagram helikopterja.

Po uvedbi nekoliko predpostavk, na primer da:

- je masa helikopterja konstantna,
- je helikopter togo telo,
- ravnina *xz* simetrijska ravnina,
- so kotni prirastki $\Delta\Psi$, $\Delta\theta$, $\Delta\phi$ majhni in tako dalje;

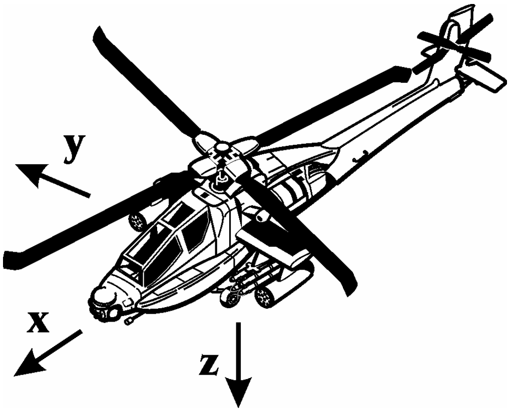
pridemo do nelinearnega matematičnega modela z odkloni v obliki:

characteristics of the helicopter, except in a special case, but rather for defining the forces and moments in a disturbed flight it is sufficient to view the rotor as a whole. Because of the large number of different helicopters, in this paper a single-rotor helicopter that has its blades connected to the hub by hinges was studied. As mentioned before, the helicopter can perform different movements and it would be very difficult to make a mathematical model that would combine all those movements. It is assumed that the helicopter is airborne and in straightforward flight. It is necessary that the helicopter, during its straightforward flight, has the following velocity components, W_x, W_y, and W_z, at nominal values, and the angle of turn ψ, the angle of roll ϕ, and the angle of climb θ, as long as the intensity of disturbance is within permitted limits. Figure 6 presents a schematic of the helicopter with a floating coordinate system tied to its center of mass, and Figure 7 presents a helicopter block diagram.

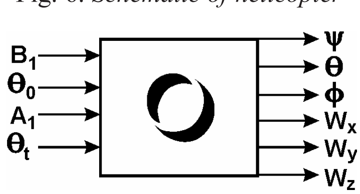
After introducing a series of assumptions, such as:

- the helicopter mass is a constant value,
- the helicopter is a rigid body,
- the 0*xz* is a plane of symmetry,
- the angle increments $\Delta\Psi$, $\Delta\theta$, $\Delta\phi$ are too small, and so on,

we come to a non-linear mathematical model with deviations in the form:



Sl. 6. *Shema helikopterja*
Fig. 6. *Schematic of helicopter*



Sl. 7. *Blokovni diagram helikopterja*
Fig. 7. *Helicopter block diagram*

$$\frac{d(\Delta W_x)}{dt}=\frac{1}{m}\left[f_1\left(\Delta W_x,\Delta W_z,\Delta\dot{\theta},u_1,u_2\right)-\left(mg\cos\tau\right)\Delta\theta\right] \tag{14}$$

$$\frac{d(\Delta W_z)}{dt}=\frac{1}{m}\left[f_2\left(\Delta W_x,\Delta W_z,\Delta\dot{\theta},u_1,u_2\right)+W_{zN}m\Delta\dot{\theta}-\left(mg\sin\tau\right)\Delta\theta\right] \tag{15}$$

$$\frac{\mathrm{d}(\Delta\theta)}{\mathrm{dt}}=\Delta\dot{\theta} \tag{16}$$

$$\frac{\mathrm{d}(\Delta\dot{\theta})}{dt}=\frac{1}{J_y}f_3\left(\Delta W_x,\Delta W_z,\Delta\dot{W}_z,\Delta\dot{\theta},u_1,u_2\right) \tag{17}$$

$$\frac{d(\Delta W_y)}{dt}=\frac{1}{m}\left[f_4\left(\Delta W_y,\Delta\dot{\phi},\Delta\dot{\psi},u_3,u_4\right)+W_{zN}m\Delta\dot{\psi}+mg\cos\tau\Delta\theta+mg\sin\tau\Delta\psi\right] \tag{18}$$

$$\frac{\mathrm{d}(\Delta\phi)}{\mathrm{dt}}=\Delta\dot{\phi} \tag{19}$$

$$\frac{\mathrm{d}(\Delta\dot{\phi})}{dt}=\frac{1}{J_x}\left[f_5\left(\Delta W_y,\Delta\dot{\phi},\Delta\dot{\psi},u_3,u_4\right)+J_{xz}\Delta\dot{\psi}\right] \tag{20}$$

$$\frac{\mathrm{d}(\Delta\psi)}{\mathrm{dt}}=\Delta\dot{\psi} \tag{21}$$

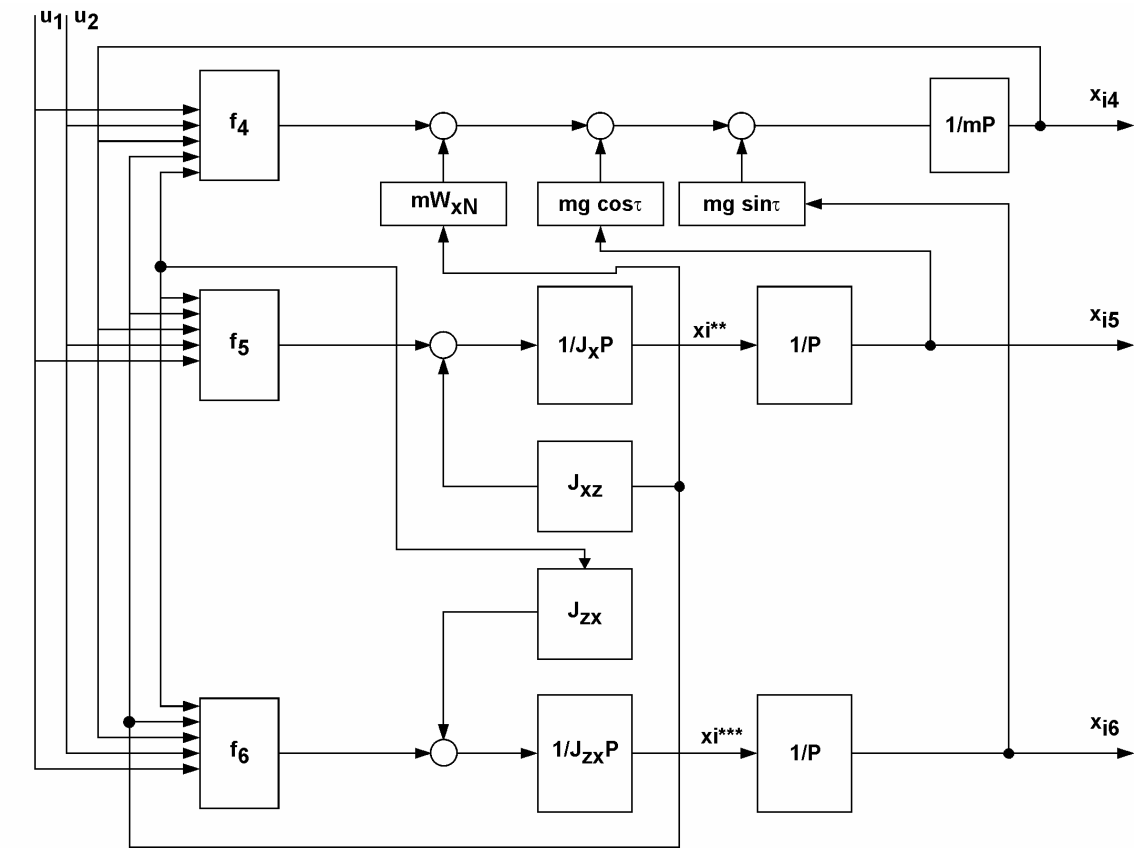
$$\frac{\mathrm{d}(\Delta\dot{\psi})}{dt}=\frac{1}{J_z}\left[f_6\left(\Delta W_y,\Delta\dot{\phi},\Delta\dot{\psi},u_3,u_4\right)+J_{xz}\Delta\dot{\phi}\right] \tag{22}$$

Kjer so:

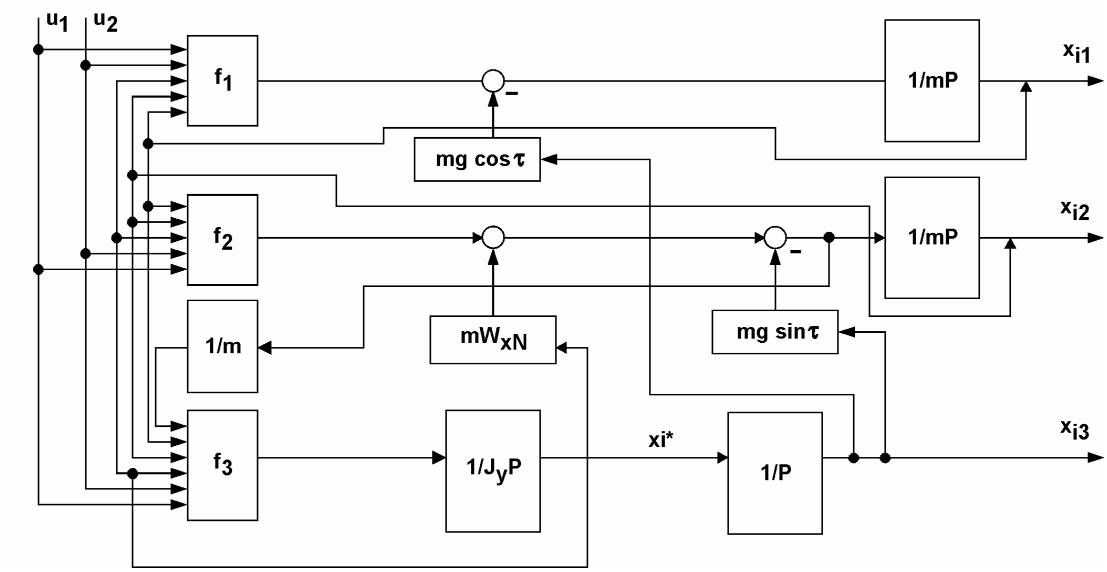
- $u_1=\Delta B_1$ – amplituda ponovitvene spremembe koraka v vzdolžni smeri (za vzdolžno gibanje),
- $u_2=\Delta\theta_0$ – sprememba skupnega koraka kraka rotorja helikopterja (za vzdolžno gibanje),

Where:

- $u_1=\Delta B_1$ – the amplitude of the cyclic change in step in the longitudinal direction (in terms of longitudinal motion),
- $u_2=\Delta\theta_0$ – the change of the collective step of the helicopter rotor blade (in terms of longitudinal motion),



Sl. 8. *Shema prečnega gibanja*
Fig. 8. *Schematic for lateral motion*



Sl. 9. *Shema vzdolžnega gibanja*

Fig. 9. *Schematic for longitudinal motion*

- $u_3=\Delta A_1$ – amplituda ponovitvene spremembe koraka v prečni smeri (za prečno gibanje) in
- $u_4=\Delta\theta_t$ – sprememba skupnega koraka repnega rotorja (za prečno gibanje).

Shematska diagrama predstavljamo na slikah 8 in 9.

- $u_3=\Delta A_1$ – the amplitude of the cyclic change in step in the lateral direction (in terms of lateral motion),
- $u_4=\Delta\theta_t$ – the change of the collective step of the tail rotor (in terms of lateral motion).

Schematic diagrams are presented in Figures 8 and 9.

4 LINEARIZIRANI MATEMATIČNI MODEL DINAMIKE LETENJA

Dokazano je, da v tehniki lahko uporabimo s sprejemljivo natančnostjo linearizirane matematične modele pod pogojem, da imajo fizikalne veličine majhna odstopanja od nominalnih vrednosti. Nelinearni matematični model dinamike letenja helikopterja ni primeren za določanje splošnih rešitev v analitični obliki, čeprav se problem rešuje s sodobno računalniško tehnologijo.

Zaradi sprejetih predpostavk bodo izstopne vrednosti, vstopne vrednosti in vektor stanja tako za vzdolžno kakor za prečno gibanje:

4 LINEARIZED MATHEMATICAL MODEL OF THE FLIGHT DYNAMICS

In technical applications it has been shown that, with an acceptable accuracy, linearized mathematical models may be used under the condition that the deviations of the physical quantities from their nominal values are small. A non-linear mathematical model of the helicopter's flight dynamics is inadequate for finding general solutions in an analytical form, even though the problem is solved with the aid of modern computer technology.

The outcome of the adopted presumptions is that the output values, input values, and the vector of state for both the longitudinal and lateral motion will be:

$$\underline{X}=\left(X_1\ldots X_9\right)^T \tag{23}$$

$$\underline{X_i}=\left(X_{i1}\ldots X_{i6}\right)^T \tag{24}$$

$$\underline{u}=\left(u_1\ldots u_4\right)^T \tag{25}$$

Vektorska enačba stanja za linearizirani matematični model z brezrazsežnimi veličinami, odstopanji, to je veličinami stanja, je enačba (26). Enačba izstopnih veličin je (27).

The vector equation of state for the linearized mathematical model with non-dimensional quantities, deviations, i.e., the quantities of state, is shown in Equation (26). Equation (27) presents the output values.

$$\underline{\dot{X}} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & 0 & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ a_{41} & a_{42} & a_{43} & a_{44} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & a_{55} & a_{56} & 0 & a_{58} & a_{59} \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & a_{75} & 0 & a_{77} & 0 & a_{79} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & a_{95} & 0 & a_{97} & 0 & a_{99} \end{bmatrix} \underline{X} + \begin{bmatrix} b_{11} & b_{12} & 0 & 0 \\ b_{21} & b_{22} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ b_{41} & b_{42} & 0 & 0 \\ 0 & 0 & b_{53} & b_{54} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & b_{73} & b_{74} \\ 0 & 0 & 0 & 0 \\ 0 & 0 & b_{93} & b_{94} \end{bmatrix} \underline{u} \qquad (26)$$

$$\underline{X_i} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \underline{X} \qquad (27)$$

Čeprav so tukaj prikazana v skupni matrici, je treba poudariti, da so vzdolžna in prečna gibanja ločena, ker je to bil eden izmed pogojev za izpeljavo tega matematičnega modela. V enačbah (26) in (27), so enačbe za vzdolžno gibanje predstavljene v prvih štirih vrsticah matrike, medtem ko preostalih pet vrstic pomeni enačbo stanja in enačbo prečnega gibanja. V enačbi (26) uporabljamo naslednje označbe:

In addition to the way this is presented, in the form of a common matrix, it should also be noted that the longitudinal and lateral motions are separated, because this was the condition for deriving this mathematical model. In Equations 26 and 27, the equations for the longitudinal motion are presented within the first four rows of the matrice, while the remaining five rows present the equation of state and the equation of lateral motion. The designations used in Equation 26 are:

$$C^* = \frac{1}{1 - i_{xz}^2 / i_x i_z} \qquad a_{11} = x_u \qquad a_{12} = x_w \qquad a_{13} = -m_c \cos\tau \qquad a_{14} = x_q \qquad a_{21} = z_u$$

$$a_{22} = z_w \qquad a_{23} = -m_c \sin\tau \qquad a_{24} = \hat{W}_{xN} + z_q \qquad a_{55} = y_v \qquad a_{56} = m_c \cos\tau \qquad a_{58} = m_c \sin\tau$$

$$a_{59} = \hat{W}_{xN} \qquad a_{41} = m_u + m_{\dot{w}} z_u \qquad a_{42} = m_w + m_{\dot{w}} z_w \qquad a_{43} = -m_{\dot{w}} m_c \sin\tau \quad a_{44} = m_q + m_{\dot{w}} \left(\hat{W}_{xN} + z_q \right)$$

$$b_{11} = x_{B_1} \qquad b_{12} = z_{B_1} \qquad b_{21} = x_{\theta_0} \qquad b_{22} = z_{\theta_0} \qquad b_{41} = m_{\dot{w}} z_{B_1} + m_{B_1} \qquad b_{42} = m_{\dot{w}} z_{\theta_0} + m_{\theta_0}$$

$$b_{53} = y_{A_1} \qquad b_{54} = y_{\theta_t} \qquad b_{73} = \left(l_{A_1} + n_{A_1} i_{xz} / i_x \right) C^* \quad b_{74} = \left(l_{\theta_t} + n_{\theta_t} i_{xz} / i_x \right) C^* \quad b_{94} = \left(n_{\theta_t} + l_{\theta_t} i_{xz} / i_z \right) C^*$$

$$a_{75} = \left(n_v i_{xz} / i_x + l_v \right) C^* \quad a_{77} = \left(l_p + n_p i_{xz} / i_x \right) C^* \qquad a_{95} = \left(n_v + l_v i_{xz} / i_z \right) C^* \quad a_{97} = \left(n_p + l_p i_{xz} / i_z \right) C^*$$

$$a_{99} = \left(n_r + l_r i_{xz} / i_z \right) C^* \qquad b_{93} = \left(n_{A_1} + l_{A_1} i_{xz} / i_z \right) C^* \quad a_{79} = \left(l_r + n_r i_{xz} / i_x \right) C^*$$

Na slikah 10 in 11 so predstavljene sheme lineariziranega matematičnega modela v vzdolžnem in prečnem gibanju.

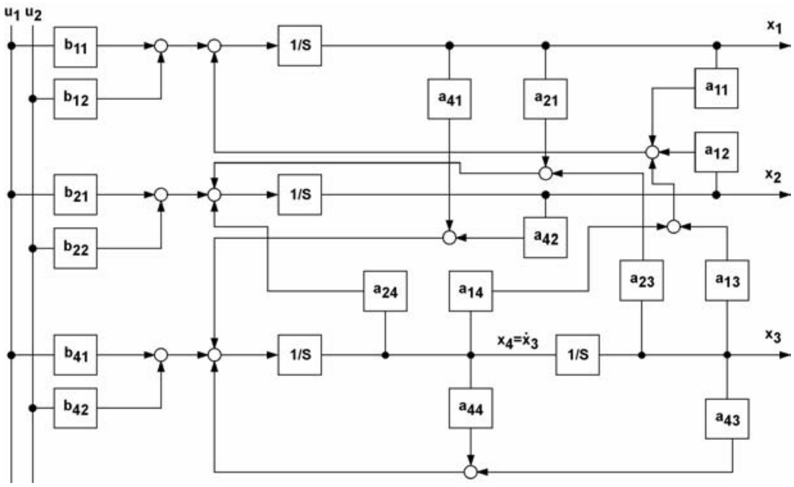
Figures 10 and 11 present schematics of the linearized mathematical model in a longitudinal and lateral motion.

5 REZULTATI PROGRAMA

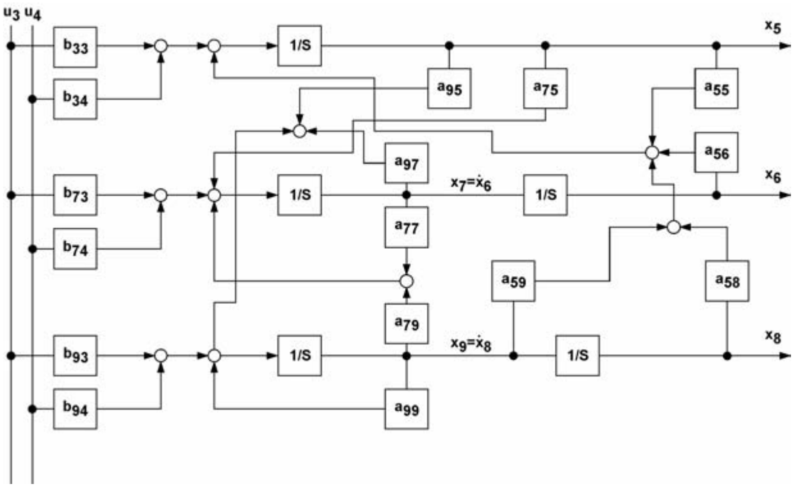
5 PROGRAM RESULTS

Program je testiran na primeru helikopterja z enim samim rotorjem, ki ima krake členkasto vpete na glavo rotorja. Helikopter je opisan z naslednjimi vstopnimi podatki: teža helikopterja *G*=45042N, količnik pokritja rotorja *s*=0,058, polmer rotorja *R*=8,1m, koeficient višine glave rotorja *h*=0,25, količnik upora δ=0,013, število krakov glavnega rotorja *b*=4, masa kraka *m*=79,6kg, količnik napredovanja rotorja

The program was tested on the example of a single-rotor helicopter for which the main rotor blades are tied to the hub over hinges. The helicopter is described by the following input data: helicopter weight, *G*=45042N; rotor abundance degree, *s*=0.058; rotor radius, *R*=8.1m; hub height coefficient, *h*=0.25; drag coefficient, δ=0.013; number of blades of the main rotor, *b*=4; blade mass, *m*=79.6kg; rotor



Sl. 10. *Shema lineariziranega matematičnega modela pri vzdolžnem gibanju*
Fig. 10. *Schematic of a linearized mathematical model when in longitudinal motion*



Sl. 11. *Shema lineariziranega matematičnega modela pri prečnem gibanju*
Fig. 11. *Schematic of linearized mathematical model when in lateral motion*

μ=0,3, vzgonski gradient profila a=5,65 1/rad, hitrost konca kraka ΩR=208m/s, masno središče kraka x_g je na 45% radija kraka R, oddaljenost členka kraka od gredi pa je 0,04R, gostota zraka na višini letenja (100m) ρ=1,215 kg/m^3. Za vzdolžno gibanje je matematični model v vektorski obliki:

operating mode coefficient, μ=0.3; gradient of lift, a=5.65; velocity of blade top, ΩR=208m/s; distance of blade mass center coefficient, x_g=0.45; distance of hinge from shaft, eR=0.04R; and air density at flight altitude (100m), ρ=1.215 kg/m^3. For longitudinal motion the mathematical model in vector form is:

$$\underline{\dot{X}} = A\ \underline{X} + b\ \underline{u}$$

$$\underline{\dot{X}} = \begin{bmatrix} -0,0509 & 0,1323 & -0,0734 & 0,00263 \\ 0,1216 & -1,2525 & 0 & 0,3 \\ 0 & 0 & 0 & 1 \\ 6,512 & 12,1 & 0 & -0,844 \end{bmatrix} \underline{X} + \begin{bmatrix} 0,1344 & 0,066 \\ 0,3578 & -0,9477 \\ 0 & 0 \\ -28,329 & 17,88 \end{bmatrix} \underline{u}$$

$$\underline{X} = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} \qquad \underline{u} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

Enačba izstopnih veličin je:

The equation at the exit is:

$$\underline{X_i} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \underline{X} \quad \text{kjer je/where is} \quad \underline{X_i} = \begin{bmatrix} X_{i1} \\ X_{i2} \\ X_{i3} \end{bmatrix}$$

Matrika A lineariziranega modela helikopterja za prečno gibanje je:

Matrix A of the linearized model of the helicopter for lateral motion is:

$$A = \begin{bmatrix} -0,15125 & 0,0734 & 0 & 0 & 0,3 \\ 0 & 0 & 1 & 0 & 0 \\ -64,42 & 0 & -2,948 & 0 & 1,378 \\ 0 & 0 & 0 & 0 & 1 \\ 55,297 & 0 & 0,413 & 0 & -1,64 \end{bmatrix}$$

$$\underline{\dot{X}} = A\ \underline{X} + B\ \underline{u}$$

$$\underline{X} = \left[X_5 \quad X_6 \quad X_7 \quad X_8 \quad X_9 \right]^T$$

$$\underline{u} = \left[u_3 \quad u_4 \right]$$

6 SKLEPI

Da bi bil matematični model dinamike helikopterskega letenja, strogo določen, bi moral biti sestavljen iz sistema nelinearnih, neustaljenih, parcialnih diferencialnih enačb. Da bi te enačbe poenostavili, smo vzeli nekaj predpostavk. Zanemarili smo elastične lastnosti helikopterja, da bi helikopter analizirali kot togo telo in tako eliminirali razpršitev parameterov. Poleg tega smo zanemarili porabo goriva in s tem neustaljenost, ki bi se pojavila zaradi časovne spremembe mase helikopterja.

Glede na to, da ima helikopter šest prostostnih stopenj, smo zaradi poenostavitve vzeli, da se gibanje da ločiti na vzdolžno in prečno gibanje in da se ta gibanja analizirajo posamično. Povdarimo, da se matematični model helikopterja nanaša na helikoptersko premočrtno gibanje s hitrostjo W. Matematični model, ki bi obsegal vsa gibanja helikopterja, vključno z vzletom in pristankom, bi bil veliko bolj zapleten. Vpliv resonance in vibracije se prav tako zanemari. Zaostajanje kraka se tukaj tudi ne upošteva, ker drugače kotna hitrost kraka v ravnini rotacije ne bi bila več nespremenljiva. Ločene analize posamičnih gibanj krakov so velika poenostavitev, zato ker obstaja velika medsebojna odvisnost med gibanji kraka. Če bi ta gibanja ne bili ločili, bi bilo nujno analizirati stabilnost vseh gibanj kraka.

Postavljanje koordinatnega začetka v vztrajnostno središče omogoča odstranitev nekaterih vztrajnostnih momentov, tako da se

6 CONCLUSIONS

The flight dynamics mathematical model of a helicopter that would be strictly determined would comprise a system of non-linear, non-stationary, partial differential equations. To simplify these equations we introduce a number of assumptions. Ignored are the elastic characteristics of the helicopter so the helicopter can be thought as a rigid body and, in this way, the dispersal of parameters is eliminated. Also, fuel consumption is disregarded and so is the non-stationarity due to the temporal change in helicopter mass being eliminated.

Because the helicopter has six degrees of freedom, for simplification it is assumed that the motion can be separated into longitudinal and lateral motions and that they can be investigated independently. It should be noted that the mathematical model of the helicopter relates to the helicopter's forward motion at velocity W. A mathematical model that would incorporate all the motions of a helicopter, all together with takeoff and landing, would be far too complicated. The influence of resonance and vibration is also ignored. The blade throughback is also ignored in this paper, because if this was not the case the blade-angle velocity in the plane of rotation would no longer be constant. A separate study of the individual motions of blades is a great simplification, because there is an interdependency of all the blade motions. If the motions are not separated, then it is necessary to analyze the stability of all the motions of the blade.

The choice of the coordinate origin in the center of inertia makes it possible to eliminate certain moments of inertia so the Euler equations can be

Eulerjeve enačbe lahko poenostavijo. Opazovanje rotorja kot celote odstrani potrebo po preučevanju posameznih gibanj krakov. V tem je v veliko pomoč uvajanje osi rotorskega diska in osi v smeri vlečne sile rotorja.

Določanje aerodinamičnih odvodov je povezano z vrsto približkov. Treba je poudariti, da poleg predpostavk pri modeliranju, uporabljamo tudi matematične poenostavitve (na primer, izpuščanje zanemarljivo majhnih vrednosti iz enačb), ki jih ni mogoče prikazati v obliki predpostavke, ker je njihov pomen tesno povezan z določeno enačbo.

Kot izstopne značilnosti je mogoče določiti projekcije vektorja lege v nepremičnem koordinatnem sistemu, povezanem s tlemi namesto projekcij hitrosti helikopterja v premičnem koordinatnem sistemu. Ta problem bi se rešil s projiciranjem hitrosti helikopterja na nepremični koordinatni sistem, nakar bi se integrirale projekcije hitrosti po času z začetnimi pogoji.

Nadaljnja analiza matematičnega modela se lahko usmeri na raziskovanje dinamičnih in statičnih lastnosti in na določanje primernega krmarjenja, ki bi helikopterju zagotovilo zahtevano dinamično obnašanje.

simplified. Viewing the rotor as a whole eliminates the need for investigating the motion of an individual blade. This is made much simpler by the introduction of the rotor disc axis and the control axis.

The determination of the aerodynamic derivatives is related to a series of approximations. It should be noted that, besides assumptions in the modeling, mathematical simplifications were also made (for example, omitting small values in the equations) which could not have been derived in the form of an assumption due to their meaning, which is tightly related to a specific equation.

It is possible to determine projections of the position vector with respect to the non-moveable coordinate system tied to Earth instead of using projections of the helicopter's velocity with respect to a moveable coordinate system such as the exit characteristics. Projecting the helicopter velocity onto a non-moveable coordinate system and then integrating the velocity projections over time with the initial conditions may solve this problem.

A further analysis of the mathematical model can be made in order to investigate the dynamic and static properties, and to determine the control that would guarantee the object to execute the required dynamic behavior.

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Naslova avtorjev: Dragan Cvetković
Univerza "Union"
Fakulteta računalniških znanosti
Knez Mihailova 6/VI
11000 Beograd, Srbija

Duško Radaković
Zvezni zavod za mere in dragocene metale
Mike Alasa 14
11000 Beograd, Srbija

Authors' addresses: Dragan Cvetković
University "Union"
Faculty of Computer Science
Knez Mihailova St. 6/VI
11000 Belgrade, Serbia

Duško Radaković
Federal Bureau for Measures and Precious Metals
Mike Alasa St. 14
11000 Belgrade, Serbia

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Določanje vijačnih lastnosti motorja z merilnimi lističi in osebnim računalnikom v ustaljenih razmerah plovbe ladje

Determining the Propulsion Characteristics of an Engine Under the Conditions of a Standard Sailing Regime by Means of Strain Gauges and a Personal Computer

Sead Cvrk - Zdravko Đukić - Milorad Rodić
(Mornarica SČG, Črna Gora; Navy SCG, Montenegro)

V tem prispevku je z uporabo merilnih lističev in osebnega računalnika, z nedotikalno metodo, opisan postopek merjenja elastične deformacije osi ladijskega vijaka. Na podlagi znanega prečnega prereza in vrste materiala osi ladijskega vijaka, je določen vrtilni moment. Z znano frekvenco osi, kotno hitrostjo in vrtilnim momentom je mogoče določiti delež koristne moči, ki se prenaša od motorja do ladijskega vijaka. Vsa uporabljena oprema pri preizkusih, tako strojna kakor programska oprema, je bila izdelana v podjetju "HOTTINGER BALDVIN MESSTEHNIK" (HBM), Darmstadt, Nemčija. Preizkus je potekal na ladji Mornarice Srbije in Črne Gore pri ustaljeni plovbi.

(Ključne besede: ladijski motorji, dizelski motorji, vijačne lastnosti, merilni listič)

This paper describes the process of measuring a propeller shaft's elastic deformation by means of a non-contact method, strain gauges and a PC. By using the known cross-section as well as the propeller shaft's material type the torque was determined. Knowing the shaft frequency, that is the radial velocity and the torque, it is possible to determine the effective power transmitted from the engine to the propeller. The equipment, i.e., the hardware and the software, was produced by HOTTINGER BALDWIN MESSTEHNIK (HBM), Darmstadt, from the Federal Republic of Germany. The experiment was carried out on a ship belonging to the Navy of Serbia and Montenegro under the conditions of a standard sailing regime.

(Keywords: ship diesel engines, propulsion systems characteristics, strain gauges)

0 UVOD

Moč ladijskega motorja se v času njegove uporabe stalno spreminja, odvisno od priključenega porabnika. Pri potisku ladje z ladijskima vijakom z nepremičnimi krili, je koristna moč na ladijskem vijaku, odvisna od števila vrtljajev in geometrijskih lastnosti ladijskega vijaka. Pri nespremenljivem premeru in koraku ladijskega vijaka, je upor ladijskega vijaka, ki ga premaguje motor, sorazmeren kvadratu števila vrtljajev ladijskega vijaka.

0 INTRODUCTION

During the exploitation of a diesel engine, the changes of engine power always depend on connected devices. When a ship is propelled by a screw, the power that the engine delivers to the fixed thread screw depends on the number of turns and the geometrical characteristics of the screw. When the screw diameter and the thread are fixed, the resistance of the propeller, which is suppressed by the engine, is proportional to the square of the number of revolutions.

$$M = k_0 \cdot n^2 \quad (1).$$

Delež koristne moči motorja na ladijskem vijaku se lahko izrazi v odvisnosti od vrtilnega momenta, ki se prenaša od ročične osi prek spojke na ladijski vijak, ta se vrti s kotno hitrostjo ω.

The effective power that an engine transmits to the screw can be expressed by the torque that the clump transfers from the crankshaft to the screw, while it revolves at angular velocity ω.

$$P_e = M \cdot \omega \qquad (2).$$

V primeru, ko motor poganja ladijski vijak z določenim korakom kril, bo moč motorja, ki jo absorbira ladijski vijak pri različnih vrtljajih [1]:

In the case when the engine drives the fixed thread screw, the power of the engine that the screw absorbs, at different numbers of revolutions, is [1]:

$$P_e = M \cdot \omega = k_0 \cdot n^2 \cdot \frac{\pi \cdot n}{30} = k_1 \cdot n^3 \qquad (3).$$

Enačba (3) pove, da se moč motorja spreminja po kubni paraboli v odvisnosti od spremembe števila vrtljajev ladijskega vijaka. Krivulja se imenuje vijačna lastnost motorja (sl. 1, krivulja 1).

Pri uporabi ladijskega motorja je zelo pomembno določiti preneseno moč na ladijski vijak pri vseh vrtljajih. Na podlagi posnete vijačne lastnosti se da določiti, v katerem režimu motor deluje v področju možnih vrtljajev, oziroma ali deluje po proračunski lastnosti vrtilnega momenta pri plovbi, lastnosti vrtilnega momenta pri plovbi s "težkim ladijskim vijakom", ali po lastnosti vrtilnega momenta pri plovbi z "lahkim ladijskim vijakom".

V ladijskih razmerah običajno nimamo na voljo opreme za merjenje vrtilnega momenta motorja (ali njegove moči) in potisne sile ladijskega vijaka. Zato je v takšnih razmerah nujno treba izvajati neposredni nadzor trupa ladje, ladijskega vijaka in motorja.

Posadki ladje, ki upravlja pogonski sestav, znatno pomaga pri rešitvi takšne naloge uporaba ustreznih metod nadzora posameznih delov pogonskega sestava ladje, posebno pa nadzor delovanja glavnih potisnih motorjev.

Ena od učinkovitih metod, s katero se lahko meri vrtilni moment in tako tudi prenesena moč na

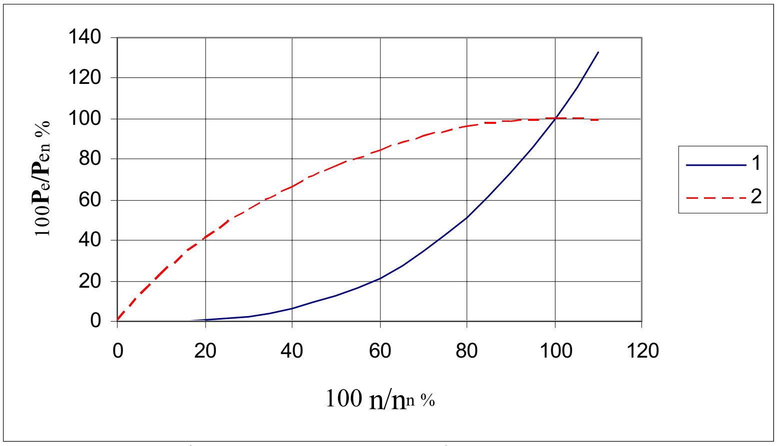
It is evident from Equation (3) that the power of the engine changes with cube parable, which depends on the number of screw revolutions. This curve is called the "screw characteristic of the engine" (Fig. 1, curve 1).

When an engine is used aboard a ship, it is very important to determine the power that the screw absorbs at different numbers of propeller revolutions, ranging from the minimum to the maximum. By using the transcribed characteristics we can determine the regime in which the engine is working at different numbers of propeller revolutions, i.e., whether it works with the forecast characteristic of the screw moment, the characteristic of the screw moment while sailing with a "hard propeller" or the characteristic of the screw moment while sailing with a "light propeller".

Ships usually do not have instruments for measuring the torque (engine power) propeller lifting, and so in this case it is necessary to perform direct control of the hull, the propeller and the engine.

To the members of the crew working in the engine room, using an appropriate method to control the functioning and condition of some of the elements in the engine room, especially of the main propulsion engine, can provide considerable help while executing this task.

One of the effective methods by which we can measure the torque and the power that the en-



Sl. 1. *Vijačna in zunanja lastnost motorja*

Fig. 1. *The screw characteristic and the outer characteristic of the engine*

ladijski vijak, je metoda z uporabo merilnih lističev in osebnega računalnika.

gine transmits to the propeller is a method based on strain gauges and a personal computer.

1 UPORABA MERILNIH LISTIČEV

1 APPLICATION OF THE STRAIN GAUGES

Merilne lističe sta odkrila leta 1938 E.E. Simons in A.C. Ruge iz Kalifornije, ZDA, neodvisno drug od drugega. Prva tovarna za industrijsko izdelavo merilnih lističev je bila zgrajena leta 1941 v Baldwin-Southwark, ZDA. V Evropi je leta 1952 podjetje ''HOTTINGER BALDVIN MESSTECHNIK'' (HBM) iz Darmstadta, Nemčija začelo izdelovati uporovne merilne lističe. Uporaba merilnih lističev je danes že zelo razširjena, unčinkovito se uporabljajo za analizo napetosti v konstrukcijah. Merilni lističi se lahko uporabljajo tudi za statična, navidezno statična in dinamična merjenja na konstrukcijah ali pa tudi na delih strojev.

Ko govorimo o merjenju pomikov in napetosti, se merilni lističi uporabljajo v področju elastičnih deformacij po Hookeovem zakonu. Merilni listič pomeni prevodnik določenega upora in je postavljen na površini merjenega predmeta. Vsaka deformacija merjenega predmeta, zaradi njegove obremenitve, povzroči sorazmerno deformacijo merilnega lističa, kar omogoča merjenje sprememb upora merilnega lističa.

V neobremenjenem stanju je upor merilnega lističa R_0, ko pa se obremeni, je po deformaciji $R_0 + \Delta R$ [2]:

Strain gauges were discovered in 1938 by E.E. Simons and A.C. Ruge (working independently of each other in California, USA). The first company to begin the industrial production of strain gauges was founded in 1941 (Baldwin-Southwark, USA). In Europe, "HOTTINGER BALDWIN MESSTECHNIK" (HBM) from Darmstadt, Germany, began producing foil strain gauges in 1952. The use of strain gauges is widespread, and they can be used for the analysis of a stress measurement in a construction. Strain gauges can be used for static, quasi-static and dynamic measurements on constructions and machine parts.

When measuring dilatation and strain, strain gauges are used in the area of elastic deformations, according to Hooke's law. The strain gauge represents a conductor of defined resistance, fastened to the surface of a measuring object. Each deformation of the measuring object, due to stress, causes a certain deformation of the strain gauge and changes its electrical resistance.

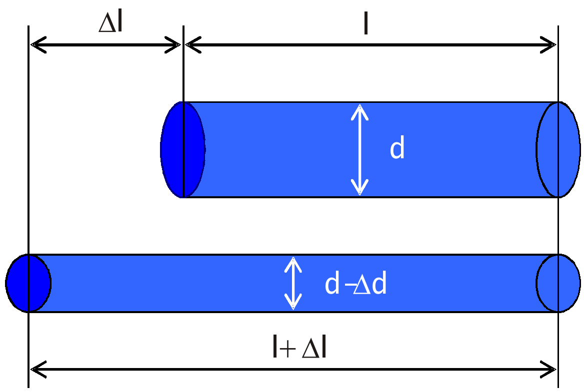
During a no-load state the strain gauge's resistance is R_0, and during a load state, i.e., after the deformation, it will be $R_0 + \Delta R$ [2].

$$R_0 = \frac{\rho \cdot l_o}{\mathrm{A}} = \frac{4 \cdot \rho \cdot l_o}{\pi \cdot d^2} \tag{4}$$

Skupna sprememba upora po deformaciji in spremembi mikrostrukture sestavnih materialov merilnega lističa je:

The total change of resistance, due to the deformation, and the change of the microstructure of the strain-gauge material is:

$$\frac{dR}{R_0} = \varepsilon \cdot (1 + \nu) + \frac{d\rho}{\rho} \tag{5}$$



Sl. 2. *Deformacija predmeta ob obremenitvi*
Fig. 2. *Deformation of an object during a load state*

Odvisnost med mehanično deformacijo in spremembo upora na merilnem lističu za raznovrstne prevodne materiale je omejena z občutljivostjo merilnega traku *k* [2].

The relationship between the mechanical deformation and the strain gauge's electrical resistance for different conductors is determined from the strain gauge's response *k*[2].

$$k = \frac{\frac{\Delta R}{R_o}}{\frac{\Delta l}{l_o}} = \frac{\frac{\Delta R}{R_o}}{\varepsilon} \quad (6).$$

Za nekatere zlitine, ki se uporabljajo pri izdelavi vlaken v merilnem lističu je občutljivost *k* tudi drugačna. Merilni listič naj bi spreminjal upor le zaradi napora v aktivni smeri (smer, v kateri se meri). Če je merilni listič obremenjen v svoji dejavni smeri, je občutljivost (*k* – količnik) definirana kot:

k is different for each alloy that is used for making the strain gauges. The strain gauge should change its resistance only due to the stress in the active direction (the direction of the measurement). If the strain gauge is loaded in its active direction, then the strain gauge's response is defined as:

$$k_l = \frac{\frac{\Delta R}{R_o}}{\varepsilon_l} \quad (7).$$

Če je merilni listič obremenjen v prečni smeri, je *k*-količnik izražen kot:

If the strain gauge is loaded in a transverse direction, then the appropriate *k* factor is defined as:

$$k_t = \frac{\frac{\Delta R}{R_o}}{\varepsilon_t} \quad (8).$$

Razmerje teh dveh količnikov določa prečno občutljivost:

The ratio of these two factors is defined as the cross response:

$$q = \frac{k_t}{k_l} \quad (9).$$

Ta učinek se zmanjša z uporabo uporovnih merilnih lističev s prečnim odebelenjem omrežja. Odvisno od vrste merilnega lističa ter dolžine omrežja je prečna občutljivost $q<0,01$ do 0,02. Merilni lističi se na splošno uporabljajo za merjenje deformacij do 3000 μm/m. Največje podaljšanje merilnega lističa je odvisno od konstrukcije in materiala ter znaša od ± 2 cm/m do 15 cm/m. V primeru velikih deformacij, merilni lističi prikazujejo nelinearne lastnosti, ki niso zanemarljive.

Merilni listič pritrdimo na testirani predmet z lepljenjem, z uporabo različnih vezivnih materialov, kar terja zelo veliko natančnost. Električna vezava merilnih lističev se izvaja v obliki Wheatstonovega mostiča. Wheatstonov mostič se lahko uporabi za merjenje upora, in to:

- za merjenje absolutne vrednosti upora s primerjanjem znanega upora,
- za merjenje relativne spremembe električnega upora.

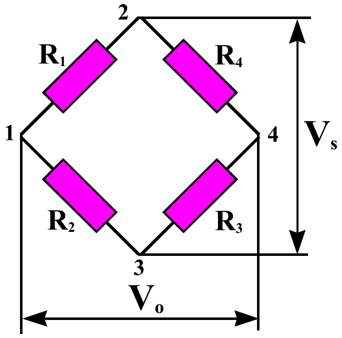
Ta način vezave merilnih lističev omogoča merjenje spremembe upora z zelo veliko natančnostjo, v mejah od 10^{-7} do 10^{-14} Ω/Ω. Merilni lističi so določeni upori, ki se povezujejo od R_1 do R_4, kakor

This effect is reduced by the use of a foil strain gauge with transversal wire thickening. The cross response is between $q<0.01$ to 0.02, depending on the strain-gauge type and the length of its grid. Strain gauges are normally used for measuring deformations up to 3000 μm/m. The maximum deformation of a strain gauge, which depends on its design and material, ranges from ±2 cm/m to 15 cm/m. In the case of extensive deformations, strain gauges show nonlinear characteristics that cannot be neglected.

The strain gauge is glued to the object of investigation using different binding materials, and it requires maximum attention. The electrical connection of the strain gauges is performed in the shape of a Wheatstone bridge. The Wheatstone bridge can be used for the resistance measurement, i.e.:

- for measurement of an absolute value of resistance by comparing it with a known resistance,
- for measurement of the relative alterations of resistance.

Strain gauges connected in this way provide a measurement of resistance alterations, ranging from 10^{-7} to 10^{-4} Ω/Ω, with a high accuracy. Strain gauges represent specific resistors, which



Sl. 3. *Wheatstonov mostiček*
Fig. 3. *The Wheatstone bridge*

je narisano na sliki 3. Točki 2 in 3 se povezujeta z virom električne napetosti V_s, bodisi z enosmernim ali z izmeničnim električnim tokom. V točkah 1 in 4 dobimo izhodno električno napetost V_0, ki izraža vrednost merjenega signala.

Načelo delovanja Wheatstonoevega mostiča se lahko predstavi s sliko 4.

Predvidevamo lahko, da je upor vira električnega toka R_G zanemarljiv ter da je notranji upor naprave za merjenje izhodnega električnega toka zelo velik. Električne napetosti V_1 in V_4 lahko izračunamo z uporabo znanih uporov R_1, R_2, R_3, R_4 in V_s.

are connected from R_1 to R_4 as shown in Figure 3. At points 2 and 3 there is the supply voltage V_s with alternating or direct current. At points 1 and 4 there is the output voltage V_0, that represents the measurement signal.

The basic functioning principles of the Wheatstone bridge can be explained with Figure 4.

It is supposed that the resistance of the source R_G is negligible, and that the inner resistance of the instrument for the measurement of the output voltage is infinite. If the resistances R_1, R_2, R_3, R_4 and V_s are known, voltages V_1 and V_4 can be calculated:

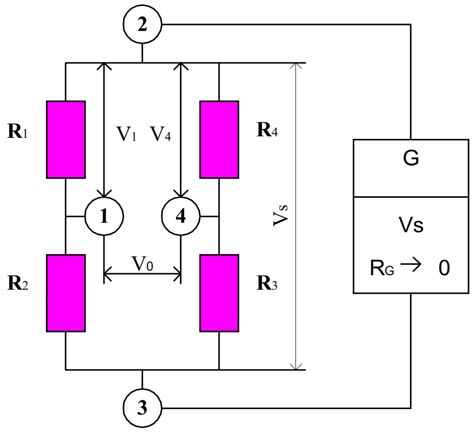
$$V_1 = \frac{R_1}{R_1 + R_2} \cdot V_s \qquad (10)$$

$$V_4 = \frac{R_4}{R_3 + R_4} \cdot V_s \qquad (11).$$

Razlika električnih napetosti V_1 in V_4 je izhodna električna napetost V_0:

The difference between V_1 and V_4 represents the output voltage V_0:

$$V_0 = V_s \cdot \left(\frac{R_1}{R_1 + R_2} - \frac{R_4}{R_3 + R_4} \right) \qquad (12).$$



Sl. 4. *Načelo delovanja Wheatstonovega mosta*
Fig. 4. *The first principles of the Wheatstone bridge*

Neuravnoteženost mostiča je določena kot relativna izhodna električna napetost:

When the bridge is not balanced it is defined as the relative output voltage.

$$\frac{V_0}{V_s}=\frac{R_1}{R_1+R_2}-\frac{R_4}{R_3+R_4} \quad (13).$$

Obstajata dva primera uravnoteženosti mostiča:
- upori upornikov so v mostiču enaki ($R_1=R_2=R_3=R_4$),
- razmerje uporov v obeh polovicah mostiča je enako ($R_1 / R_2 = R_4 / R_3$).

V obeh primerih, ko je vrednost električnih napetosti $V_0 / V_s = 0$, je mostič uravnotežen. Če se vrednosti uporov v mostiču $R_1...R_4$ spremenijo za določeno razliko ΔR, mostič ni uravnotežen, pojavi se določena izhodna električna napetost V_0. V tem primeru je relativna izhodna električna napetost:

There are two cases when the bridge is balanced:
- the electrical resistances of the bridge are equal ($R_1=R_2=R_3=R_4$),
- the proportion of the electrical resistance on both sides of the bridge is equal ($R_1 /R_2=R_4/R_3$).

In both cases $V_0/V_S=0$, and the bridge is balanced. If the electrical resistances in the bridge, $R_1...R_4$, change their values by ΔR, the bridge is not balanced, and there is a certain output voltage, V_0. In this case the relative output voltage is:

$$\frac{V_0}{V_S}=\left(\frac{R_1+\Delta R_1}{R_1+\Delta R_1+R_2+\Delta R_2}-\frac{R_4+\Delta R_4}{R_3+\Delta R_3+R_4+\Delta R_4}\right) \quad (14).$$

Ko je $\Delta R_i << R_i$, se lahko relativna izhodna električna napetost izrazi tudi:

Because of fact that $\Delta R_i << R_i$, the relative output voltage can be expressed as:

$$\frac{V_0}{V_S}=\frac{1}{4}\left(\frac{\Delta R_1}{R_1}-\frac{\Delta R_2}{R_2}+\frac{\Delta R_3}{R_3}-\frac{\Delta R_4}{R_4}\right) \quad (15).$$

Če pa je $\Delta R_i /R_i = k\varepsilon_i$, je relativna izhodna električna napetost:

Considering $\Delta R_i /R_i = k\varepsilon_i$, the relative output voltage is:

$$\frac{V_0}{V_S}=\frac{k}{4}\left(\varepsilon_1-\varepsilon_2+\varepsilon_3-\varepsilon_4\right) \quad (16).$$

Izhodna električna napetost z mostiča je torej funkcija:
- električne napetosti napajanja mostiča V_s,
- *k*-koeficienta merilnega lističa in
- deformacije ali spremembe električne napetosti v vejah ε_1 do ε_4.

The output voltage V_0 is a function of:
- the input voltage of the bridge V_s,
- the *k* strain-gauge factor,
- the deformation or change of voltage in the bridge's branches ε_1 to ε_4.

2 OPIS IN REZULTATI PREIZKUSA

2 DESCRIPTION AND RESULTS OF THE EXPERIMENT

Preizkus je izvajan v ustaljenih razmerah plovbe ladje. Pojem ustaljene razmere plovbe pomeni, da ladja pluje v določeni smeri in v mirnem morju. Eksperimentalno določanje vijačne lastnosti dvotaktnega ladijskega dizelskega motorja, z merilnimi lističi in osebnim računalnikom, z nedotikalno metodo smo izvedli na ladji Mornarice Črne Gore. Dolžina ladje je 96,5 m, širina 12,5m in standardni izpodriv 1470 ton. Vgrez ladje na premcu je 2790 mm, na krmi pa 3240 mm. Ladjo poganjajo dva glavna dizelska motorja in ena plinska turbina prek lastnih pogonskih osi. Na koncu vsake pogonske osi je trikrilni ladijski vijak z

The experiment was carried out under the standard sailing-regime conditions of a navy vessel. The standard sailing regime means that the ship is sailing on a given course and still at sea. The experimental determination of the screw characteristics of a two-stroke naval diesel engine by means of strain gauges and a personal computer, a no-contact method, was performed on a Serbian and Montenegrin Navy vessel. The length of the ship was 96.5 m, the width 12.5 m, and the standard displacement 1470 t. The drift on the prow was 2.79 m; the drift on the stern was 3.24 m. The ship is pronepremičnimi krili. Dizelski motorji so vrstni, vsak s po devet valji v dveh vrstah v navpičnem bloku. Motor je vrste 68B in je dvotaktni z močjo 5880 kW. Rabi dizelsko gorivo DS in olje SAE-50. Pri izvajanju preizkusa sta ladjo poganjala dva motorja, plinska turbina pa ni bila uporabljena. Os plinske turbine se je pri tem vrtela prosto. Položaj ladje, s katere se je začelo snemanje vijačne lastnosti je azimut pravi ω_p=047 °, oddaljenost d=0,3 M na otok Mamula. Smer plovbe ladje v času preizkusa je bila K_p=136 °. Morje je bilo 0 do 1 po Beaufortovi lestvici stanja morja, temperatura zraka 12 °C, barometrski pritisk 1005 mbarov, veter jugovzhodni 3 vozli, relativna vlažnost 68 % in temperatura morja 14 °C.

Merjenje je bilo izvedeno s postavljanjem merilnih lističev in merilne opreme na pogonsko os levega ladijskega vijaka. Mesto postavljanja merilnega lističa na osi je bilo med spojko motorja in odrivnega ležaja.

Del pogonske osi ladijskega vijaka, kjer so bili pritrjeni merilni lističi, je bilo v obliki obročastega prečnega prereza velikosti 260/80 mm. Pogonska os ladijskega vijaka je iz litega jekla z modulom elastičnosti E = 215 MPa.

Shematski prikaz postavljanja in vezave merilne naprave je prikazan na sliki 5. Na pogonsko os ladijskega vijaka sta bila pritrjena dva para merilnih lističev tipa "XY21-6/350" povezana v Wheatstonov mostič. Lističi so bili postavljeni pod kotom 180° drug na drugega. Napajanje merilnih lističev je izvajano z enosmernim električnim tokom 9 V. Merilni signal Wheatstonovega mostiča je potekal do predajnika in čez predajno anteno do sprejemnika merilnega signala. Vir električne energije, oddajnik in antena so bili postavljeni na obročasti disk iz plastične snovi, da bi izločili motnje, vse skupaj pa pritrjeno na pogonsko os ladijskega vijaka. Na pogonsko os ladijskega vijaka je bil pritrjen tudi temni listič s svetlim lističem čez njega, za registriranje števila vrtljajev pogonske osi ladijskega vijaka. Na pogonski osi ladijskega vijaka je bil na določenem razmiku postavljen sprejemnik merilnega signala in bralnik števila vrtljajev.

Sprejemnik merilnega signala in pretvornik števila vrtljajev sta bila povezana z elektronsko merilno napravo "SPIDER-8", ki je bila povezana z osebnim računalnikom. Programska oprema, ki omogoča merjenje in obdelovanje izmerjenih podatkov, se imenuje "CATMAN 3.0". Vsa ta oprema, strojna in programska je izdelana v podjetju "HOTTINGER BALDWIN MESSTECHNIK" (HBM), Darmstadt, Nemčija.

Računalniški program "CATMAN 3.0" deluje v delovnem sistemu MS Windows in omogoča

pelled by two diesel engines and one gas turbine via independent propeller shafts. On each shaft there are three bladed propellers with fixed blades. The diesel engines are linear, placed in two rows with nine cylinders each, and in a vertical block. The type of engine is a 68B, two stroke, with a rated power of 5880 kW. The engine uses diesel fuel, and SAE 50 motor oil. When the experiment was performed the ship was propelled by two diesel engines, and though the gas turbine was not used its shaft rotated freely. The position of the ship when the propeller characteristic was recorded was: azimuth real ω_p=047, distance from Mamula island d=0.3 M. The course was K_p=136. The sea conditions were 0 to 1, air temperature t=12°C, pressure p=1005 mbar, wind SE, 3 knots, humidity 68%, sea temperature 14°C.

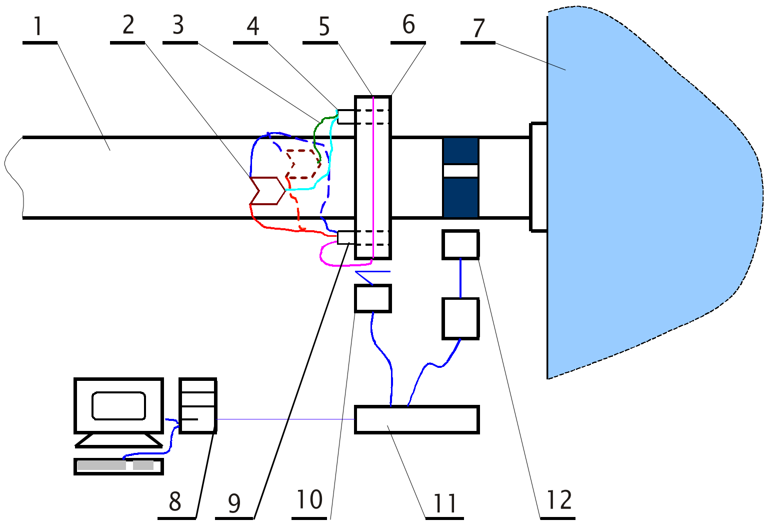
The measurement was performed by placing the strain gauges and the measuring equipment on the left shaft, between the clutch and the thrust bearing.

The strain gauges were placed on a shaft with an annular cross-section of 260/80 mm. The shafts were made of forged steel with elastic modulus E=215 MPa.

A schematic review of installing and connecting the measuring equipment is shown in Figure 5. Two pairs of strain gauges, type "XY21-6/350", were placed on the shaft and connected in the Wheatstone bridge. The strain gauges were installed at an angle of 180^0. The strain-gauge circuit feed was a DC voltage of 9V. The measuring signal from the Wheatstone bridge was carried to the emitter, and through an aerial delivered to the receiver. The circuit feed, emitter and antenna were placed on an annular disk (that has to be made of plastic to eliminate the backset) that was installed on the shaft. A dark ribbon with a light ribbon over it was also put all around the shaft to provide a measurement of the number of revolutions. Near the shaft, at a certain distance, a receiver and a transducer of the number of revolutions were installed.

The receiver and the transducer were linked to an electronic measuring device named "SPIDER-8"; the "SPIDER-8" was linked to a personal computer. The software that makes possible the measurement and data processing is "CATMAN 3.0". The hardware and software were produced by "HOTTINGER BALDWIN MESSTECHNIK" (HBM), Darmstadt, Germany.

"CATMAN 3.0" is software designed to work with MS Windows. It allows the user to focus his or



1 – pogonska os ladijskega vijaka, 2 - merilni lističi, 3 – el. prevodniki, 4 - vir el. energije, 5 - antena, 6 - obročast nosilnik, 7 – motor, 8 – osebni računalnik, 9 – oddajnik merilnega signala, 10 – sprejemnik merilnega signala, 11 – "SPIDER-8", 12 – pretvornik števila vrtljajev osi ladijskega vijaka

1 – propeller shaft; 2 – strain gauge; 3 – conductors; 4 – power supply; 5 – antenna; 6 –annular disc; 7 – engine; 8 – personal computer; 9 – emitter; 10 – receiver; 11 – "SPIDER-8"; 12 – transducer

Sl. 5. *Shematski prikaz postavitve in povezave merilne opreme*
Fig. 5. *Diagrammatic view of the installation and the connections of the measuring equipment*

uporabniku popolno koncentracijo za merjenje. "CATMAN 3.0" je namenjen za uporabo interaktivne ali avtomatične merilne programske opreme, prav tako pa ga je mogoče uporabljati kot podlago za razvoj posebnih uporab [3].

"SPIDER-8" je elektronska merilna naprava za merjenje fizikalnih spremenljivk, to so delo, moč, pritisk, pospešek, hitrost ali temperatura. Prek osebnega računalnika je povezan na tiskalnik. Sinhronizacija se izvaja s pomočjo programske opreme in upravljanjem prek računalnika. Ima štiri digitalne ojačevalnike, ki delujejo na frekvenci 4,8 kHz in 8 kanalov oštevilčenih od 0 do 3 in od 4 do 7. Vsak kanal deluje z lastnim analogno-digitalnim (A/D) pretvornikom, ki dovoljuje merilne hitrosti od 1/s do 9600/s, kar zagotavlja popolno pokritost obsega mehaničnih merilnih opravil [4].

Merilni lističi, ki so uporabljeni pri merjenju deformacije pogonske osi ladijskega vijaka, so posebne serije Y, vrste XY21-6/350, izdelani iz dveh lističev, tako da oblikujejo dvojico merilnih lističev. Notranji upor merilnih lističev je 350 Ω, a njihova občutljivost je k = 2,07. Največja napetost električnega toka v merilnem lističu je 19 V. Videz merilnega lističa je prikazan na sliki 6.

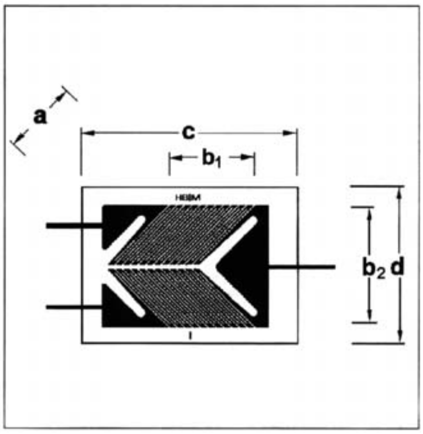
Izmere merilnega lističa na sliki 6 so: a=6 mm, b_1=7,8 mm, b_2=10 mm, c=17,5 mm in d=12,7 mm.

her attention primarily on the tasks of measuring. "CATMAN" is designed to work with interactive or automatic measuring software, but it can also be used as a matrix for special applications [3].

The "SPIDER-8" is an electrical measuring device for the measurement of changeable physical values like strain, force, pressure, acceleration and temperature. It is linked to a personal computer through the printer connection. All the adjustments of the device are performed by the software, i.e., by a personal computer. There are four digital amplifiers that work with a frequency of 4.8 kHz, and eight channels numbered from 0 to 3 and from 4 to 7. Each channel works with a separate analogue to digital converter (A/D) that allows a measuring rate from 1/s to 9600/s, which means that it covers the complete range of mechanical measuring tasks [4].

The strain gauges that were used for the shaft deformation measurement are from a specially shaped series Y, type XY21-6/350, made from two gauges that form the strain-gauge pair. The strain-gauge resistance is 350 Ω, and the sensitivity is k=2.07. The maximum voltage of the strain gauge is 19V. For details see Figure 6.

The dimensions of the strain gauge according to Figure 6 are as follows: a=6 mm, b_1=7.8 mm, b_2=10 mm, c=17.5 mm and d=12.7 mm.



Sl. 6. *Videz merilnega lističa* XY21-6/350
Fig.6. *Strain gauge* XY21-6/350

Za začetek postopka merjenja moramo v program "CATMAN" vnesti vse podatke, ki prikazujejo lastnosti pogonske osi ladijskega vijaka:
- modul elastičnosti E,
- strižni modul G,
- Poissonov količnik *í*,
- odpornostni moment prečnega prereza osi W_p,
- torzijski moment M_d.

V program je bilo še nujno treba vnesti podatke o sinhronizaciji merilne opreme po metodi kretnice. Pri takšni metodi sinhronizacije in glede na uporabljeno vrsto merilnih lističev, vrednost izstopne napetosti električnega toka mostiča 2 mV/V ustreza vrednosti deformacije merilnega lističa 1000 μm/m, kar se mora upoštevati pri določanju torzijskega momenta.

Odpornostni moment za obročasti prečni prerez se določa z enačbo [5]:

To start the measurement it is necessary to input the following initial shaft data in the "CATMAN" program:
- coefficient of elasticity, E (elastic modulus),
- shear modulus, G,
- Poisson's coefficient,
- moment of drag shaft's cross-section, W_p,
- moment of torsion, M_d.

Besides this data it is also necessary to input the calibration data of the measuring equipment. The "shunt" calibration method was applied in this case. With this method of calibration, considering the type of strain gauge used, a strain-gauge deformation of 1000 μm/m corresponds to a bridge output voltage of 2 mV/V, which must be taken into consideration when determining the moment of torsion.

The polar drag moment for an annular cross-section is defined as [5]:

$$W_p = \frac{D^4 - d^4}{16 \cdot D} \cdot \pi \qquad (17).$$

Strižni modul se določa z enačbo [5]:

The shear modulus is defined [5]:

$$G = \frac{E}{2 \cdot (1 + \nu)} \qquad (18).$$

Za jeklo je vrednost $\nu = 0{,}3$.
Torzijski moment se določi [2]:

For steel $\nu = 0.3$.
The moment of torsion is [2]:

$$M_d = \frac{1}{2} \cdot W_p \cdot G \cdot \varepsilon_i \qquad (19),$$

ε_i pomeni izmerjeno vrednost deformacije osi.

Moč, ki jo motor oddaja ladijskemu vijaku preko osi, znaša [1]:

ε_i represents the measured shaft-deformation value.

The power that the engine delivers to the screw through the propeller shaft is [1]:

$$P = M_d \cdot \omega \qquad (20).$$

Vrednost moči se vnese kot začetni podatek v program “CATMAN”, ki v vsakem trenutku omogoča določanje moči, ki jo motor odda osi vijaka. Menjava vrednosti oddane moči motorja se lahko spremlja stalno v daljšem časovnem koraku ali pa v koraku nekaj sekund.

Tako je izvedeno merjenje vijačne lastnosti ladijskega motorja v celotnem obsegu vrtljajev ročične osi od 273 min^{-1} do 602 min^{-1}. Moč je snemana na 9 delovnih točk, in to za vsako točko v 10 sekundnem časovnem koraku merjenja. V vsakem 10 sekundnem časovnem koraku je izmerjenih po 250 vrednosti. Izmerjeni rezultati so prikazani v preglednici 1.

Na sliki 7 je grafično prikazana sprememba moči za vsak vrtljaj ročične osi na podlagi izmerjene vrednosti deformacije osi ladijskega vijaka v 10-sekundnem časovnem koraku.

Za pridobitev vijačne lastnosti ladijskega motorja so uporabljene srednje izmerjene vrednosti moči v vsakem časovnem koraku. Vijačna značilka ladijskega dizelskega motorja je grafično prikazana na sliki 8 (krivulja 3).

We input the formula for power, as initial data, into the “CATMAN” program, thus providing the determination of the power that the engine transmits through the propeller shaft to the screw at any moment. The power change can be observed continuously during a long period or during a period of a few seconds, depending on the requirements.

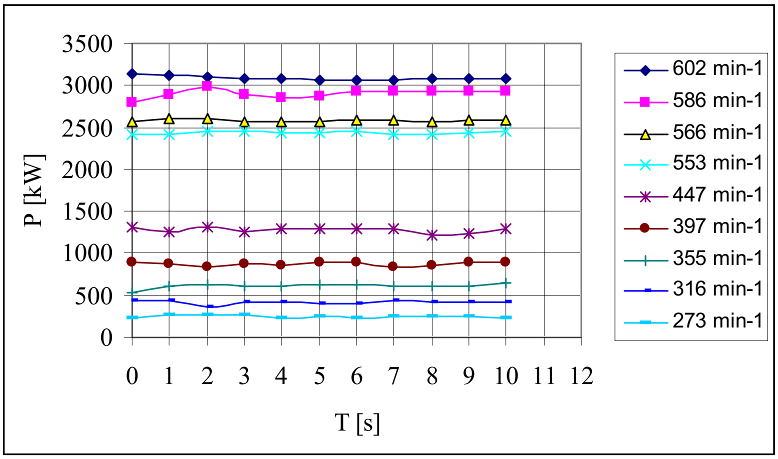
In this way, the propeller characteristic for the engine, from a minimum number of crankshaft revolutions, 273 min^{-1}, to 602 min^{-1}, achieved under the given conditions, was recorded. The power was recorded at nine working points, at an interval of 10 seconds for each point. During each of these intervals 250 values were measured. The measured values are shown in Table 1.

Figure 7 illustrates the change of power, for each number of crankshaft revolutions, based on the measured values of propeller deformation during an interval of 10 seconds.

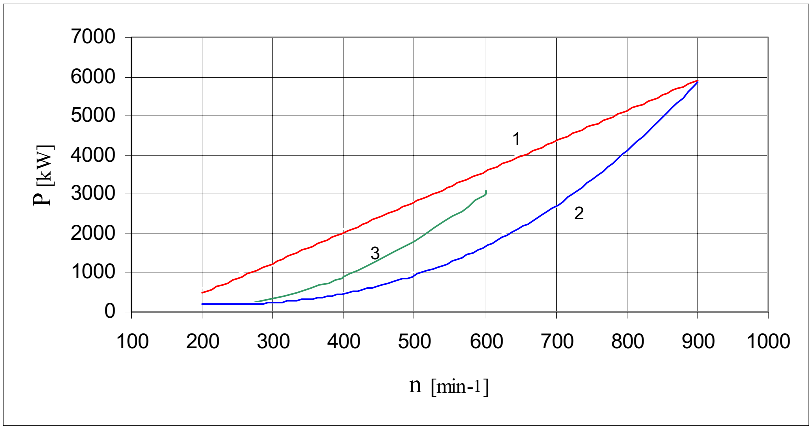
The mean values of the power at each interval were used to determine the screw characteristic. The screw characteristic of the diesel engine is illustrated in Figure 8 (curve 3).

Preglednica 1. *Izmerjeni rezultati moči za posamezna števila vrtljajev osi motorja*
Table 1. *Measured values of power for different numbers of shaft revolutions*

n min^{-1}	273	316	355	397	447	553	566	586	602
P_{sr} kW	241,27	414,28	612,22	870,33	1283,98	2432,64	2587,33	2902,47	3088,79



Sl. 7. *Grafični prikaz spremembe moči dizelskega motorja v 10-sekundnem časovnem koraku pri številu vrtljajev od 273 do 602* min^{-1}
Fig. 7. *The change of diesel engine power during a 10-second interval for numbers of revolutions ranging from 273* min^{-1} *to 602* min^{-1}



Sl. 8. *Grafični prikaz vijačne značilke ladijskega motorja*
Fig. 8. *The screw characteristic (curve 3)*

Na sliki 8 je predstavljena zgornja mejna vijačna značilka motorja (krivulja 1) in vijačna značilka pri vožnji ''naprej'' (krivulja 2), ki ji je dal proizvajalec v navodilu za uporabo motorja 68B, narisane pa so na podlagi izidov testiranja motorjev po vgradnji na novi ladji [6]. Pri testiranju sta ladjo poganjala dva dizelska motorja, plinska turbina pa je mirovala, pri čemer se je vrtela samo os ladijskega vijaka.

Na sliki 8 je vidno, da se z merilnimi lističi izmerjena vijačna značilka znatno razlikuje od vijačne značilke proizvajalca v navodilu ter predstavlja delo motorja pri ''težkem ladijskem vijaku''. Razlaga je lahko naslednja:

- ladja ni bila na popravilu 4 leta ter so podvodni deli trupa in ladijski vijak ''obrasli'', kar pomeni velik upor pri premikanju ladje.

Figure 8 shows the upper engine-power limit (curve 1) and the screw characteristics for driving "ahead" (curve 2), given in the manufacturer's manual for the engine type 68B. These curves are based on the results achieved during an investigation of a diesel engine aboard a ship, after it was built. During the investigation the ship was propelled by two diesel engines, without a gas turbine, although its shaft rotated freely.

As you can see in Figure 8, it is obvious that the screw characteristic transcribed with the use of the strain gauges is different from the screw characteristic given in the manual by the manufacturer, and represents an engine working in the ''hard propeller'' regime. We can find the explanation in the following:

- Because the ship was not at dock for four years the underwater parts of the ship were "overgrown" and this represents a large resistance to the movement of the ship.

3 SKLEP

Z metodo snemanja vijačne značilke pridobljeni eksperimentalni podatki na dejanski ladji so pokazali, da ladijski motor deluje po krivulji "težkega ladijskega vijaka", kar nam pove, da ladja ne more razviti take hitrosti plovbe kakor ladja s čistim podvodnim delom. Da bi se dosegla nujna hitrost ladje, bi bilo treba povečati število vrtljajev motorja, to pa ima za posledico preobremenitev motorja. Iz diagrama je razvidno, da je že na 600 min^{-1} vrtljajev ročične osi, krivulja bližja zunanji mejni značilki motorja, to pomeni da so vsi parametri delovnega postopka blizu zgornjih meja. Ugotovimo lahko, da motor ne more delati na načrtovanem številu vrtljajev (n = 900 min^{-1}), ladja pa ne more doseči načrtovane

3 CONCLUSION

The experimental data acquired by this method of transcribing the screw characteristic, on a concrete ship, show that the engine is working in the "hard propeller characteristic", and that this ship cannot achieve the same speed as a ship whose underwater part and propellers are clean. To achieve the necessary speed the number of engine revolutions must be increased, which would cause the engine to be overloaded. The transcribed screw characteristic shows that at 600 crankshaft revolutions per minute the curve is nearing the outer boundary of the engine's characteristics, i.e., all the parameters of the process are near their upper limits. This means that the engine is not able to work with the projected number of revolutions hitrosti oziroma delo vsega pogonskega sestava je negospodarno.

Kakor vse znane metode, ima tudi ta svoje dobre in slabe strani.

Dobre strani te metode so:
- merilni lističi in pretvorniki po načelu merilnih lističev so zelo majhnih mas, kar pomeni, da nimajo vztrajnosti,
- merilni lističi ne delujejo na testirani predmet,
- merilni lističi so se pokazali kot zelo uporabni za dolgotrajna dinamična testiranja z velikim številom ponovitev (delo motorja),
- zaznavala po načelu merilnih lističev delujejo na zelo nizkih in zelo visokih tlakih (od 10^{-7} mbar do 10000 bar),
- glede na zgornje mejne frekvence nimajo omejitev, kar pomeni, če so merilni lističi pravilno postavljeni, sprejemajo vse dinamične spremembe na testiranem predmetu,
- ko so merilni lističi postavljeni na predmetu, se lahko po testiranju zaščitijo s posebno gumijasto zaščito in se nato lahko ponovno uporabijo.

Slabe strani metode so:
- največje še dovoljene temperature za uporabo merilnih lističev so do 350 °C,
- merilni listič je občutljiv na parazitske obremenitve,
- merilni lističi so občutljivi na vlago, zato jih je treba obvezno zaščititi s posebno gumijasto zaščito.

Povzamemo lahko, da se metoda z merilnimi lističi uspešno uporablja za nadzor trupa ladje in ladijskega vijaka ter nadzor ustreznosti vgrajenih ladijskih vijakov za dejansko ladjo oziroma ladijski motor.

(n_n=900 min^{-1}), and the ship is not able to achieve its projected velocity, and that the work of the propulsion complex is not economic.

Like other known methods, this one has both advantages and disadvantages.

The advantages of this method:
- Strain gauges and strain-gauge transducers are very light, which means that there is no inertia.
- Strain gauges have no influence on the object of the investigation.
- Strain gauges proved to be very convenient for long-term dynamic investigations of a large number of cycles (in this case engine work).
- Strain-gauge transducers can endure both low and high pressures (from 10^{-7} mbar to 10000 bar).
- There are no upper frequency limits, so if they are properly installed, strain gauges can record all the dynamic changes of the object of the investigation.
- Once the gauges are installed on an object they can be protected with a special rubber band, so the measurement can be repeated, when required, even after a long period of time.

The disadvantages of this method:
- Strain gauges can be used up to a maximum temperature of 350^{0}C, except for special strain-gauge transducers, which can stand higher temperatures;
- Strain gauges are sensitive to so-called parasite stress;
- Strain gauges are sensitive to moisture, so it is necessary to protect them with a special rubber.

The conclusion is that we can use this method successfully to check the condition of the hull and the screw, as well as to determine whether the screw is suitable for the particular hull and engine.

4 OZNAKE
4 INDEX

vrtilni moment	M	Nm	torque
stalnica	k_0		constant
število vrtljajev	n	min^{-1}	number of revolutions
nominalno število vrtljajev	n_n	min^{-1}	number of revolutions-nominal
moč	P	kW	power
koristna moč	P_e	kW	effective power
nominalna koristna moč	P_{en}	kW	effective power-nominal
kotna hitrost	ω	s^{-1}	angular velocity
azimut dejanski	ω_p	°	real azimuth
Ludolfovo število	π		Ludolf's number
stalnica	k_1		constant
dejanska smer	K_p	°	real course
električna upornost	R	Ω	electric resistance
specifična upornost materiala	ρ	Ωmm^2/m	specific resistance of material

dolžina	l	mm	length
premer	d	mm	diameter
površina	A	mm^2	surface
relativno podaljšanje	ε	mm/m	relative extension
relativno podaljšanje vzdolžno	ε_l	mm/m	relative along extension
relativno podaljšanje prečno	ε_t	mm/m	relative across extension
Poissonov količnik	ν		Poisson's coefficient
faktor občutljivosti	k		factor of sensitivity
prečna občutljivost	q		across sensitivity
električna napetost izhodna	V_o	V	outgoing voltage
električna napetost vhodna	V_s	V	voltage supply
odpornostni moment prereza	W_p	mm^3	polar moment of cross section resistance
premer	D	mm	diameter
strižni modul	G	kPa	shear modulus
modul elastičnosti	E	kPa	elastic modulus
torzijski moment	M_d	Nm	moment of torsion
čas	T	s	time

5 LITERATURA
5 LITERATURE

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Naslov avtorjev: mag. Sead Cvrk
mag. Zdravko Đukić
mag. Milorad Rodić
Mornarica SČG
Ul. Maršala Tita 2
85000 Bar, Črna Gora
cvrk@cg.yu
zdravko.djukic@cg.yu
roda@cg.yu

Authors' Address: Mag. Sead Cvrk
Mag. Zdravko Đukić
Mag. Milorad Rodić
Navy SCG
St. Maršala Tita 2
85000 Bar, Crna Gora
cvrk@cg.yu
zdravko.djukic@cg.yu
roda@cg.yu

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Uporaba zvočne jakosti in preizkusne načinovne analize za določitev hrupa dizelskega motorja

The Application of a Sound-Intensity Analysis and an Experimental Modal Analysis for Determining the Noise Emissions of a Diesel Engine

Predrag Petrović
(Institute "Kirilo Savić", Serbia)

Motor z notranjim zgorevanjem predstavlja večkratno vzbujan vir vibracij in hrupa, ki izvira iz sestavov, katerih delovna energija se spremeni v energijo zvočnega valovanja. Energija, ki jo absorbira sestav motorja, vzbuja lastna nihanja večjih motornih delov (blok motorja, zbiralnik olja, glava valja itn.), skozi katerih površine seva zvok.

Za določitev stopnje zvočne emisije v posameznih delih motorja pri različnih hitrostih delovanja so bile narejene podrobne analize v podjetju "Industrija motora Rakovica" iz Beograda, z uporabo preizkusne načinovne analize in zvočne jakosti. V tem pomenu je bila ugotovljena povezava med lastno frekvenco in emitiranim zvokom na posameznih zunanjih površinah motorja.

Del rezultatov, dobljenih med temi raziskavami, je predstavljen v tem prispevku.

(Ključne besede: dizelski motorji, emisija hrupa, zvočna jakost, načinovna analiza)

The internal combustion engine represents a multi-exciting source of vibration and noise that originates from its assemblies, and whose energy of operation is transformed into sound-wave energy. The energy absorbed in the engine's structure excites the natural modal oscillations of the larger engine parts (cylinder block, oil sump, cylinder head, etc.), through whose surfaces the sound is radiated.

To determine the level of emitted sound in individual areas of the engine at various running speeds, detailed research was carried out at Industrija motora Rakovica of Belgrade using experimental modal analyses and sound-intensity measurements. In this way a correlation was made between the natural modal frequencies and the emitted sound from particular external areas of the diesel engine.

Some of the results obtained in the course of these investigations are presented in this paper.

(Keywords: diesel engine, noise emissions, sound intensity, modal analysis)

0 UVOD

Raziskovalno delo pri pojavu nastajanja zvoka v motorjih z notranjim zgorevanjem poteka v več smereh. Prva obsega zgorevalni postopek, vključno s plinskim tokom skozi dovod in izpuh. Druga smer v razvoju se nanaša na moteče pojave, kakršni so udarci, drsenje, resonance gibljivih delov, npr. kolenasta gred, bati in podobno. Tretja skupina pokriva raziskave sestavne togosti in dušenja (blok, glava, zbiralnik itn.). Pogon odmične gredi, pomožni mehanizmi in agregati predstavljajo še eno skupino ali smer raziskovalnega dela na področju hrupa motorjev.

0 INTRODUCTION

Research work on the way noise is generated by internal combustion engines can be conducted in several directions. The first involves the combustion processes, including the gas flow during inlet and exhaust. The second direction of research relates to disturbance processes, such as the impacts, the sliding, and the resonance of the moving parts, e.g., the crankshaft and the pistons. The third group covers research on structure stiffness and damping (block, head, sump, etc.). The timing gear, auxiliary mechanisms and aggregates represent another group or course of research work in the field of engine noise.

Področje raziskav v tem prispevku je pojav nastanka hrupa v sestavu motorja, ki ga povzročajo premični deli, na primer kolenasta gred z batnim mehanizmom.

Raziskave so bile narejene pri podjetju "Industrija motora Rakovica" na S54 visokem štirivaljnem dizelskem motorju. Namen teh raziskav je bila sprememba v konstrukcijskih rešitvah osnov razvitega mehanizma nastanka zvoka, da bi zmanjšali stopnjo hrupa.

1 SPEKTER HRUPA, KI GA USTVARJA MOTORNI SESTAV

1.1 Izvir zvoka

Slika 1a) prikazuje sestav motorja, ki je namenjen tem raziskavam. Sestoji iz bloka motorja, kolenaste gredi z vztrajnikom, štiribatnim mehanizmom in oljnim zbiralnikom z mazalno črpalko.

Sestav poganja električni motor s spremenljivo kotno hitrostjo. Vseeno je mogoče simulirati delovni pojav in nastanek hrupa v področju motorja. Udarne sile se povečujejo s povečevanjem kotne hitrosti in večanjem zračnosti. Med delovnim postopkom se sile povečajo zaradi tlaka zgorevalnega plina. Vendar je hkrati sunek med zračnostmi na splošno odvisen od vztrajnosti, ki postane bolj intenzivna zaradi vibracij kolenaste gredi. Zaradi lastnih vibracij se kolenasta gred elastično deformira s povečanjem moči teh sunkov.

Pojav nastanka zvočnih valov, povzročen s sunki v ležajih in podobnimi motnjami, je zapleten. Lahko ga razdelimo v naslednje faze:

1. Primarni zvočni val nastane pri točki sunka z neposrednim stikom bližnjih površin. Ta zvok se širi skozi okolišni prostor v motorju, še posebej v zbiralniku olja. Tu se ojači z resonanco in prodre skozi zbiralnik olja in blok motorja v okolico (sl. 1a).
2. Iz točke sunka se energija prenese na zunanje površine bloka in zbiralnika olja. Prenos poteka z elastičnimi deformacijami, ki se širijo kot valovi. Ko val doseže zunanje površine, se energija prenese na okolico kot zvočni valovi (sl. 1b).
3. Valovi elastičnih deformacij vzbujajo lastne (modalne) vibracije. Načinovne vibracije bloka motorja in oljnega zbiralnika so

The scope of the research in this work is the noise-generation process in the engine structure, caused by the moving parts, i.e., the crankshaft with the piston mechanism.

The research was carried out at Industrija motora Rakovica of Belgrade on a S54 high 4-cylinder diesel engine. The aim of the research was to make modifications to the design solutions on the basis of the developed mechanism of noise generation in order to reduce the noise levels.

1 THE NOISE SPECTRUM GENERATED BY ENGINE ASSEMBLIES

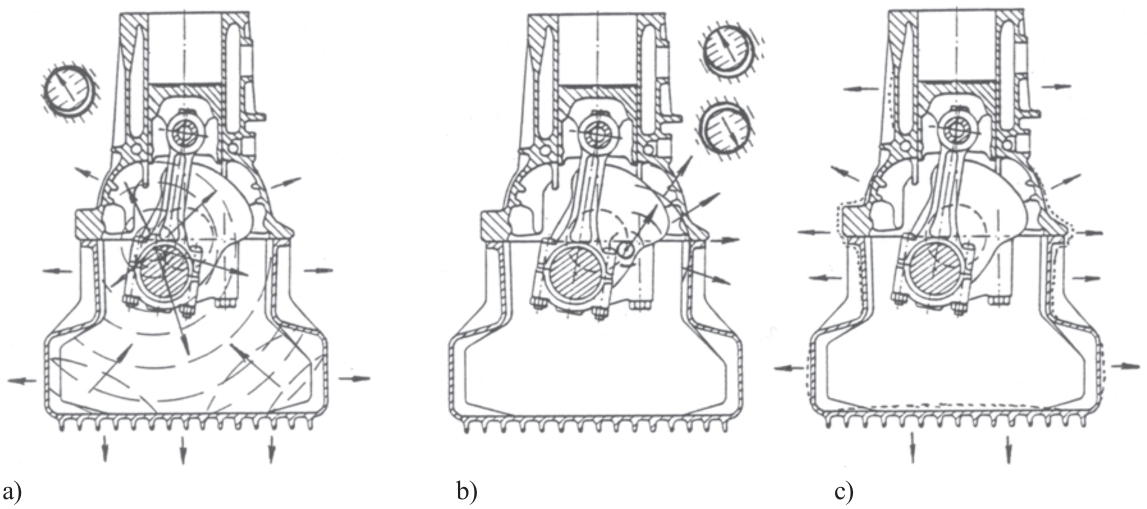
1.1 Noise excitation

Figure la shows the engine assembly that was the subject of these examinations. It consists of an engine block, a crankshaft with a flywheel, four piston mechanisms, and an oil sump with a lubrication pump.

The assembly is operated by an electric motor with a variable angular speed. Nevertheless, it is possible to simulate the operation process and the noise generation in this engine area. Impact forces increase with the angular speed and with the clearance magnitude. During the working process, because of the combustion gas pressure, the forces are increased, but the impact within the clearances generally depends on the inertia, which becomes more intensive due to crankshaft vibrations as well. Because of its own vibrations, the crankshaft elastically deforms with the increase in the intensity of these impacts.

The process of sound-wave generation, caused by the impacts in the bearings and by similar disturbances, is complex. It can be divided into the following stages:

1. Primary sound waves occur at the point of impact in the direct contact of contiguous surfaces. This sound spreads through the enclosed space in the engine, especially in the oil sump. Here, it is amplified by the resonance and penetrates through the engine sump and block walls into the environment (Fig. 1a).
2. From the impact point, energy is transmitted to the external surfaces of the block and the sump. The transmission is carried out by means of elastic deformations spreading as waves. When a wave reaches the external surfaces, the energy is transmitted to the surroundings as sound waves (Fig. 1b).
3. The waves of elastic deformation excite the engine parts' natural (modal) vibrations. The modal vibrations of the engine block and the oil sump are the most



Sl. 1. *Sestav testnega motorja in pojav nastanka hrupa: a) sunek v reži ročičnega ležaja in primarno nastajanje hrupa, b) sunek v reži kolenaste gredi in nastanek valov v elastični sestavi motorja, c) lastna nihanja motorja in drugotno nastajanje hrupa*

Fig. 1. *The tested engine assembly and the process of noise generation: a) impact in the clearance of the connecting-rod bearing and the primary noise generation, b) impact in the clearance of the crankshaft bearing and the wave generation in the elastic structure of the engine, c) natural vibrations of the engine structure and secondary noise generation*

najpomembnejše. Ta dva dela imata velike površine, ki oddajajo zvok in sta v neposrednem stiku z okolico. Tako se oddajajo zvočni valovi s frekvenco, ki je enaka njihovi lastni frekvenci sten teh delov. Slika 1c) prikazuje vibracije in zvok nastale na ta način.

1.2 Meritve hrupa ločenih motornih sestavov

Motorni sestavi s slike 1 so bili preizkušeni v brezodmevnem prostoru. Pogon je bil izveden iz sosednjega prostora z uporabo električnega motorja s spremenljivo kotno hitrostjo. V brezodmevnem prostoru je bil tlak merjen 1 m stran od testnega predmeta.

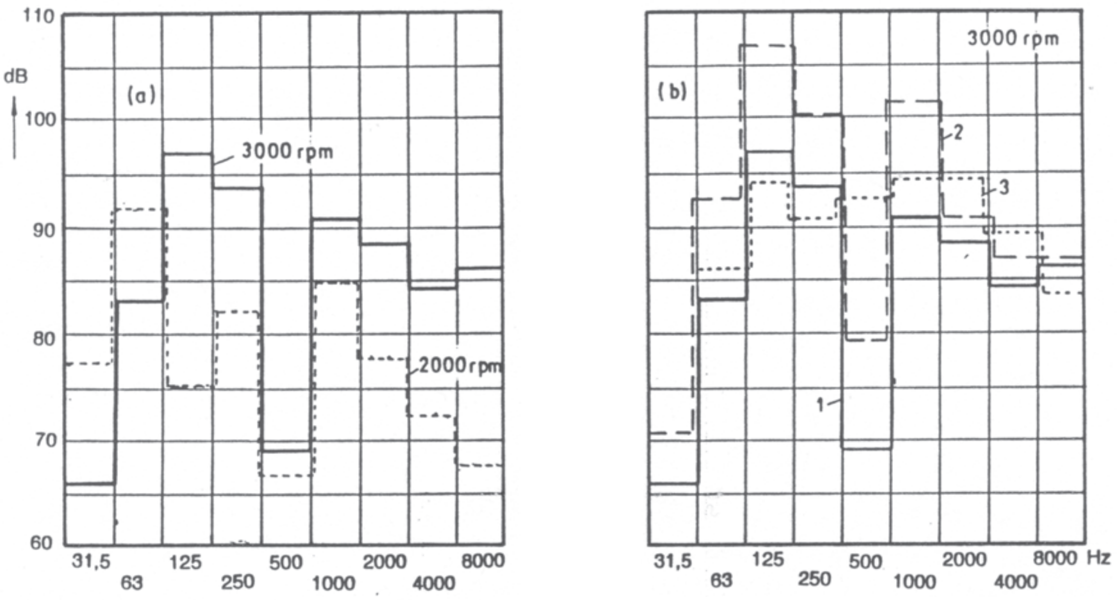
Slika 2 prikazuje spekter hrupa v različnih preizkusnih razmerah. Na sliki 2a) sta primerjana spektra hrupa oddana iz motornih sestavov (sl. 1) pri dveh hitrostih vrtenja. Slika 2b) vsebuje primerjavo spektrov hrupa, ki ga oddaja sestav motorja (črta 1), spekter hrupa, ki ga oddaja celoten od zunaj gnan motor (črta 2) in spekter hrupa avtomobilskega motorja z zgorevanjem pri polni obremenitvi (črta 3). Na podlagi primerjav zapisanih spektrov lahko naredimo naslednje sklepe.

important. These parts have large surfaces to emit the sound and are in direct contact with the surroundings. In this way, sound waves are emitted, the frequencies of which are equal to the individual frequencies of the walls of these parts. Figure 1c, designates the vibration and sound generated in this way.

1.2 Measurement of the noise of a separate engine assembly

The engine assembly shown in Figure 1 was tested in an anechoic chamber. The propulsion was effected from an adjacent room by means of an electric motor with variable angular speed. In the anechoic chamber, the acoustic pressure was measured at a distance of 1 m from the tested object.

Figure 2 illustrates the noise spectra for different experimental conditions. In Figure 2a is a comparison of the noise spectrums emitted by the engine assembly (Fig.1) for two rotation speeds. Figure 2b contains a comparison of the noise spectra emitted by the engine assembly (line 1), the noise spectra emitted by the complete externally operated engine without combustion (line 2), and the noise spectra of the automotive engine with combustion under full-load conditions (line 3). On the basis of the comparison of the spectra of registered noise, the following conclusions can be drawn.



a) b)

Sl. 2. *Spektri hrupa: a) motorni sestav, predstavljen na sliki 1, b) celoten od zunaj gnan motor v primerjavi s spektrom hrupa motornega sestava (1 s slike a) in avtomobilski motor z zgorevanjem pod polno obremenitvijo (3)*

Fig. 2. *The noise spectra of: a) the engine assembly presented in Fig. 1, b) the complete engine driven externally (2) in comparison with the noise spectrum of the engine assembly (1 - from Fig.a) and the noise spectrum of the automotive engine with combustion under full-load conditions (3)*

1. Spekter hrupa, ki ga oddajata kolenasta gred in batni mehanizem v bloku motorja, je razdeljen v dva ločena pasova. V nizkofrekvenčnem območju se frekvenca visokih stopenj hrupa ujema s frekvenco sunka v glavnem ležaju. V visoko frekvenčnem področju se frekvenca hrupa približno ujema z lastno frekvenco kosa. Nizkofrekvenčni pas predstavlja vsiljeni del spektra, visokofrekvenčni pa lastni del spektra.
2. S povečanjem kotne hitrosti (iz 1000 na 4200 vrt/min) se frekvenca sunka poveča, kar lahko vidimo na vsiljenem delu spektra: najvišja raven zvočnega tlaka je pri 2000 vrt/min v oktavi od 63Hz in v 125Hz pri 3000 vrt/min (sl. 2a). Oblika lastnega dela spektra ni spremenjena, ker lastna frekvenca delov motorja ni odvisna od frekvence vzbujanja.
3. Oblika spektra hrupa (črta - sl. 2b) dobljena z motornim sestavom, predstavljenim na sliki 1, je enaka kakor spekter hrupa v celoti zunanje gnanega motorja (črta 2 - sl. 2b). Kaže, da so vztrajnostne sile in sile zaradi sunka v reži v glavnem ležaju najpomembnejše motnje, ki

1. The spectrum of noise emitted by the assembly of the crankshaft and the piston mechanism in the engine block is divided into two separated bands. In the low-frequency range the frequency of the high noise levels is approximately the same as the frequencies of impact in the main bearings. In the high-frequency band, the noise frequency is approximately the same as with the parts' natural frequencies. The band of lower frequencies represents a forced part of the spectrum, and that of the higher frequencies represents a natural part.
2. With an increase in the angular speed (from 1000 to 4200 rpm.) the frequency of the impacts increases, which can be seen in the forced part of the spectrum: the highest level of sound pressure is at 2000 rpm in the octave of 63 Hz, and in the 125 Hz range at 3000 rpm (Fig. 2a). As a result, the shape of the natural part of the spectrum is not changed, because the frequency of the engine parts' natural vibrations does not depend upon the frequency of excitation.
3. The shape of the noise spectrum (line - Fig. 2b) generated by the engine assembly presented in Figure 1 is the same as the noise spectrum of the complete engine driven externally (line 2 - Fig. 2b). It shows that the inertial forces and the impact forces

povzročajo hrup. Oddajanje tega hrupa je odvisno od frekvence in dušilnih lastnosti bloka, zbiralnika in podobnih motornih delov. Stopnja hrupa celotnega motorja je odvečna energija, zapravljena z udarci v celotni strukturi in s utripanjem tlaka.

4. Stopnja hrupa celotnega zunanje gnanega motorja je nekoliko manjša od hrupa avtomobilskega motorja pod polno obremenitvijo (črta 3 - sl. 2b). Med zgorevanjem so sunki v režah dušeni. V primerjavi z od zunaj gnanim motorjem je absorbirana energija v sestavi motorja razsipana.

in the clearances in the main bearings are the most important disturbances causing the structural noise. The emission of this noise depends on the frequency and the damping characteristics of the block, the sump and similar engine parts. The noise level of the complete engine is higher because of the energy absorbed by impacts in the complete engine structure and by the pressure pulsation.

4. The noise level of the complete engine, driven externally, is somewhat higher than the noise level of the automotive engine under full-load conditions (line 3 - Fig. 2b). During the combustion, the clearance impacts and the parts' inertial forces are dumped. In comparison with the engine driven externally, the absorbed energy in the engine structure is distressed.

2 FREKVENČNA ANALIZA

2.1 Vzbujane frekvence

V frekvenčnem spektru posnetega hrupa (sl. 2), so zvočne tlačne stopnje povečane pri prvih treh oktavah (31,5; 63 in 125 Hz) z namenom, da se najvišja stopnja premakne na višjo oktavo (iz 63 na 125 Hz) s povečanjem vzbujane frekvence. Frekvenca najvišjih stopenj hrupa v vsiljenem delu spektra se ujema z vzbujano frekvenco.

V vseh spektrih je najnižja zvočna tlačna stopnja pri oktavi s srednjo frekvenco 500Hz. Ta oktava jasno ločuje vsiljeni del spektra od vzbujanega. Zato so ti spektri zelo značilni. V drugih mehanskih sistemih se delno prekrivajo ali so oddaljeni drug od drugega , kar jih naredi neprimerne za primerjavo.

2.2 Lastne frekvence

V frekvenčnih spektrih oddanega hrupa, prikazanih na sliki 2, se območje nad 1000 Hz ne spremeni ne po legi ne po obliki. Spreminja se samo velikost zvočnega tlaka. To dokazuje, da so zvočni valovi v tem delu spektra posledica lastnih nihanj delov motorja. Da bi to izboljšali, so bile narejene obširne raziskave, še posebno na bloku in zbiralniku. Modalno testiranje je bilo izvedeno s sunkovitim vzbujanjem in merjenjem vibracij kot odziva.

Primerjava je narejena med odzivom v obliki pospeška (a) in vzbujanja v obliki sile (F), dobljene z množenjem mase kladiva in njegovega pospeška ob udarcu. Slika 3 kaže frekvenčni spekter, dobljen na ta

2 FREQUENCY ANALYSIS

2.1 Exciting frequencies

In the frequency spectra of registered noise (Fig.2), the sound-pressure levels are increased for the first three octaves (31.5, 63 and 125Hz) with the tendency that the highest level moves to the higher octaves (from 63 to125Hz) with the increase of the impact frequency. The frequency of the highest noise level in the forced part of the spectra coincides with the impact frequency.

In all the spectra the lowest acoustic pressure level is in the octave with a mean frequency at 500Hz. This octave clearly separates the forced part of the spectrum from the natural. Therefore, these spectra are very characteristic. In other mechanical systems they partially coincide or are distant from one another, which makes them unsuitable for a comparison.

2.2 Natural frequencies

In the frequency spectra of the emitted noise shown in Figure 2, the area above 1000 Hz does not change its position or its shape during the change of operating conditions; only the magnitude of the acoustic pressure changes. This proves that the sound waves in this area of the spectrum occur due to the natural oscillation of the engine parts. In order to improve this, comprehensive examinations of the natural vibrations of the engine parts were made, especially of the block and the sump. The modal testing was carried out by excitation with the method of impact and by measuring the vibrations as a response.

A comparison was made between the response expressed in terms of acceleration (a) and the excitation in terms of force (F), obtained by multiplying the hammer način. Razmerje med odgovorom in vzbujanjem je na ordinati a/F izraženo z m/Ns^2 in s frekvenco na abscisi.

Blok motorja je bil vzbujen z načinovnim kladivom na podporah, kjer nalega kolenasta gred. To so mesta, kjer se pojavi vzbujanje v dejanskih obratovalnih okoliščinah. Odziv je bil merjen na bočni strani bloka. S premikanjem točke vzbujanja iz ležaja na ležaj in točke merjenja odziva, je bila največja intenzivnost odziva vedno na frekvenci 2800 Hz. Slika 3 prikazuje rezultat ene od teh meritev.

Zbiralnik olja je tankostenski z ojačitvenimi rebri. Vzbujanje je bilo izvedeno z udarci z načinovnim kladivom na prirobnico od povezave z blokom, hrup pa je bil merjen iz bočne strani. Dobljenih je bilo več frekvenc (sl. 3), pri katerih je bila stopnja odziva izredno velika. To so frekvence 2400, 3500 in 4600 Hz.

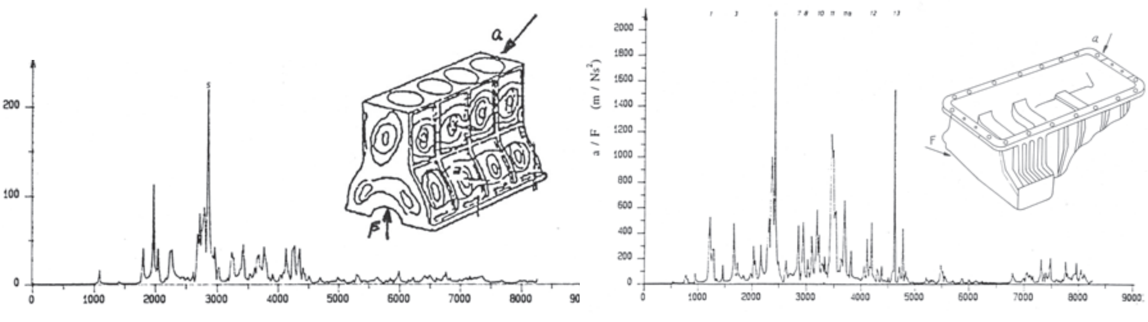
Vrhovi v visokofrekvenčnem področju spektra so sestavljeni iz lastnih frekvenc motornih delov. Poleg lastnih frekvenc bloka in zbiralnika so bile vsebovane še lastne frekvence kolenaste gredi, vztrajnika, ročic, oljne črpalke in drugih delov. Te frekvence so bile vključene tako, da se je po sunku iz cone sunka osnovni zvočni val razširil s frekvenco enako lastnim frekvencam delov, vpletenih v sunek neposredno. Vse te frekvence predstavljajo lastni del spektra enotskega zvočne tlačne stopnje od 1 do 8 kHz. Zato so potrebna dodatna testiranja, da bi podrobno preučili mehanizem izvira zvoka v strukturi tako zapletenega mehanskega sistema. To je analiza gibanja motilnih valov skozi dele motorja z uporabo metode končnih elementov, kar ni vsebovano v tem prispevku. Druga možnost je lociranje točk

mass and its acceleration at the impact. Figure 3 shows the frequency spectra obtained in this way. The response/excitation ratio is of the ordinate a/F, expressed in m/Ns^2 and the frequency on the abscissa.

The engine block was excited by modal hammer impacts on the supports where the crankshaft lies. These are the locations where the excitation is introduced during real operating conditions, too. The response was measured from the lateral sides of the block. By displacing the excitation point from bearing to bearing and the point response measurement, the highest intensity response was always for the 2800 Hz frequency. Figure 3 shows the result of one of these measurements.

The oil sump has thin rib-stiffened walls. The excitation was carried out by striking a modal hammer on the flange from a connection with the block, and the response was measured from the lateral sides. Several frequencies were obtained (Fig. 3b), for which the response level was extraordinarily high. These frequencies were 2400, 3500 and 4600 Hz.

The peaks in the high-frequency part of the spectrum in Figure 2 consist of the engine parts' natural frequencies. Besides the block's and the sump's natural frequencies the frequencies of the crankshaft, the flywheel, the connecting rods, the oil pumps and other parts were also recorded. These frequencies were included in such a way that, after the impact from the zone of the stroke, primary sound waves spread with frequencies equal to the natural frequencies of the parts directly involved in the impact. All of these frequencies together represent the natural part of the spectrum of the unified sound-pressure level from 1 to 8 kHz. Therefore, additional testing is necessary in order to study in detail the mechanism of the origin of the sound in the structure of such a complex mechanical system, i.e., the analysis of the motion of disturbance waves through engine parts by applying the final-element method, which is not included in this work. Another



a) b)

Sl. 3. *Izbrani rezultati načinovnih testov: a) za blok motorja, b) za zbiralnik olja*
Fig. 3. *Selected modal test results: a) for engine block, b) for engine sump*

v prostoru, od koder so zvočni valovi ustreznih frekvenc.

3 ANALIZA LOKACIJ ZVOČNIH VIROV V MOTORNEM SESTAVU

Za določitev prostorske razporeditve zvočnih valov ustreznih frekvenc, so bile izvedene meritve zvočne intenzivnosti celotnega motorja pri polnih obremenitvah. Meritve so bile narejene za vse oktave v frekvenčnem spektru in samo značilne so prikazane na sliki 4.

Slika 4 prikazuje porazdelitev zvočne jakosti za vsiljeni del spektra in točno za oktave s srednjo frekvenco območja pri 125 Hz in 250 Hz. Zvočna jakost je najvišja v oktavi s 125 Hz, največje vrednosti 110 dB (A) pa so sproščene v območju vrtenje kolenaste gredi.

Razpon najvišje zvočne jakosti se razprostira na desno stran. Ker je na tej strani vztrajnik, lahko predpostavimo, da so sunki v ležajih povečani zaradi večje mase. Jakost je večja v območju izpostavljenih delov oljnega zbiralnika. Lahko sklenemo, da so to zvočni valovi, ustvarjeni s sunkom, ki prodira skozi stene motornega zbiralnika.

4 SKLEP

Veliko različnih preizkusov in analiz v zvezi s strukturnim hrupom IMR S54 dizelskega motorja ponuja naslednje ugotovitve:

1. Stopnja mehanskega hrupa je blizu stopnji celotnega hrupa motorja pri polni obremenitvi.

possibility is to locate the points in space from where sound waves of corresponding frequencies come.

3 ANALYSIS OF THE LOCATION OF THE SOUND SOURCES IN THE ENGINE'S STRUCTURE

In order to determine the spatial layout of the sources of sound waves of corresponding frequencies, the measurements of the sound intensity of the complete engine under full-load conditions were made. The measurements were made for all octaves in the frequency spectrum, but only the typical ones are shown in Figure 4.

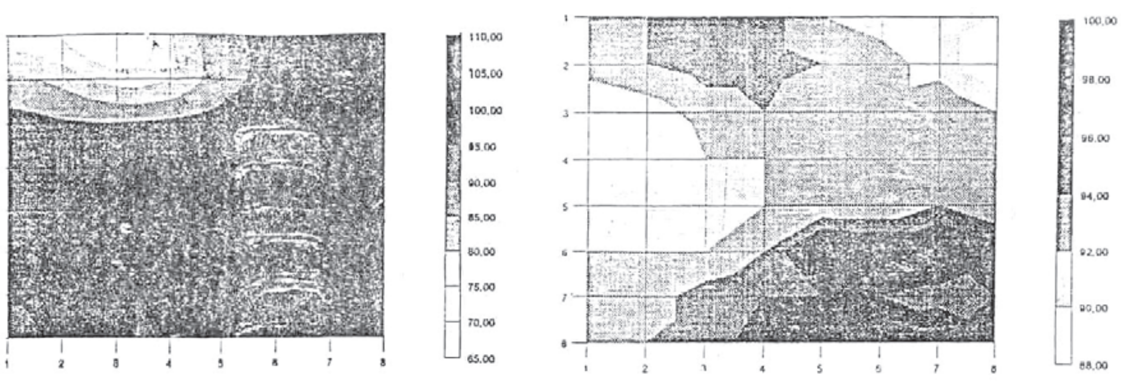
Figure 4 illustrates the sound-intensity maps for the forced part of the spectrum and precisely for octaves having the means of frequency range at 125 Hz and 250 Hz. The sound intensity is highest in the octave of 125 Hz, and the highest values of 110 dB(A) are found in the crankshaft's rotating area.

The range of the highest sound intensity spreads to the right-hand side. Since the flywheel is on that side, it may be supposed that the strokes in the bearings are amplified because of the increased mass. The intensity is higher in the area of the extended part of the sump. It can be concluded that these are the sound waves generated by the stroke, which penetrated through the engine sump's walls.

4 CONCLUSION

Our experiments and analyses concerning the structural noise of the IMR S54 diesel engine suggest the following:

1. The level of mechanical noise is close to the total noise level of the engine under full-load



Sl. 4. *Zvočni obrisi v vsiljenem delu spektra hrupa: a) oktava s srednjo frekvenco 125 Hz, b) oktava s srednjo frekvenco 250 Hz*

Fig. 4. *Sound maps in the forced part of noise spectrum: a) octave with the mean frequency of 125 Hz, b) octave with the mean frequency of 250 Hz*

Na razdalji 1 m, pri 4200 vrt/min je splošna stopnja mehanskega hrupa 104 dB(A), stopnja obremenjenega motorja med zgorevalnim postopkom pa je 105 dB(A). To kaže, da je delež mehanskega hrupa v celotnem hrupu pomemben. Če se poveča zračnost, se mehanska stopnja hrupa znatno poveča.

2. Spekter mehanskega hrupa je razdeljen v del z vsiljenimi frekvencami (sunki) in del z lastnimi frekvencami delov motorja. Najvišja stopnja vsiljenega dela spektra je na oktavi s srednjo vrednostjo 125 Hz. Frekvenca najvišje stopnje hrupa se približno ujema s frekvenco sunkov v zračnosti glavnega ležaja.
3. Za vse oktave v spektru je narejena porazdelitev zvoka po metodi zvočne jakosti. Te kažejo, da največja jakost hrupa prodira skozi območje kolenaste gredi. V tem območju se udarci dogajajo v zračnosti ležajev. V tem delu je togost stene najmanjša, zato se pojavijo ojačana lastna nihanja. Tam je zračni prostor v notranjem delu motorja. V tem prostoru se zračni hrup poveča in prehaja skozi sorazmerno tanke stene.

conditions. At a distance of 1 m, at 4200 rpm, the general level of mechanical noise is 104 dB(A), and that of the loaded engine during the combustion process is 105 dB(A). This suggests that the share of mechanical noise in the total noise is significant. When the clearances are increased, the mechanical noise level can increase considerably.

2. The spectrum of the mechanical noise is divided into the part with forced frequencies (strokes) and the part with the engine parts' natural frequencies. The highest level is in the forced part of the spectra, for the octave with a medium frequency of 125Hz. The frequency of the highest noise level approximately coincides with the frequency of the strokes in the main-bearing clearances.
3. For all octaves in the spectrum, sound maps are made using the sound-intensity method. They show that the highest noise-intensity penetrates from the crankshaft area. In this area, the impacts occur in the bearing clearances. In this area the wall stiffness is the lowest, and amplified individual vibrations occur. There is an air gap in the internal area of the engine. In this space, the air noise increases and passes through relatively thin walls.

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Avtorjev naslov: dr. Petrović Predrag
Institute “Kirilo Savič”
Vojvode Stepe 51
11000 Beograd, Srbija
mpm@eunet.yu

Author’s Address: Dr. Petrović Predrag
Institut “Kirilo Savič”
Vojvode Stepe 51
11000 Belgrade, Serbia
mpm@eunet.yu

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Poročila - Reports

IFToMM - Mednarodna federacija za promocijo znanosti o mehanizmih in strojih - The International Federation for the Promotion of Mechanism and Machine Science

V Sloveniji deluje sekcija mednarodne organizacije IFToMM že od leta 1995 in namen prispevka je predstavitev, prikaz organizacije in delovanje IFToMM-a in možnosti za povezovanje ter objavljanje slovenskih raziskovalcev na srečanjih IFToMM po vsem svetu.

Dejavnost IFToMM je definirana s statutom [http://130.15.85.212/indexa.html]. Najširše jo opišemo kot znanost o mehanizmih in strojih s poudarkom na teoriji in praksi na področju oblike, gibanja, dinamike ter vodenja strojev, mehanizmov in njihovih elementov skupaj z industrijsko uporabo. Dejavnost IFToMM-a se razširja tudi na druga področja kot so: biomehanika in področja povezana z okoljskimi problemi. V polje obravnave sodijo tudi premene energij in informacij.

Prvi svetovni kongres o temi mehanizmov in strojev je bil septembra 1965 v Varni v Bolgariji. Bolgarska delegacija je v okviru kongresa predlagala ustanovitev IFToMM-a, the International Federation for the Theory of Machines and Mechanisms. Zamisel so sprejeli delegati na kongresu in tako je bi ustanovljen mednarodni koordinacijski komite za stroje in mehanizme z zastopniki iz dvajsetih držav.

Rezultat štiriletnega dela komiteja je bila ustanovna skupščina 27. septembra 1969 v Zakopanih na Poljskem v času drugega svetovnega kongresa za teorijo strojev in mehanizmov. Na tem srečanju je bila ustanovljena mednarodna federacija za teorijo strojev in mehanizmov ter sprejet statut organizacije.

Na ustanovni skupščini so bili navzoči zastopniki iz držav: Avstralije, Avstrije, Bolgarije, Čehoslovaške, Vzhodne Nemčije, Zvezne republike Nemčije, Madžarske, Indije, Italije, Nizozemske, Norveške, Poljske, Romunije, Velike Britanije, ZDA, ZSSR in Jugoslavije. Do leta 2003 ima IFToMM petinštirideset članic iz držav vsega sveta.

V obdobju od 1996 do 1999 je bila izvedena prenova vloge IFToMM-a glede na razvoj informacijske tehnologije. Prenova še traja, vendar je vidnih že nekaj rezultatov te prenove. Eden od predlogov se je navezoval na ime federacije. Generalna skupščina je podprla spremembo izvirnega imena IFToMM in tako je od leta 2000 ime federacije IFToMM, the International Federation for the Promotion of Mechanism and Machine Science.

Trenutno v IFToMM deluje pet stalnih komisij za:
- povezovanje - komunikacijo,
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- zgodovino znanosti o mehanizmih in strojih,
- publikacije in
- standardizacijo in terminologijo.

Ob stalnih komisijah je še trinajst tehničnih komitejev za:
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- ozobja,
- sisteme človek - stroj,
- ročične in sledne mehanizme,
- mehatroniko,
- mikromehaniko,
- dinamiko večmasnih sistemov,
- nelinearna nihanja,
- zanesljivost,
- robotiko,
- dinamiko rotorjev,
- transportne mehanizme in
- tribologijo.

IFToMM je organizator in soorganizator mnogih znanstvenih srečanj. Termini in seznami so sprotno objavljeni na spletni strani IFToMM-a. Izdaja ali pa soizdaja tudi štiri strokovne revije:
- Mechanism and Machine Theory (http://www.elsevier.com/wps/find/journaldescription.cws_home/303/description#description),
- Problems of Mechanics (http://pam.edu.ge/),
- Journal of Gearing and Transmission (http://sjf.stuba.sk/NEWDV/Journals/GAT.htm) in
- Electronic Journal of Computational Kinematics (http://www-sop.inria.fr/coprin/EJCK/EJCK.html).

Najpomembnejši za vse člane IFToMM-a in raziskovalce, ki se ukvarjajo s teorijo strojev in mehanizmov, je vsekakor svetovni kongres, ki poteka vsaka štiri leta v eni od držav članic IFToMM-a.

Od prvega ustanovnega kongresa v Varni v Bolgariji leta 1965 so bili svetovni kongresi še v Zakopanih na Poljskem leta 1969, Kuparih v

Jugoslaviji leta 1971, Newcastlu v Veliki Britaniji leta 1975, Montrealu v Kanadi leta 1979, New Delhiju v Indiji leta 1983, Sevilli v Španiji leta 1987, Pragi na Češkem leta 1991, Milanu v Italiji leta 1995, Oulu na Finskem leta 1999 in zadnji na Kitajskem v mestu Tianjin leta 2004.

Slovenski nacionalni komite je leta 1994 ustanovil prof. dr. Igor Janežič s Fakultete za strojništvo v Ljubljani.

Slovenija je postala polnopravna članica IFToMM leta 1995 v Milanu. Pred tem pa so slovenski raziskovalci in strokovnjaki sodelovali s svojimi prispevki preko Jugoslovanskega nacionalnega komiteja. Slovenski nacionalni komite je do junija 2004 vodil izr.prof.dr. Igor Janežič s Fakultete za strojništvo v Ljubljani. Od junija 2004 naprej za dobo štirih let pa slovenski nacionalni komite vodi prof. dr. Karl Gotlih s Fakultete za strojništvo v Mariboru. V prvem obdobju se je delovanje slovenskega nacionalnega komiteja osredotočilo na priprave na udeležbo na svetovnem kongresu IFToMM. Slovenski delegati so bili navzoči skoraj na vseh kongresih in ob dejstvu, da se prispevki za kongres izbirajo po strogem postopku, je to za slovensko znanost na področju mehanizmov in strojev velik uspeh.

Naslednja svetovna konferenca IFToMM bo letos v Franciji v kraju Besançon. Razpisni postopek za prispevke na konferenci je že končan, vse informacije o svetovnem kongresu so na spletni strani kongresa: http://www.iftomm2007.com/.

prof.dr. Karl Gotlih
prof.dr. Igor Janežič

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Osebne vesti - Personal Events

Doktorat in diplome - Doctor's and Diploma Degrees

DOKTORAT

Na Fakulteti za strojništvo Univerze v Mariboru je z uspehom zagovarjal svojo doktorsko disertacijo:

dne *16. januarja 2007*: **mag. Martin Volmajer**, z naslovom: "Modeliranje dvofaznih tokov v vbrizgalni šobi" (mentorica: prof. dr. Breda Kegl).

S tem je navedeni kandidat dosegel akademsko stopnjo doktorja znanosti.

DIPLOMIRALI SO

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv univerzitetni diplomirani inženir strojništva:

dne *1. februarja 2007*: Blaž KLUN, Andraž REKELJ, Dejan ŠTRUS.

Na Fakulteti za strojništvo Univerze v Mariboru so pridobili naziv univerzitetni diplomirani inženir strojništva:

dne *25. januarja 2007*: Matjaž FRANC, David KOLAR, Andrej KOPUŠAR.

*

Na Fakulteti za strojništvo Univerze v Ljubljani sta pridobila naziv diplomirani inženir strojništva:

dne *11. januarja 2007*: Boštjan BARTOLJ, Marko NOVAKOVIČ.

Na Fakulteti za strojništvo Univerze v Mariboru je pridobil naziv diplomirani inženir strojništva:

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Since 1992, the Journal of Mechanical Engineering has been published bilingually, in Slovenian and English. The two texts must be compatible both in terms of technical content and language. Papers should be as short as possible and should on average comprise 8 pages. In exceptional cases, at the request of the authors, speciality papers may be written only in Slovene, but must include an English abstract.

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- Rezultati, ki naj bodo jasno prikazani, po potrebi v obliki slik in preglednic.
- Razprava, v kateri naj bodo prikazane povezave in posplošitve, uporabljene za pridobitev rezultatov. Prikazana naj bo tudi pomembnost rezultatov in primerjava s poprej objavljenimi deli. (Zaradi narave posameznih raziskav so lahko rezultati in razprava, za jasnost in preprostejše bralčevo razumevanje, združeni v eno poglavje.)
- Sklepi, v katerih naj bo prikazan en ali več sklepov, ki izhajajo iz rezultatov in razprave.
- Literatura, ki mora biti v besedilu oštevilčena zaporedno in označena z oglatimi oklepaji [1] ter na koncu članka zbrana v seznamu literature. Vse opombe naj bodo označene z uporabo dvignjene številke[1].

THE FORMAT OF THE PAPER

The paper should be written in the following format:
- A Title, which adequately describes the content of the paper.
- An Abstract, which should be viewed as a mini version of the paper and should not exceed 250 words. The Abstract should state the principal objectives and the scope of the investigation, the methodology employed, summarize the results and state the principal conclusions.
- An Introduction, which should provide a review of recent literature and sufficient background information to allow the results of the paper to be understood and evaluated.
- A Theory
- An Experimental section, which should provide details of the experimental set-up and the methods used for obtaining the results.
- A Results section, which should clearly and concisely present the data using figures and tables where appropriate.
- A Discussion section, which should describe the relationships and generalisations shown by the results and discuss the significance of the results making comparisons with previously published work. (Because of the nature of some studies it may be appropriate to combine the Results and Discussion sections into a single section to improve the clarity and make it easier for the reader.)
- Conclusions, which should present one or more conclusions that have been drawn from the results and subsequent discussion.
- References, which must be numbered consecutively in the text using square brackets [1] and collected together in a reference list at the end of the paper. Any footnotes should be indicated by the use of a superscript[1].

OBLIKA ČLANKA

Besedilo članka naj bo pripravljeno v urejevalnilku Microsoft Word. Članek nam dostavite v elektronski obliki.

Ne uporabljajte urejevalnika LaTeX, saj program, s katerim pripravljamo Strojniški vestnik, ne uporablja njegovega formata.

Enačbe naj bodo v besedilu postavljene v ločene vrstice in na desnem robu označene s tekočo številko v okroglih oklepajih

THE LAYOUT OF THE TEXT

Texts should be written in Microsoft Word format. Paper must be submitted in electronic version.

Do not use a LaTeX text editor, since this is not compatible with the publishing procedure of the Journal of Mechanical Engineering.

Equations should be on a separate line in the main body of the text and marked on the right-hand side of the page with numbers in round brackets.

Enote in okrajšave

V besedilu, preglednicah in slikah uporabljajte le standardne označbe in okrajšave SI. Simbole fizikalnih veličin v besedilu pišite poševno (kurzivno), (npr. *v, T, n* itn.). Simbole enot, ki sestojijo iz črk, pa pokončno (npr. ms^{-1}, K, min, mm itn.).

Vse okrajšave naj bodo, ko se prvič pojavijo, napisane v celoti v slovenskem jeziku, npr. časovno spremenljiva geometrija (ČSG).

Slike

Slike morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot sl. 1, sl. 2 itn. Posnete naj bodo v ločljivosti, primerni za tisk, v kateremkoli od razširjenih formatov, npr. BMP, JPG, GIF. Diagrami in risbe morajo biti pripravljeni v vektorskem formatu, npr. CDR, AI.

Pri označevanju osi v diagramih, kadar je le mogoče, uporabite označbe veličin (npr. *t, v, m* itn.), da ni potrebno dvojezično označevanje. V diagramih z več krivuljami, mora biti vsaka krivulja označena. Pomen oznake mora biti pojasnjen v podnapisu slike.

Vse označbe na slikah morajo biti dvojezične.

Preglednice

Preglednice morajo biti zaporedno oštevilčene in označene, v besedilu in podnaslovu, kot preglednica 1, preglednica 2 itn. V preglednicah ne uporabljajte izpisanih imen veličin, ampak samo ustrezne simbole, da se izognemo dvojezični podvojitvi imen. K fizikalnim veličinam, npr. *t* (pisano poševno), pripišite enote (pisano pokončno) v novo vrsto brez oklepajev.

Vsi podnaslovi preglednic morajo biti dvojezični.

Seznam literature

Vsa literatura mora biti navedena v seznamu na koncu članka v prikazani obliki po vrsti za revije, zbornike in knjige:

[1] A. Wagner, I. Bajsić, M. Fajdiga (2004) Measurement of the surface-temperature field in a fog lamp using resistance-based temperature detectors, *Stroj. vestn.* 2(2004), pp. 72-79.

[2] Vesenjak, M., Ren Z. (2003) Dinamična simulacija deformiranja cestne varnostne ograje pri naletu vozila. *Kuhljevi dnevi '03*, Zreče, 25.-26. september 2003.

[3] Muhs, D. et al. (2003) Roloff/Matek Maschinenelemente – Tabellen, 16. Auflage. *Vieweg Verlag*, Wiesbaden.

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Only standard SI symbols and abbreviations should be used in the text, tables and figures. Symbols for physical quantities in the text should be written in italics (e.g. *v, T, n,* etc.). Symbols for units that consist of letters should be in plain text (e.g. ms^{-1}, K, min, mm, etc.).

All abbreviations should be spelt out in full on first appearance, e.g., variable time geometry (VTG).

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Figures must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Fig. 1, Fig. 2, etc. Pictures may be saved in resolution good enough for printing in any common format, e.g. BMP, GIF, JPG. However, graphs and line drawings sholud be prepared as vector images, e.g. CDR, AI.

When labelling axes, physical quantities, e.g. *t, v, m,* etc. should be used whenever possible to minimise the need to label the axes in two languages. Multi-curve graphs should have individual curves marked with a symbol, the meaning of the symbol should be explained in the figure caption.

All figure captions must be bilingual.

Tables

Tables must be cited in consecutive numerical order in the text and referred to in both the text and the caption as Table 1, Table 2, etc. The use of names for quantities in tables should be avoided if possible: corresponding symbols are preferred to minimise the need to use both Slovenian and English names. In addition to the physical quantity, e.g. *t* (in italics), units (normal text), should be added in new line without brackets.

All table captions must be bilingual.

The list of references

References should be collected at the end of the paper in the following styles for journals, proceedings and books, respectively:

[1] A. Wagner, I. Bajsić, M. Fajdiga (2004) Measurement of the surface-temperature field in a fog lamp using resistance-based temperature detectors, *Stroj. vestn.* 2(2004), pp. 72-79.

[2] Vesenjak, M., Ren Z. (2003) Dinamična simulacija deformiranja cestne varnostne ograje pri naletu vozila. *Kuhljevi dnevi '03*, Zreče, 25.-26. september 2003.

[3] Muhs, D. et al. (2003) Roloff/Matek Maschinenelemente – Tabellen, 16. Auflage. *Vieweg Verlag*, Wiesbaden.

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