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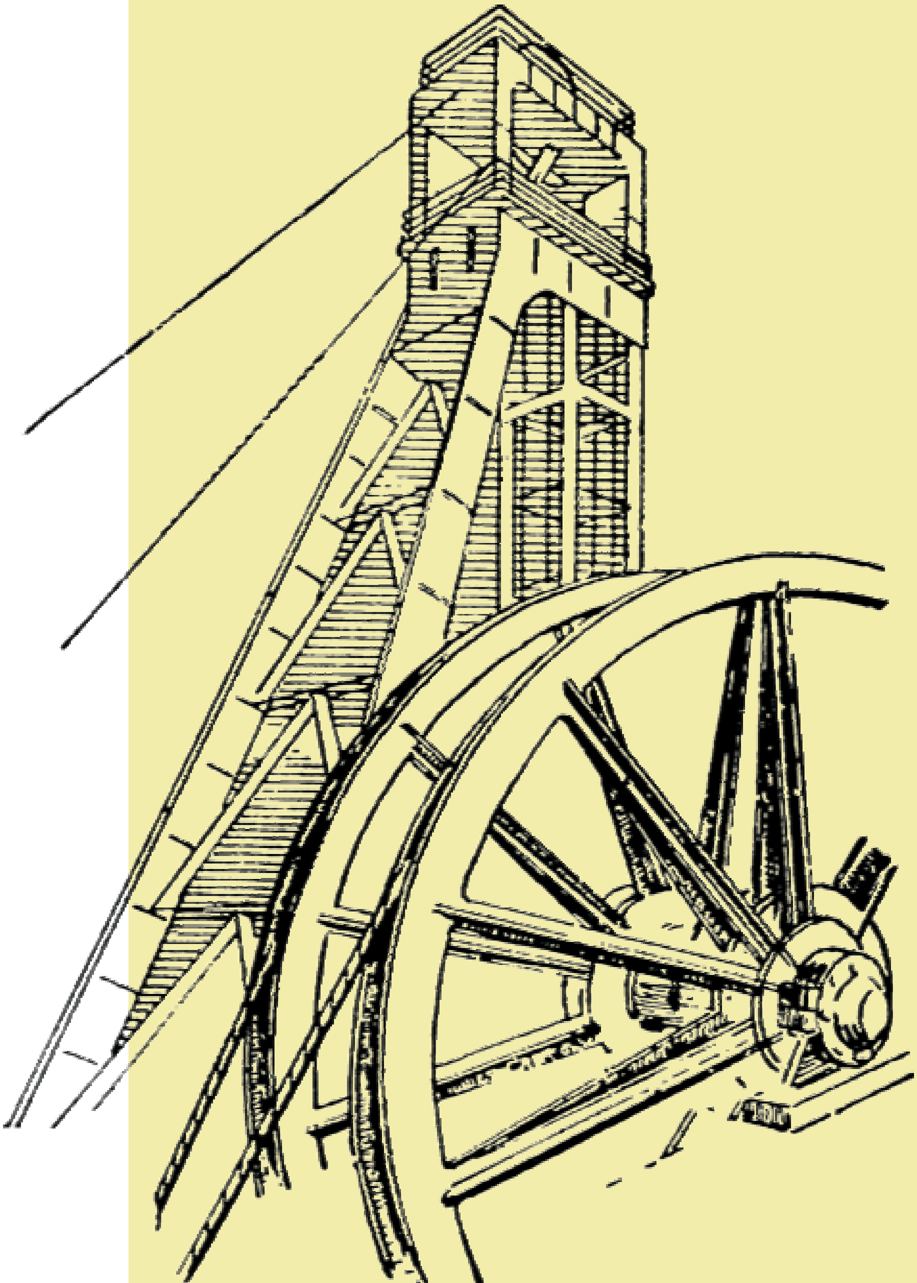

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Odvijanje preje z navitka - obravnava kinematičnih in dinamičnih lastnosti preje

Yarn unwinding from packages – a discussion on the kinematic and dynamic properties of yarn

Stanislav Praček - Danilo Jakšič

Obravnavamo odvijanje preje z navitkov, kar je ključnega pomena pri številnih tekstilnih procesih. Izpeljemo zelo splošen sistem diferencialnih enačb, ki opisujejo gibanje preje med odvijanjem.

Opisan je fizikalni pomen posameznih členov, ki nastopajo v enačbah, s posebnim poudarkom na navideznih silah v vrtečem se koordinatnem sistemu. Prikažemo tudi, kako lahko v kvazistacionarnem približku sistem enačb numerično rešimo in dobimo sliko preje v prostoru med odvijanjem.

(Ključne besede: gibanje preje, lastnosti kinematične, lastnosti dinamične, enačbe diferencialne)

We discuss yarn unwinding from packages, which is of chief importance in many textile processes. We derive a very general system of differential equations that describe the motion of the yarn during unwinding.

We discuss the physical meaning of individual terms in the equations with special emphasis on virtuals forces, which appear in rotating coordinate systems. We also show how the equations can be numerically solved in the quasistationary approximation in order to obtain an image of yarn in space during unwinding.

(Keywords: yarn motion, kinematic properties, dynamic properties, partial differential equations)

0 UVOD

Nihanja mehanske napetosti, do katerih prihaja med odvijanjem preje z navitka, povzročajo številne težave in lahko vplivajo na učinkovitost tekstilnega postopka in na kakovost končnega izdelka. Ta nihanja so še posebej opazna pri vzdolžnem odvijanju, pri katerem je navitek nameščen nepremično, preja pa se hitro odvija in teče stran od navitka v smeri njegove osi. Pomembno je, da poiščemo obliko navitka, pri kateri bo gibanje preje takšno, da bo napetost v preji majhna in čim bolj enakomerna.

Odvijanje preje bomo obravnavali s teoretičnega vidika. Izpeljali bomo sistem diferencialnih enačb, ki opisuje gibanje preje med odvijanjem. Enačbe bomo izpeljali z najmanjšim številom privzetkov, tako da bodo čim bolj splošne. Pri tem bomo dali velik poudarek fizikalnim

0 INTRODUCTION

Oscillations of tension in yarn, which appear when the yarn is unwinding from a package, cause many problems and can degrade the efficiency of the textile process and the quality of the end product. These oscillations are particularly strong in axial unwinding, where the package is stationary and the yarn is being withdrawn in the direction of package axis. It is thus important to find the optimum shape of the package for which the motion of the yarn will be such that the yarn tension will be small and as steady as possible.

The unwinding will be discussed from the theoretical point of view. We will derive a system of differential equations that provides a description of the yarn motion during the unwinding. We will derive these equations using a minimal set of assumptions, so that the resulting equations will retain their generality. An razlagam posameznih matematičnih izrazov in členov, ki se v njih pojavljajo: namen prispevka ni le razviti računski formalizem, temveč tudi bralcu omogočiti razumevanje bistvenih fizikalnih dejavnikov, ki lahko vplivajo na končni rezultat. Zato bomo bolj izdatno, kakor je sicer v navadi, spregovorili o opisu preje kot krivulji v prostoru in o njeni parametrizaciji, o podobnosti s hidrodinamičnim problemom toka tekočin (razlika med lokalnim in substancialnim odvodom), o uporabi Newtonovega zakona pri razsežnih telesih in o tem, kako opišemo napetostno stanje v enorazsežnih telesih. Na koncu bomo pokazali še, kako zapišemo enačbe v vrtečem se koordinatnem sistemu, opisali bomo navidezne "sistemske" sile, ki jih pri tem dobimo, ter izpeljali pogoj, ki ga dobimo zaradi privzetka neraztezností preje.

1 OPIS PREJE IN KINEMATIČNE LASTNOSTI

Pri obravnavi gibanja preje običajno zanemarimo prečno razsežnost preje. Z drugimi besedami, mislimo si, da je preja neskončno tanka in da jo zato lahko obravnavamo kot enorazsežni predmet. Takšni približki so v mehaniki pogosti: tudi kovinske žice, strune glasbenih inštrumentov, elastike, vlakna in podobne dolge, vendar tanke predmete, obravnavamo kot idealno tanka telesa. Napaka, ki jo s takšnih približkom storimo, je zanemarljivo majhna. Poleg tega privzamemo, da je preja neraztezna: to pomeni, da zanemarimo raztezke v preji, vendar pa kljub temu upoštevamo napetost v preji. Dokazano je bilo, da vodi ta približek le k majhni napaki pri običajno uporabljeni preji [1].

Enorazsežno telo opišemo kot krivuljo v prostoru. Najlaže jo podamo v parametrizirani obliki: vsako točko na krivulji podamo z njenim krajevnim vektorjem $\mathbf{r}(s)$, pri čemer je s parameter, s katerim oštevilčimo točke na krivulji. Pri opisu preje je najbolj naravna in pripravna parametrizacija z ločno dolžino, kar pomeni, da je s dolžina preje med izbrano točko $\mathbf{r}(s)$ in izbranim izhodiščem. Pri odvijanju preje z navitkov je najbolj primerna izbira izhodišča vodilo, skozi katerega prejo vlečemo z nespremenljivo hitrostjo (sl. 1).

Prejo odvijamo s hitrostjo V skozi vodilo O, ki je tudi izhodišče koordinatnega sistema. Točka **Dv** je točka dviga, to je točka, v kateri preja zapusti

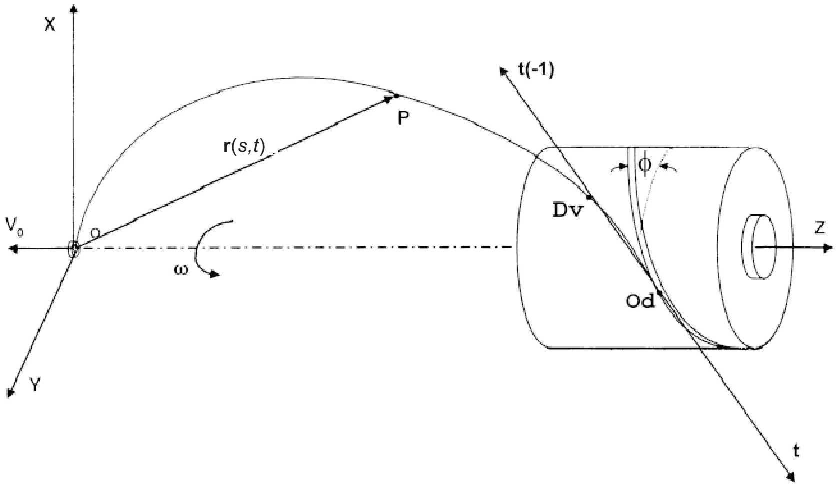
emphasis will be given to the physical interpretations of the mathematical expressions and of the various terms that appear in them: the purpose of this paper is not only to develop a formalism for the calculations, but also to lead to an understanding of the key physical elements that have a direct influence on the final result. For this reason we will amply describe details that are usually neglected, such as the description of the yarn as a curve in space and its parametrisation, the similarity with the hydrodynamical problem of liquid flow (the difference between the local and the substantial derivative), the use of Newton's law for a description of the extended bodies and the description of the elastic state of one-dimensional objects. We will show how the transition to the rotating cylindrical coordinate system is accomplished and how this leads to virtual "system" forces. The condition resulting from the non-extensibility of the yarn will also be given.

1 DESCRIPTION OF THE YARN AND THE KINEMATIC PROPERTIES

The lateral dimensions of the yarn are usually neglected in descriptions of yarn motion. In other words, we consider the yarn to be infinitely thin, so that it can be described as a one-dimensional object. Such approximations are common in mechanics, they are used for objects such as metal wires, the strings of musical instruments, fibers and other long, but thin objects, that can be considered as ideally thin. This approximation leads to a small error that can be safely neglected. We furthermore assume that the yarn is not extensible: by this we mean that any elongation is neglectable; however, we do take into account the tension in the yarn. It has been shown that this assumption leads to only a small error with commonly used yarns [1].

A one-dimensional body can be mathematically described as a space curve. It can be most conveniently given in parametric form: each point on the curve is described by its coordinates (radius vector) $\mathbf{r}(s)$, where s is some parameter used to number the points on the curve. For yarns the most natural and useful parametrisation is given by its arc length. Parameter s is then the length of yarn between the chosen point $\mathbf{r}(s)$ and the origin. A very convenient choice of the origin for yarn-unwinding problems is the guide through which the yarn is being pulled away with constant velocity (Fig. 1).

The yarn is being withdrawn with unwinding speed V through a guide O, which also serves as the origin of the coordinate system. Point **Dv** is the lift-off point, i.e., the point where the yarn leaves the surface



Sl. 1. *Odvijanje preje z valjastega navitka*
Fig. 1. *Yarn unwinding from a cylindrical package*

površino navitka in naprej ustvarja balon. Točka **Od** je točka, kjer se preja začne odvijati in drseti po navitku. Kot ϕ je kot navijanja preje na valjasti navitek. Vektor **k** je tangentni vektor na prejo v točki odvijanja.

Zanimalo nas bo gibanje preje, torej časovno spreminjanje lege krivulje **r**(s) v prostoru. Zato uvedemo še dodaten parameter t, ki podaja trenutek, ob katerem ima krivulja obliko **r**(s,t=*konst*). Rečemo lahko tudi, da je funkcija **r**(s,t) pri izbranem stalnem času t "trenutna slika preje v prostoru", kakor bi jo posneli s fotoaparatom. Časovni potek odvijanja preje zato podamo kot dvoparametrično vektorsko funkcijo **r**(s,t).

Pri kinematiki odvijajoče se preje naletimo na podobno težavo kakor pri hidrodinamičnem problemu toka tekočin [2]. Problema sta si podobna v tem, da imamo tudi tukaj opravka s prejo, ki "teče" proti vodilu vzdolž svoje "struge", ki jo v nekem trenutku t_o podaja funkcija **r**($s,t=t_o$). Dejansko sta pri preji sočasno prisotni dve različni gibanji: "tok" preje, ki jo vlečemo proti vodilu (to gibanje je v vsaki točki tangentno na krivuljo **r**($s,t=t_o$)), ter spreminjanje "struge" same, zaradi odvijanja preje z navitka.

Lega preje je, kakor rečeno, odvisna tako od ločne doline s kakor od časa t: **r**=**r**(s,t). Iz zaporednih opazovanj lege pri eni in isti ločni dolžini dobimo *lokalni časovni odvod*, ki ga označimo z ∂**r**/∂t. Ta odvod pa ni enak hitrosti preje! Enak je spreminjanju "struge" preje, ne upošteva pa dejstva, da preja "teče po strugi" s hitrostjo odvijanja V.

of the packages to form the balloon. Point **Od** is the unwinding point, where the yarn starts to slide on the surface of the package. Angle ϕ is the angle of winding on the package. Vector **k** is the tangent vector on the yarn at the unwinding point.

We are interested in yarn motion, i.e., the time variation of the position **r**(s) of the yarn in space. We therefore introduce an additional parameter t, which gives us a moment in time when the form of the yarn is **r**(s,t=*const*). In other words, the function **r**(s,t) at fixed time t is a "snapshot of the yarn in space" as taken by a camera. The process of yarn unwinding is therefore described using a two-parameter vector function **r**(s,t).

In a kinematic description of yarn unwinding we face a similar problem to that in the hydrodynamic problem of liquid flow [2]. Both problems are similar in that the yarn also "flows" in the direction of the guide along its "riverbed", which at time t_o is given by the function **r**($s,t=t_o$). In fact there are two simultaneous motions of the yarn: the "flow" of the yarn being pulled through the guide (this motion is at every point tangent to the curve **r**($s,t=t_o$)) and the time variation of the "riverbed" itself due to the unwinding of the yarn from the package.

The position of a point on the yarn depends on two parameters: the arc length s and the time t: **r**=**r**(s,t). If we observe the position of the yarn at a fixed arc length we obtain a *local time derivative*, denoted by ∂**r**/∂t. This derivative, however, is not equal to the yarn velocity. Instead, it is equal to the velocity of the changes of the "riverbed", but it does not take into account that the yarn "flows within the riverbed" with the unwinding speed V.

Če hočemo izmeriti hitrost izbrane točke preje, ne smemo preje opazovati pri nespremenljivem s, temveč se moramo vzdolž "toka" gibati skupaj s prejo. Gibanje odseka preje opiše funkcija $\mathbf{r}(s(t),t)$, pri čemer je $s(t)$ ločna dolžina obravnavanega odseka preje ob času t. Lega tega odseka je odvisna samo od časa. Hitrost dobimo kot totalni odvod, $\mathbf{v}=d(\mathbf{r}(s(t),t)/\mathrm{d}t$. V hidrodinamiki je takšen odvod znan kot *substancialni odvod*. Z *lokalnim odvodom* $\partial\mathbf{r}/\partial t$ ga povežemo z uporabo pravil diferencialnega računa:

If one wants to measure the velocity of a chosen point on the yarn, one should not observe the yarn at fixed s, but should instead follow the "flow" of the yarn. The motion of a short segment of the yarn is described by the function $\mathbf{r}(s(t),t)$, where $s(t)$ is the arc-length of the segment at time t. The position of the segment is a function of time only. The velocity can be obtained using a total derivative, $\mathbf{v}=d(\mathbf{r}(s(t),t))/dt$. Such a derivative is known in hydrodynamics as a *substantial derivative*. It can be related to the *local derivative* $\partial\mathbf{r}/\partial t$ using the chain rule of calculus:

$$\frac{\mathrm{d}\mathbf{r}(s(t),t)}{\mathrm{d}t}=\frac{\partial\mathbf{r}}{\partial t}+\frac{\partial\mathbf{r}}{\partial s}\frac{\mathrm{d}s}{\mathrm{d}t} \qquad (1).$$

Sedaj upoštevamo privzetek, da je preja neraztezna. Če prejo odvijamo z odvijalno hitrostjo V, ki se s časom ne spreminja, potem za vsak kratek odsek preje velja $s(t)=s_o-Vt$. Predznak minus dobimo zato, ker prejo vlečemo v smeri vodila, zato se ločna dolžina $s(t)$ izbranega odseka zmanjšuje s časom linearno proti nič. V poljubni točki na preji tedaj velja $ds/dt=-V$. Zapišemo torej:

We now take into account that the yarn was assumed inextensible. If the yarn is withdrawn with an unwinding speed V that is constant with time, then for any short segment of the yarn we have $s(t)=s_o-Vt$. We obtain a minus sign because the yarn is being pulled in the direction of the guide, so that the arc-length $s(t)$ to a given segment decreases with time linearly toward zero. Therefore we have $ds/dt=-V$ at any point of the yarn. We can then write:

$$\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t}=\frac{\partial\mathbf{r}}{\partial t}-V\frac{\partial\mathbf{r}}{\partial s} \qquad (2).$$

Ker je parametrizacija z ločno dolžino naravna parametrizacija, je $\partial\mathbf{r}/\partial s$ enotski tangentni vektor $\boldsymbol{k}$ na prejo v dani točki. Končna enačba za hitrost se torej glasi:

As arc-length parametrisation is a natural parametrisation of a curve, the derivative $\partial\mathbf{r}/\partial s$ is equal to the unit tangent vector $\mathbf{k}$ to the yarn at a given point. The final expression for the velocity of a segment is therefore:

$$\mathbf{v}=\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t}=\frac{\partial\mathbf{r}}{\partial t}-V\mathbf{k} \qquad (3).$$

Prvi člen opisuje "spreminjanje struge", drugi člen pa tangentni "tok" preje proti vodilu. Na tem mestu moramo poudariti, da izraz (3) nikakor ne pomeni, da je tangentna komponenta hitrosti enaka $-V$ v vseh točkah preje, saj lahko tudi člen $\partial\mathbf{r}/\partial t$ vsebuje komponento v tej smeri. Medtem ko je tangenta komponenta hitrosti po definiciji naloge enaka V pri vodilu, je tangentna komponenta zagotovo enaka nič v točki odvijanja **Od**, kjer se preja ravno začne premikati.

Vpeljemo lahko abstraktni operator totalnega časovnega odvoda D, ki sledi gibanju točke na preji:

The first term describes the changing "riverbed" and the second term gives the tangential "flow" of the yarn along the riverbed in the direction of the guide. At this point we should emphasize that the expression (3) in no way implies that the tangential component of the velocity is equal to $-V$ at all points on the yarn, because the term $\partial\mathbf{r}/\partial t$ can also contain a component along this direction. Indeed, while the tangential component of the velocity is from the definition of the problem equal to V at the guide, it is clearly equal to zero at the unwinding point **Od** where the yarn just starts to move.

We can introduce an abstract total time derivative operator D, which follows the motion of a point along the yarn:

$$D=\frac{\mathrm{d}}{\mathrm{d}t}=\frac{\partial}{\partial t}-V\frac{\partial}{\partial s} \qquad (4).$$

Če operator D uporabimo na krajevnem vektorju $\mathbf{r}$, dobimo izraz (2). Hitrost gibanja odseka

By applying the operator D on a radius vector $\mathbf{r}$, we obtain expression 1. The velocity of the yarn segment preje je torej $\mathbf{v}=D\mathbf{r}$. Pričakujemo torej, da bomo dobili pospešek odseka preje, če operator D uporabimo dvakrat na krajevnem vektorju: $\mathbf{a}=D^2\mathbf{r}$. Dobimo:

is therefore $\mathbf{v}=D\mathbf{r}$. We can expect that the acceleration of a yarn segment is given by applying the operator D twice on the radius vector: $\mathbf{a}=D^2\mathbf{r}$. We obtain:

$$D^2\mathbf{r} = \left(\frac{\partial}{\partial t} - V\frac{\partial}{\partial s}\right)^2 \mathbf{r} = \left(\frac{\partial^2}{\partial t^2} - 2V\frac{\partial^2}{\partial s\partial t} + V^2\frac{\partial^2}{\partial s^2}\right)\mathbf{r} \quad (5),$$

torej

or

$$\mathbf{a} = \frac{\partial^2\mathbf{r}}{\partial t^2} - 2V\frac{\partial\mathbf{k}}{\partial t} + V^2\frac{\partial\mathbf{k}}{\partial s} \quad (6).$$

Ta rezultat lahko preverimo tudi z neposrednim izračunom pospeška brez uporabe operatorja D.

We can ascertain that this is in fact the correct expression for acceleration by a direct calculation without using the operator D.

2 DINAMIKA: NEWTONOV ZAKON ZA ODSEK PREJE

Gibanje preje bomo opisali v inercialnem opazovalnem sistemu, v katerem velja Newtonov zakon $\mathbf{F}=m\mathbf{a}$, kjer so $\mathbf{F}$ sila na telo, $\mathbf{a}$ pospešek, m pa masa telesa. Newtonov zakon je zapisan v obliki, ki je uporabna za obravnavo gibanja snovnih delcev (na primer atomov), togih teles (krogel, planetov itn.), ter za opis gibanja *težišča* deformljivih teles kot celote. Pri preji, ki je deformljivo telo, nas ne zanima, kako se giblje preja kot celota, temveč kako se spreminja oblika preje same. Zato prejo v mislih razrežemo na (infinitezimalno) kratke odseke dolžine δs in uporabimo Newtonov zakon za vsak odsek posebej.

Oglejmo si najprej, katere sile delujejo na naš sistem, torej na kratek odsek preje, katerega eno krajišče je v točki $\mathbf{r}(s)$, drugo krajišče pa v točki $\mathbf{r}(s+\delta s)$. Očitno je odsek izpostavljen sili težnosti $\mathbf{F}_t=m\mathbf{g}$ (m je masa odseka preje, $\mathbf{g}$ pa težnostni pospešek). Izkaže se, da je sila težnosti zanemarljiva v primerjavi z drugimi silami, zato jo zanemarimo [3]. Če se odsek premika po zraku, nanj deluje tudi sila zračnega upora $\mathbf{F}_{zr}$:

2 DYNAMICS: NEWTON'S LAW FOR A YARN SEGMENT

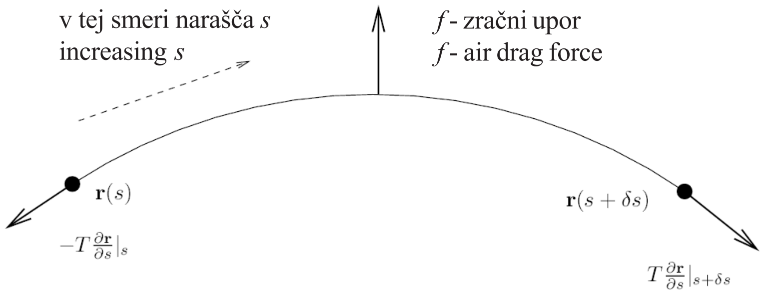
We will describe yarn motion in an inertial observation frame where Newton's law $\mathbf{F}=m\mathbf{a}$ is valid. Here, $\mathbf{F}$ is the force acting on the body, $\mathbf{a}$ is the acceleration and m is the mass of the body. This form of Newton's law is appropriate for describing the motion of material particles (such as atoms), rigid bodies (balls, planets etc.) and for describing the motion of the *center of mass* of deformable bodies. The yarn is deformable and we are not interested in how it moves as a whole. We are interested instead in the changes of the form of the yarn. We therefore divide the yarn into (infinitesimally) short segments of length δs and apply Newton's law to each segment individually.

First we need to determine which forces act on our system, i.e., on the short segment of yarn whose one extremity is $\mathbf{r}(s)$ and other extremity is $\mathbf{r}(s+\delta s)$. The force of gravity $\mathbf{F}_t=m\mathbf{g}$ (m is the mass of the segment and $\mathbf{g}$ the gravitational acceleration) acts on the segment. It turns out that the effect of gravitation can usually be neglected in comparison to the other forces [3]. If the segment is moving through the air, there is also a contribution from the air drag force $\mathbf{F}_{zr}$:

$$F = \frac{1}{2}c_u\rho v_n^2 S \quad (7),$$

kjer so: c_u koeficient zračnega upora, ρ gostota zraka, $\mathbf{v}_n$ pravokotna komponenta hitrosti, S pa čelni prerez odseka preje ([4] in [3]). Reynoldsevo število je višje od 1000 v tistih delih preje, kjer je hitrost največja, in nižje drugod. Kljub temu uporabimo kvadratni zakon zračnega upora na celotni dolžini preje, saj velja v tistih delih preje, kjer je učinek zračnega upora največji.

where c_u is the coefficient of air drag, ρ is the density of the air, v_n is the normal component of the velocity and S is the frontal area of the yarn segment ([4] and [3]). The Reynolds number is higher than 1000 on the parts of the yarn with the highest velocity and smaller elsewhere. Nevertheless, we use the law of quadratic air drag on the entire length of the yarn because it is valid on those parts of the yarn where it has the largest effect.



Sl. 2. *Sila na odsek preje*
Fig. 2. *Forces acting on a yarn segment*

Na kratek odsek preje pa neposredno delujeta tudi preostala kosa preje na obeh straneh obravnavanega odseka (sl. 2), zato na vsako krajišče deluje neka sila. Ti sili sta posledica notranjega napetostnega stanja zaradi natezne obremenjenosti preje, podobno kakor pri napeti elastiki.

Na odsek preje delujejo sile zaradi napetosti in sila zračnega upora.

V trorazsežnih telesih (kontinuih) napetostno stanje opišemo z napetostnim tenzorjem, v enorazsežnem telesu, kakršna je preja, pa zadostuje skalarna količina, imenovana napetost T. Ta pove, kakšna sila deluje na rob enorazsežnega telesa zaradi deformacij in ima enoto sile [N]. Definiramo jo z enačbo:

In addition to these obvious forces, there are also forces imparted on the segment by the remaining yarn on each side of the segment, see Fig. 2, so that there is an additional force on each extremity of the segment. These two forces are a consequence of the internal elastic state due to elastic strain on the yarn, similar to the case of a stretched elastic band.

Forces of tension and air friction force act on a short yarn segment.

In three-dimensional continuum bodies the stress state is given by the stress tensor, whereas in one-dimensional bodies such as the yarn, a single scalar quantity is sufficient. This quantity is called the tension, and it is denoted by T. The tension is numerically equal to the force that acts on an extremity of a one-dimensional body due to deformations and it has the same unit as force, i.e., Newton [N]. It is defined with the equation:

$$\mathbf{F} = T\mathbf{k} \tag{8}$$

kjer sta $\mathbf{F}$ sila na rob obseka preje, vektor $\mathbf{k}$ pa tangentni vektor na prejo v točki prijemališča sile $\mathbf{F}$, torej v robni točki. Sila na rob preje v točki $\mathbf{r}(s)$ je:

where $\mathbf{F}$ is the force acting on the extremity of the segment, vector $\mathbf{k}$ is a tangent vector on the yarn at the point of the application of the force $\mathbf{F}$, i.e., at the extremity. The force on the extremity at $\mathbf{r}(s)$ is therefore:

$$-T(s)\mathbf{k}(s) \tag{9}$$

sila na drugi rob v točki $\mathbf{r}(s+\delta s)$ pa:

and the force on the other extremity at $\mathbf{r}(s+\delta s)$ is

$$T(s+\delta s)\mathbf{k}(s+\delta s) \tag{10}$$

Drugi Newtonov zakon za odsek preje zato zapišemo kot:

Newton's second law for a segment of yarn can be expressed as

$$m\mathbf{a} = T(s+\delta s)\mathbf{k}(s+\delta s) - T(s)\mathbf{k}(s) + \mathbf{F}_{zr} \tag{11}$$

Masa odseka je $m=\rho\delta s$, kjer je ρ linearna gostota (masa na enoto dolžine preje), silo F_{zr} pa

The mass of the segment is $m=\rho\delta s$, where ρ is the mass of yarn per unit length. The force $\mathbf{F}_{zr}$ can zapišemo kot $\mathbf{F}_{zr}=\mathbf{f}_{zr}\delta s$, kjer je $\mathbf{f}_{zr}$ linearna gostota sile zračnega upora (torej sila zračnega upora na enoto dolžine preje). Zato enačbo (11) delimo z δs in naredimo limiti proti infinitezimalno kratki dolžini odseka, $\delta s \rightarrow 0$:

be written as $\mathbf{F}_{zr}=\mathbf{f}_{zr}\delta s$, where $\mathbf{f}_{zr}$ is the linear density of the air drag force (the air drag force per unit length). By dividing Equation (11) by δs and going to the limit of an infinitesimally short segment length, $\delta s \rightarrow 0$, we obtain:

$$\rho \mathbf{a} = \lim_{\delta s \to 0} \frac{T(s+\delta s)\mathbf{k}(s+\delta s) - T(s)\mathbf{k}(s)}{\delta s} + \mathbf{f}_{zr} \quad (12).$$

Limita v zgornjem izrazu je po definiciji odvod funkcije $T(s)\mathbf{k}(s)$ po ločni dolžini s. Končni rezultat, torej gibalna enačba za infinitezimalno kratek odsek preje, je:

The limit in this expression is, by definition, the arc-length derivative of the function $T(s)\mathbf{k}(s)$. The final result, the equation of motion of an infinitesimally short segment of yarn, is then

$$\rho \mathbf{a}(s) = \frac{\partial}{\partial s}\Big(T(s)\mathbf{k}(s)\Big) + \mathbf{f}_{zr}(s) \quad (13).$$

Če uporabimo rezultat za pospešek, (6), jo lahko zapišemo tudi v obliki:

Using the expression (6) for the acceleration, the equation of motion can also be put in the form

$$\rho \left(\frac{\partial^2 \mathbf{r}}{\partial t^2} - 2V\frac{\partial \mathbf{k}}{\partial t} + V^2 \frac{\partial \mathbf{k}}{\partial s} \right) = \frac{\partial}{\partial s}\Big(T\mathbf{k}\Big) + \mathbf{f}_{zr} \quad (14).$$

3 PREHOD V VRTEČI SE VALJNI KOORDINATNI SISTEM

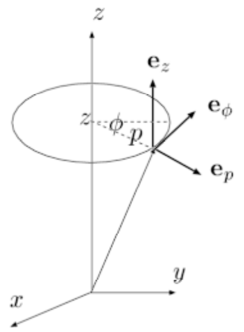
Pri odvijanju preje z navitka ustvarja preja "balon" (slika 1): preja se z veliko kotno hitrostjo vrti okoli osi Z in v eni periodi oriše rotacijsko telo z enim ali več "trebuhi". Oblika rotacijskega telesa - balona, se v času ene periode vrtenja spremeni le malo. Celotno gibanje krivulje $\boldsymbol{r}(s)$ lahko torej razstavimo na dve gibanji z različnima značilnima časoma. Prvo gibanje je vrtenje krivulje okoli osi Z in ima kratek značilni čas (reda $2\pi/\omega$, kjer je ω kotna hitrost: to je čas, v katerem se odvije en ovoj niti). Drugo gibanje je spreminjanje oblike balona in ima dolg značilni čas (ta je velikostnega reda časa, v katerem se odvije ena plast).

Takšen razcep je primeren predvsem za navitke (oziroma plasti), pri katerih je število ovojev veliko, torej predvsem za natančno navite navitke. Recimo, da ima ena plast navitka okoli 100 ovojev niti. Tedaj se oba značilna časa razlikujeta za dva velikostna reda. Imamo torej opravka z dvema gibanjema na zelo različnih časovnih merilih, zato je smiselno, da takšen razcep izrecno upoštevamo v naših enačbah. Pri navitkih z manjšim številom ovojev je razcep manj uporaben in naloge se je bolje lotiti z neposrednim numeričnim reševanjem enačbe (14), kar pa je izjemno težko.

3 TRANSITION TO A ROTATING CYLINDRICAL COORDINATE SYSTEM

The unwinding yarn forms a "balloon" (Fig. 1): the yarn rotates with a high angular velocity around the Z axis and with one turn it defines the contour of a rotational body with one or several balloons. The shape of the rotational body – the balloon – changes only a little in one period of the motion. The motion of the curve $\mathbf{r}(s)$ can therefore be decomposed into two separate motions with two different characteristic times. The first motion is the rotation of the rigid curve around the Z axis. It has a short characteristic time $2\pi/\omega$, where ω is the angular velocity. In this time one loop of the yarn is unwound. The second motion corresponds to the time-varying form of the balloon. This has a long characteristic time, of the order of the time in which one layer of the yarn is unwound from the package.

Such a decomposition makes sense only for packages (or layers) where the number of loops in a layer is high, i.e., for precision-wound packages. Let one layer have 100 loops of yarn. Then both characteristic times differ by two orders of magnitude and it is beneficial to take this decomposition explicitly into account in our equation of motion. In packages with a smaller number of loops such a decomposition is less useful and the problem is best approached by directly numerically solving the Equation (14); however, this is a very difficult task.



Sl. 3. *Valjni koordinatni sistem*
Fig. 3. *Cylindrical coordinate system*

Vsaka točka ima lastno trojico osnovnih vektorjev $\mathbf{e}_p$,$\mathbf{e}_\phi$,$\mathbf{e}_z$.

Najprej se iz kartezičnega koordinatnega sistema preselimo v valjnega. Ta je bolj primeren za probleme, v katerih obstaja simetrijska os. Počasi spreminjajoče se rotacijsko telo, balon, dejansko ima takšno simetrijsko os, zato bo obravnava *hitrega* dela gibanja (vrtenja) v takšnem koordinatnem sistemu lažja. V tem koordinatnem sistemu točko opišemo s koordinatami p (oddaljenost točke od osi z), polarnim kotom ϕ in višino točke z, kakor je prikazano na sliki 3. Spremembo zapišemo z naslednjimi enačbami:

To each point there corresponds a different triplet of basis vectors $\mathbf{e}_p$, $\mathbf{e}_\phi$, $\mathbf{e}_z$.

We first affected the change from a Cartesian to a cylindrical coordinate system. A cylindrical coordinate system is more appropriate for problems that possess a symmetry axis. The slowly deforming rotational body, the balloon, does have such an axis, therefore the *fast* motion (rotation) can be handled more easily in this coordinate system. In the cylindrical system the position of a point is given by coordinates p (the distance from the Z axis), the polar angle ϕ and the height z, as shown in Fig. 3. The transformation can be expressed using the following equations:

$$p = \sqrt{x^2 + y^2}, \quad \phi = \arctan(y/x), \quad z = z \tag{15}$$

Krajevni vektor zapišemo kot:

The radius vector can be put in the form:

$$\mathbf{r} = p\mathbf{e}_p + z\mathbf{e}_z \tag{16}$$

Vektorji $\mathbf{e}_p$, $\mathbf{e}_\phi$ in $\mathbf{e}_z$ so osnovni vektorji v točki $\mathbf{r}$. Paziti moramo na dejstvo, da ima vsaka točka svojo trojico osnovnih vektorjev: vektorja $\mathbf{e}_p$ in $\mathbf{e}_\phi$ sta odvisna od kota ϕ, kar je razvidno s slike 3. Vektor $\mathbf{e}_z$ pa je enak v vseh točkah. Odvisnosti od parametrov s in t zapišemo še izrecno v obliki:

Vectors $\mathbf{e}_p$, $\mathbf{e}_\phi$ and $\mathbf{e}_z$ are the basis vectors proper to point $\mathbf{r}$. We have to pay attention to the fact that each point has its proper triplet of basis vectors: vectors $\mathbf{e}_p$ and $\mathbf{e}_\phi$ depend on the polar angle ϕ, as shown in Fig. 3; vector $\mathbf{e}_z$ is the same in all points. For clarity we can write the dependence of the different terms in the expression for the radius vector on parameters s and t explicitly:

$$\mathbf{r}(s,t) = p(s,t)\mathbf{e}_p(\phi(s,t)) + z(s,t)\mathbf{e}_z \tag{17}$$

V nadaljevanju bomo potrebovali še razmerji:

Later we will need the following two relations

$$\frac{\partial \mathbf{e}_p}{\partial \phi} = \mathbf{e}_\phi, \qquad \frac{\partial \mathbf{e}_\phi}{\partial \phi} = -\mathbf{e}_p, \tag{18}$$

ki sta osnovna lastnost valjnih koordinatnih sistemov in ju dobimo, če naredimo infinitezimalno

which are a basic property of cylindrical coordinate systems and can be obtained by performing an infinitesimal zavrtitev koordinatnega sistema okoli osi z za kot $\delta\phi$. Z njima lahko tudi dokažemo, da velja:

rotation of the coordinate system around the z axis. These relations can be used to derive two useful formulas:

$$\dot{\mathbf{e}_p} = \frac{\partial \mathbf{e}_p}{\partial \phi}\frac{\partial \phi}{\partial t} = \dot{\phi}\mathbf{e}_\phi \tag{19}$$

in

and

$$\dot{\mathbf{e}_\phi} = \frac{\partial \mathbf{e}_\phi}{\partial \phi}\frac{\partial \phi}{\partial t} = -\dot{\phi}\mathbf{e}_p \tag{20}$$

Tu pika nad simbolom označuje parcialni odvod po času, $\partial/\partial t$.

Hitro gibanje je vrtenje preje okoli osi z kot celote. To pomeni, da se pri tem gibanju polarni koti vseh točk spremenijo za enak kot na enoto časa. To zapišemo kot:

Here the dot above a symbol denotes a partial derivative with respect to time, $\partial/\partial t$.

The fast motion corresponds to the rotation of the yarn as a whole around the z axis. In other words, the polar angle of each point on the yarn changes by the same amount per unit time. This can be expressed as:

$$\phi(s,t) = \omega t + \theta(s,t) \tag{21}$$

Tu smo predpostavili, da je kotna hitrost vrtenja ω, stalna. Poudariti moramo, da je kot $\phi(s,t)$ polarni kot točke v inercialnem valjnem sistemu (p, ϕ, z), kot $\theta(s,t)$ pa polarni kot točke znotraj vrtečega se koordinatnega sistema (p,ϕ,z). Če točka v vrtečem se sistemu "miruje" (θ je stalen), potem se točka v inercialnem sistemu enakomerno vrti okoli osi z s kotno hitrostjo ω. Če se kotna hitrost s časom spreminja, moramo zgornjo enačbo popraviti in dobimo:

Here we assumed that the angular velocity of rotation, ω, is constant. We point out that the angle $\phi(s,t)$ is the polar angle of the point in the inertial cylindrical system (p, ϕ,z), while the point $\theta(s,t)$ is the polar angle of the point in the rotating cylindrical system (p,θ,z). If a point is "motionless" in the rotating frame (i.e., if θ is constant), then such a point rotates in the inertial system with a constant angular velocity ω around the z axis. If the angular velocity varies, the previous equation has to be modified to read:

$$\phi(s,t) = \int_{t_0}^{t} \omega(\tau)\mathrm{d}\tau + \theta(s,t) \tag{22}$$

Hitrost $\boldsymbol{v}=D\mathbf{r}$ in pospešek $\boldsymbol{a} = D^2\mathbf{r}$ izračunamo z neposrednim odvajanjem krajevnega vektorja (17). Podroben izračun lahko bralec najde v viru [5], tu pa bomo navedli le končni rezultat.

Uvedemo vektor relativne hitrosti $v_{\mathrm{rel}} = \dot{r}\mathrm{e}_{\mathrm{r}} + r\dot{\theta}\mathrm{e}_\phi + \dot{z}\mathrm{e}_{\mathrm{z}}$: to je hitrost počasnega (relativnega) gibanja v hitro vrtečem se koordinatnem sistemu. Hitrost točke na preji lahko potem zapišemo kot:

Velocity $\mathbf{v}=D\mathbf{r}$ and acceleration $\mathbf{a} = D^2\mathbf{r}$ have to be calculated by explicit differentiation of the expression for the radius vector (17). A detailed account of this calculation can be found in Ref. [5], here we will only provide the final result.

We introduce the relative velocity vector $v_{\mathrm{rel}} = \dot{r}\mathrm{e}_{\mathrm{r}} + r\dot{\theta}\mathrm{e}_\phi + \dot{z}\mathrm{e}_{\mathrm{z}}$: this is the velocity of the slow (relative) movement within the rapidly rotating coordinate system. The velocity of a point on the yarn can then be expressed as:

$$\mathbf{v} = D\mathbf{r} = \mathbf{v}_{\mathrm{rel}} + \boldsymbol{\omega} \times \mathbf{r} - V\mathbf{k} \tag{23}$$

Razvidno je, od kod izvirajo posamezni členi:
1. člen $\mathbf{v}_{\mathrm{rel}}$ je, kakor je rečeno, relativna hitrost gibanja točke P v vrtečem se koordinatnem sistemu;
2. člen ωx$\mathbf{r}$ je hitrost kroženja točke P okoli osi Z s trenutno kotno hitrostjo $\omega(t)$;
3. člen $-V\mathbf{k}$ je hitrost, ki jo ima točka P na preji zaradi tega, ker prejo vlečemo skozi vodilo.

The origin of the different terms is fairly clear:
1. the term $\mathbf{v}_{\mathrm{rel}}$ is the relative velocity of the point P in the rotating coordinate system;
2. the term $\omega\times\mathbf{r}$ is the velocity of the circular motion of point P around the Z axis with momentary angular velocity $\omega(t)$;
3. the term $-V\mathbf{k}$ is the velocity of the point P because the yarn is withdrawn through the guide.

Če uvedemo še relativni pospešek $a_{rel} = (\ddot{r} - r\dot{\theta}^2)\mathrm{e}_r + (2\dot{r}\dot{\theta} + r\ddot{\theta})\mathrm{e}_\theta + \ddot{z}\mathrm{e}_z$, lahko z njim zapišemo pospešek kot [5]:

Introducing the relative acceleration $a_{rel} = (\ddot{r} - r\dot{\theta}^2)\mathrm{e}_r + (2\dot{r}\dot{\theta} + r\ddot{\theta})\mathrm{e}_\theta + \ddot{z}\mathrm{e}_z$ we can write the acceleration in the form [5]:

$$\mathbf{a} = \mathbf{a}_{\mathrm{rel}} + 2\boldsymbol{\omega}\times\mathbf{v}_{\mathrm{rel}} - 2V\boldsymbol{\omega}\times\mathbf{r}' + \boldsymbol{\omega}\times(\boldsymbol{\omega}\times\mathbf{r}) + \dot{\boldsymbol{\omega}}\times\mathbf{r} - 2V\mathbf{v}_{\mathrm{rel}}' + V^2\mathbf{r}'' \quad (24).$$

Tu znak ′ pomeni parcialni odvod po ločni dolžini s, torej $\partial/\partial s$. Uvedemo lahko operator totalnega časovnega odvoda $\mathcal{D}$, ki sledi gibanju izbrane točke znotraj vrtečega se koordinatnega sistema:

Here the suffix ′ denotes the partial derivative with respect to the arc length s, i.e. $\partial/\partial s$. We can introduce a formal operator of the total time derivative $\mathcal{D}$, which follows the motion of the chosen point within the rotating coordinate system:

$$\mathfrak{D} = \frac{\partial}{\partial t}\Big|_{(p,\theta,z)} - V\frac{\partial}{\partial s} \quad (25).$$

To, da operator sledi gibanju izbrane točke znotraj vrtečega se koordinatnega sistema, pomeni, da pri odvajanju izraza (21) ali (22) po času zanemarimo člen z ω. Tako dosežemo, da opravek odvajanja po času deluje *znotraj* vrtečega se koordinatnega sistema (p, θ, z), namesto v inercialnem sistemu (p, ϕ, z), na kar smo opomnili z oznako (p, θ, z) pri operatorju za odvajanje v izrazu (25). Tako dobimo na primer:

By requiring that the operator follows the motion within the rotating coordinate system we mean that when calculating the time derivative of the expressions (21) or (22) we should not take into account the term in ω. In this way we ensure that the time derivation applies *within* the rotating coordinate system (p, θ, z), instead of in the inertial system (p, ϕ, z). As a reminder we write the subscript (p, θ, z) after the time derivative in the expression (25). For example, we thus obtain:

$$\begin{aligned} \mathfrak{D}\mathbf{r} &= \mathbf{v}_{\mathrm{rel}} - V\mathbf{k}, \\ \mathfrak{D}^2\mathbf{r} &= \mathbf{a}_{\mathrm{rel}} - 2V\dot{\mathbf{k}} + V^2\mathbf{r}''. \end{aligned} \quad (26).$$

Dobljena izraza se od ustreznih izrazov za $\mathcal{D}\mathbf{r}$ (enačba (3)) in za $\mathcal{D}^2\mathbf{r}$ (enačba (5)) razlikujeta v tem, da se v njima pojavljata relativna hitrost in pospešek namesto absolutne hitrosti in pospeška.

Z uporabo operatorja $\mathcal{D}$ lahko pospešek zapišemo v krajši obliki:

These expressions differ from the expressions for $\mathcal{D}\mathbf{r}$ (Eq. (3)) and $\mathcal{D}^2\mathbf{r}$ (Eq. (5)) in that they involve relative velocity and acceleration in place of their absolute counterparts.

Using the $\mathcal{D}$ operator we can write the acceleration in a compact form:

$$\mathbf{a} = \mathfrak{D}^2\mathbf{r} + 2\boldsymbol{\omega}\times(\mathfrak{D}\mathbf{r}) + \boldsymbol{\omega}\times(\boldsymbol{\omega}\times\mathbf{r}) + \dot{\boldsymbol{\omega}}\times\mathbf{r} \quad (27).$$

Gibalno enačbo lahko tedaj zapišemo v obliki [5]:

Finally, the equation of motion can be put in the following form [5]

$$\rho(\mathfrak{D}^2\mathbf{r} + 2\boldsymbol{\omega}\times\mathfrak{D}\mathbf{r} + \boldsymbol{\omega}\times(\boldsymbol{\omega}\times\mathbf{r}) + \dot{\boldsymbol{\omega}}\times\mathbf{r}) = \frac{\partial}{\partial s}(T\mathbf{k}) + \mathbf{f}_{\mathrm{zr}} \quad (28).$$

To je iskana enačba gibanja preje. Prvi člen na levi pomeni relativni pospešek, podobno kakor običajni drugi odvod po času v inercialnih koordinatnih sistemih. Naslednji trije členi so sistemske (navidezne) sile, ki se pojavijo v neinercialnih vrtečih se sistemih:

1. $-\rho 2\omega\times\mathcal{D}\mathbf{r}$ pomeni Coriolisovo silo. To silo poznamo tudi na zemeljski obli: zaradi vrtenja Zemlje okoli svoje osi je tir predmetov, ki letijo vodoravno, ukrivljen proti desni na severni polobli, in proti levi na južni polobli.

This is the equation of motion of the yarn that we sought. The first left-hand term corresponds to the relative acceleration, in analogy to the more familiar second time derivative of the radius vector in inertial coordinate systems. The following three terms correspond to the system (virtual) forces that appear in non-inertial rotating systems:

1. $-\rho 2\omega\times\mathcal{D}\mathbf{r}$ corresponds to the Coriolis force. Such a force is also present on the Earth: due to the rotation of the planet, the trajectory of objects in motion in the horizontal plane deviates to the right in the northern hemisphere and to the left in the southern hemisphere.

2. $-\rho\omega\times(\omega\times\mathbf{r})$ kaže v radialni smeri navzven: to je dobro znana centrifugalna sila.
3. $-\rho\dot{\omega}\times\mathbf{r}$ ustvari sistemsko silo v sistemih, katerih kotna hitrost se spreminja s časom (na Zemlji je zanemarljiva).

Sistemske sile, ki delujejo na kratek odsek preje, so prikazane na sliki (4). Centrifugalna in Coriolisova sila sta dobro poznani, poudarili pa bi radi sistemsko silo $-\rho\dot{\omega}\times\mathbf{r}$, o kateri se do sedaj v poznani literaturi ni govorilo.

Običajni valjni navitki so sestavljeni iz plasti preje z izmenjujočimi se koti navijanja ϕ: v eni plasti je ta kot pozitiven, v naslednji pa negativen [6]. Kotna hitrost ω v ustaljenem stanju je odvisna od kota navijanja in je v preprostem približku podana z [7]:

2. $-\rho\omega\times(\omega\times\mathbf{r})$ is directed radially outward: this is the well-known centrifugal force.
3. $-\rho\dot{\omega}\times\mathbf{r}$ describes a system force in rotating frames, where the angular velocity changes with time (on Earth this force is negligible).

The system forces that act on a short segment of yarn are shown in Fig. (4). The centrifugal and Coriolis forces are well known; however, we would like to emphasize the role of the system force $-\rho\dot{\omega}\times\mathbf{r}$, which was not taken into account in the literature, to the best of our knowledge.

Typical cylindrical packages consist of layers of yarn with an alternating winding angle ϕ: in one layer this angle is positive and in the next layer it is negative [6]. The steady-state angular velocity ω depends on the winding angle, and in a simple approximation it is given by [7]:

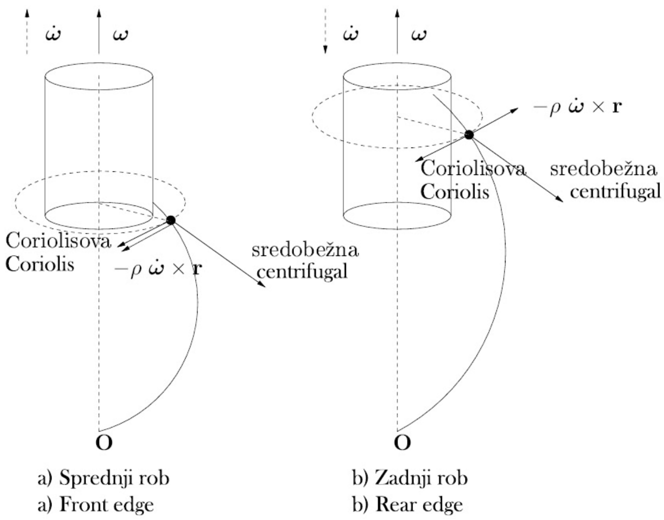
$$\omega = \frac{V}{c}\frac{\cos\phi}{1-\sin\phi} \quad (29).$$

Kotna hitrost je približno nespremenljiva v sredini navitka: večja je med odvijanjem v smeri proti zadnji strani navitka (ϕ >0) in manjša med odvijanjem v smeri proti prednji strani navitka (ϕ <0). Na obeh robovih navitka se kotna hitrost spremeni dokaj naglo: ko točka odvijanja doseže prednji rob navitka, se zveča, ko doseže zadnji rob navitka, se zmanjša. Zato sistemska sila $-\rho\dot{\omega}\times\mathbf{r}$ kaže v smeri Coriolisove sile, ko je točka dviga preje na sprednjem robu navitka, ko se kotna hitrost ω povečuje. Vektor kotnega pospeška $\dot{\omega}$ je na sliki narisan črtkano. Ko pa je točka dviga preje na zadnjem robu navitka, ta sila kaže v nasprotni smeri od Coriolisove sile, saj se tedaj kotna hitrost ω zmanjšuje in kaže vektor kotnega pospeška $\dot{\omega}$ v nasprotni smeri kakor na sprednjem robu navitka. Na sredini navitka, ko so razmere navidezno ustaljene in se s časom spreminjajo le počasi, te sile ni. (To seveda velja le za plasti z velikim številom ovojev, torej za natančno navite navitke.)

Omenjena sila ima vpliv na gibanje preje na robovih navitka, kjer se kot navijanja obrne. Tako hitra sprememba kota navijanja povzroči naglo spremembo kotne hitrosti ω, kar pomeni, da je kotni pospešek $\dot{\omega}$ velik. Zato je tudi sistemska sila $-\rho\dot{\omega}\times\mathbf{r}$ velika in spremeni dinamiko preje. Iz navidezno ustaljenih razmer pridemo tedaj v prehodno območje, ko se gibanje preje naglo spreminja. Na robovih lahko zato prihaja do nestabilnosti v obliki balona, nitka se lahko zagozdi in pretrga.

The angular velocity is approximately constant in the middle of the package: it is higher during unwinding toward the rear end of the package (ϕ>0) and lower during unwinding toward the front end of the package (ϕ <0). It changes rather abruptly at the edges of the package: it increases when the unwinding point reaches the front end of the package and it decreases when it reaches the rear end of the package. Therefore, the system force $-\rho\dot{\omega}\times\mathbf{r}$ is directed in the same direction as the Coriolis force when the lift-off point is near the front edge of the package, where the angular velocity ω is increasing. The angular acceleration vector ω is depicted in the figure by a dashed arrow. On the other hand, when the lift-off point is on the rear edge of the package, the direction of this force is opposite to the direction of the Coriolis force since the angular velocity ω is then decreasing and the angular acceleration vector $\dot{\omega}$ has the opposite direction as it has on the front edge of the package. In the middle part of the package, where the conditions are quasi-stationary and hardly change with time, this force is not present. (This is of course only true for layers with a large number of loops, i.e., for precision-wound packages.)

This force exerts an influence on the yarn motion near the edges of the package, where the winding angle changes. Such a sudden change of the winding angle leads to a rapid change of the angular velocity ω, which means that the angular acceleration $\dot{\omega}$ is high. For this reason the system force $-\rho\dot{\omega}\times\mathbf{r}$ is also substantial and it can modify the dynamics of the yarn motion. Near the edges the quasi-stationary state changes to a transient state when the yarn motion is changing rapidly. This can lead to instability of the balloon form, the yarn can jam and then break.



Sl. 4. *Sistemske sile na kratek odsek preje*
Fig. 4. *System forces acting on a segment of the yarn*

Na kratek odsek preje delujejo sredobežna, Coriolisova sila in sila $-\rho\dot{\omega}\times\mathbf{r}$.

Centrifugal, Coriolis and $-\rho\dot{\omega}\times\mathbf{r}$ forces act on a segment of the yarn.

4 POGOJ NERAZTEZNOSTI

Vzeli smo, da je preja neraztezna, s čimer smo imeli v mislih, da smemo zanemariti elastični raztezek preje. Poglejmo, kaj to pomeni z matematičnega vidika. Izberimo si dve bližnji točki na preji, A s parametrom s in B s parametrom $s+\delta s$. Ker je parameter s ločna dolžina od izhodišča koordinatnega sistema, ki smo ga postavili na vodilo, je dolžina preje med točkama A in B kar δs. Točki A in B povezuje vektor $\delta\mathbf{r}=\mathbf{r}_A-\mathbf{r}_B$, tako da je razdalja med točkama A in B enaka $|\delta\mathbf{r}|$. V limiti $\delta s\to 0$ je razdalja med točkama enaka dolžini preje, ki povezuje točki, zato velja:

4 CONDITION FOR INEXTENSIBILITY

We have assumed that the yarn is inextensible in the sense that we can neglect the elastic elongation in the yarn. We now show what this means from a mathematical point of view. We choose two nearby points on the yarn: A with parameter s and B with parameter $s+\delta s$. As the parameter s is the arc-length from the origin of the coordinate system, chosen in the guide, the length of yarn between points A and B is δs. Points A and B can be joined by a vector $\delta\mathbf{r}=\mathbf{r}_A-\mathbf{r}_B$ so that the distance between points A and B equals $|\delta\mathbf{r}|$. In the limit $\delta s\to 0$ the distance between the points is equal to the length of yarn between the points, so that:

$$|\delta\mathbf{r}| = \delta s \quad (30).$$

To lahko zapišemo tudi kot $|\partial\mathbf{r}/\partial s|=1$, s pomočjo zveze $\mathbf{x}\cdot\mathbf{x}=|\mathbf{x}||\mathbf{x}|$ pa dobimo izraz [8]:

This can also be written as $|\partial\mathbf{r}/\partial s|=1$. Using the relation $\mathbf{x}\cdot\mathbf{x}=|\mathbf{x}||\mathbf{x}|$ we obtain the expression [8]:

$$\mathbf{r}'\cdot\mathbf{r}' = 1 \quad (31).$$

Odvajamo izraz (16) po parametru s:

We calculate the arc-length derivative of expression (16):

$$\begin{aligned}\mathbf{r}' &= p'\mathbf{e}_p + p\mathbf{e}_p' + z'\mathbf{e}_z \\ &= p'\mathbf{e}_p + p\frac{\partial\mathbf{e}_p}{\partial\phi}\phi' + z'\mathbf{e}_z \\ &= p'\mathbf{e}_p + p\phi'\mathbf{e}_\phi + z'\mathbf{e}_z,\end{aligned} \quad (32)$$

in izračunamo skalarni produkt, iz enačbe(31) pa dobimo iskani pogoj nerazteznosti:

then we calculate the scalar product in Eq. (31). We obtain the inextensibility condition in the form:

$$\mathbf{r}' \cdot \mathbf{r}' = (p')^2 + p^2(\phi')^2 + (z')^2 = 1 \quad (33).$$

Če izračunamo odvod po ločni dolžini enačbe(21), dobimo $\phi'=\theta'$, zato smemo tudi zapisati:

By calculating the arc-length derivative of Equation (21) we obtain $\phi'=\theta'$, so we can also write

$$\mathbf{r}' \cdot \mathbf{r}' = (p')^2 + p^2(\theta')^2 + (z')^2 = 1 \quad (34).$$

5 NUMERIČNO SIMULIRANJE ODVIJANJA PREJE

5 NUMERICAL SIMULATION OF YARN UNWINDING

Tri komponente vektorske enačbe (28) in skalarna enačba (34) skupaj sestavljajo sistem štirih nelinearnih diferencialnih enačb za štiri neznane funkcije: p,θ,z, ki opisujejo obliko in gibanje preje, ter napetost T v preji. Problem bo popolnoma določen, če podamo še robne in začetne pogoje.

Pogosto je preja gosto vzporedno navita na navitkih. Tedaj se (v vrtečem se valjnem opazovalnem sistemu) razmere le malo spremenijo v času odvijanja enega navoja in smemo uporabiti navidezno ustaljeni približek. V tem primeru časovne odvode v gibalni enačbi zanemarimo, vso časovno odvisnost pa prenesemo na robne pogoje (ker se točka dviga počasi premika po navitku). Začetnih pogojev v tem primeru sploh ne potrebujemo.

Prvi robni pogoj je, da gre preja skozi vodilo v izhodišču, kar zapišemo kot $\mathbf{r}(s=0)=0$, ali $p(0)=0$, $\theta(0)=0$, $z(0)=0$. V resnici si lahko robni pogoj za θ izberemo poljubno, vendar je $\theta=0$ najbolj praktična izbira. V točki dviga mora preja biti zvezna in ne sme biti prelomljena. Od tod sledita pogoja o zveznosti:

The three components of the vector equation Eq. (28) and the scalar equation Eq. (34) constitute a system of four nonlinear differential equations for four unknown functions: p,θ,z, that describe the form and motion of the yarn and the tension T. The problem will be fully defined if the boundary and initial conditions are known.

The yarn is often densely wound in parallel on the package. In this case the conditions (as observed in the rotating cylindrical system) hardly change in the time required for unwinding one loop and the quasi-stationary approximation applies. In this case we can neglect all the time derivatives in the equation of motion and transfer the time dependence to the changing boundary conditions (because the lift-off point slowly moves on the surface of the package). Knowing the initial conditions is not necessary since we have reduced the calculation to a boundary-value problem.

The first boundary condition is given by the fact that the yarn is withdrawn through the guide, which can be mathematically expressed as $\mathbf{r}(s=0)=0$, or equivalently $p(0)=0$, $\theta(0)=0$, $z(0)=0$. In fact the boundary condition for θ can be arbitrary, but we choose $\theta(0)=0$ for convenience. In the lift-off point the curve has to be continuous with a continuous first derivative. This gives two conditions of continuity:

$$\mathbf{r}(s = s^+_{\mathrm{Dv}}) = \mathbf{r}(s = s^-_{\mathrm{Dv}}) \text{ in } \mathbf{r}'(s = s^+_{\mathrm{Dv}}) = \mathbf{r}'(s = s^+_{\mathrm{Dv}}). \quad (35).$$

Z indeksoma + oziroma - tukaj označujemo točko tik za, oziroma tik pred točko dviga. Nazadnje velja še, da je preja v točki dviga tangenta na navitek, kar zapišemo kot:

Indices + and - denote a point on the yarn just before and just after the lift-off point. Finally, we take into account that at the lift-off point the yarn is tangential to the package, which gives:

$$p'(s = s_{\mathrm{Dv}}) = 0. \quad (36).$$

Gibalne enačbe moramo integrirati numerično. Pri tem uporabljamo strelsko metodo,

The equations of motion have to be integrated numerically. For this we use the shooting method that we ki jo bomo sedaj opisali. V izhodišču s=0 si izberemo začetne približke za odvode p', θ' in z' in za napetost T (izkaže se, da te štiri količine niso med seboj neodvisne, zato zadostuje, da si izberemo le dve, na primer p' in T). Nato gibalne enačbe integriramo, dokler ne zadenemo navitka; ustavimo se lahko na primer tedaj, ko je koordinata z enaka koordinati z točke dviga. Strel je uspešen, če v končni točki v okviru vnaprej izbrane natančnosti velja $p(s_{Dv})$=c in $p'(s_{Dv})$=0, kjer je c polmer valja. Če nismo "zadeli", moramo račun ponoviti pri ustrezno popravljenih začetnih vrednostih za r' in T.

Numerični postopek smo izvedli z uporabo numeričnih rutin iz zbirke numeričnih napotkov [9]. Diferencialne enačbe smo integrirali z Runge-Kuttovo metodo, pri streljanju pa smo uporabili Powellovo metodo.

Pri iskanju optimalne oblike navitka moramo določiti ne le obliko balona, temveč moramo rešiti še problem drsenja preje po navitku, ki ga tu nismo opisali. Zaradi oprijemanja preje in zaostale napetosti preje v navitku kratek odsek preje drsi po navitku in prihaja do trenja, namesto da bi se preja vzdignila v balon takoj v točki odvijanja. V drsečem delu preje zaostala napetost pade na vrednost napetosti v balonu v točki dviga.

Tudi ta naloga se prevede na reševanje sistema diferencialnih enačb s streljanjem, rešitve pa nato zlepimo v točki dviga z uporabo zgoraj zapisanih pogojev o zveznosti. Oblika navitka določa robne pogoje v točki odvijanja (**Od** na sliki 1). Optimiranje navitkov poteka tako, da ponavljamo celoten račun za različne oblike navitkov in iščemo takšno obliko, ki vodi k najmanjši napetosti v preji. Metoda optimiranja je najbolj učinkovita za natančno navite navitke z gostim navitjem, pri katerih imajo prehodni pojavi na robovih navitka majhen učinek na celotno dinamiko odvijanja.

now describe. At the origin s=0 we choose starting approximations for the derivatives p', θ', z' and for the tension T (it turns out that these four quantities are not mutually independent and we only need to set two quantities, for example p' and T). We integrate the differential equations until we "hit" the package; the stopping condition can, for example, be that the current coordinate z is equal to the coordinate z of the lift-off point. A shot is successful if at the final point the equations $p(s_{Dv})$=c (c is the package radius) and $p'(s_{Dv})$=0 are fulfilled within some predetermined numerical accuracy. If we "missed", we need to repeat the calculation for suitably modified starting values of p' and T.

We implemented the numerical procedure using numerical routines from the Numerical Recipes library [9]. The differential equations are integrated using the Runge-Kutta method and the shooting is done using the Powell method.

For optimizing the package construction we have to determine not only the shape of the balloon, but also the sliding motion of the yarn on the surface of the package, which we have not described in this paper. Due to stiction and the residual tension of the yarn in the package, a short segment of yarn slides on the surface of the package and it rubs against it, instead of immediately lifting off in the balloon at the unwinding point. In this part of the yarn the residual tension of the yarn in the package is reduced to the value of tension in the balloon at the lift-off point.

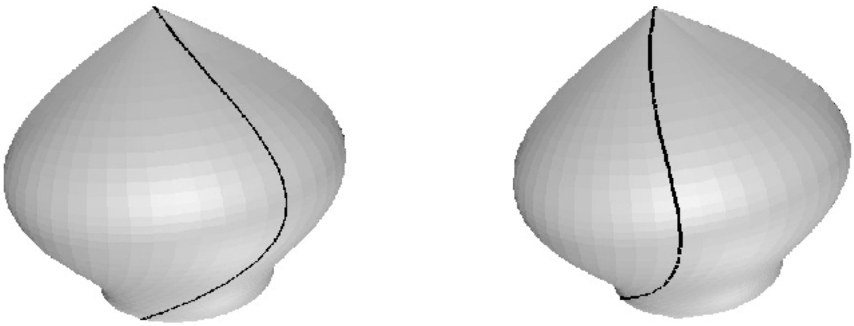
The problem of sliding motion can also be reduced to solving a system of differential equations using the shooting method. The solutions are then glued together at the lift-off point using the conditions of the continuity that we described, while the construction of the package determines the boundary conditions at the unwinding point (**Od** on Fig. 1). The process of optimization involves repeating the calculations for different package designs and searching for the design that gives the least possible tension in the yarn. The optimisation method is most efficient for precision-wound packages with dense layers, where the transient effects at the package edges have a small effect on the overall dynamics of the unwinding process.

6 PRIMER IZRAČUNA

Na sliki 5 sta prikazana dva pogleda na "balon", ki smo ga dobili po zgoraj opisanem numeričnem postopku. Slika ustreza poenostavljenemu računu, pri katerem nismo upoštevali drsenja preje po navitku, v polni meri pa so upoštevani vplivi sredobežne in Coriolisove sile ter zračnega upora. Takšen izračun je odvisen od

6 EXAMPLE OF A CALCULATION

Figure 5 represents two views of the "balloon" that we calculated using the numerical methods described above. The figure corresponds to a simplified calculation which does not take into account the sliding motion of yarn on the surface of the package. It does, however, fully take into account the effects of the centrifugal and Coriolis forces, as well as the effect of the air drag. Such



Sl. 5. *Dva pogleda na "balon": črna krivulja pomeni trenutno lego preje, siva ploskev pa je rotacijska ploskev, ki jo preja oriše v eni periodi vrtenja okoli osi. Obe sliki sta zaradi boljšega prikaza skrčeni za faktor štiri vzdolž osi vrtenja.*

Fig. 5. *Two views of the "balloon": the black curve shows the current position of the yarn, while the gray surface is the surface of revolution, that the yarn generates in one periode of its rotational motion around the axis. Both figures are scaled with a ratio of one fourth in the direction of the axis for reasons of clarity.*

enega samega brezrazsežnega parametra (p_o, brezrazsežnega koeficienta zračnega upora) in od enega robnega pogoja (navpične razdalje z_{Dv}, na kateri leži točka dviga). Parameter p_o je enak [8]:

$$p_0 = 8cdc_u\rho_{zrak} / \mu_{preja} \qquad (37),$$

kjer so: c polmer navitka, d premer preje, c_u koeficient zračnega upora, ρ_{zrak} gostota zraka in μ_{preja} linearna gostota preje. Izbrali smo si parameter p_o =4 in razdaljo z=12.

Dobljena rotacijska ploskev ("balon") ima trebuh, ki nastane zaradi sredobežne sile. Kakovostno podobno sliko bi dobili tudi z uporabo preprostega modela, v katerem zanemarimo Coriolisovo silo in zračni upor. Učinek teh sil pa je v resnici znaten, kar je razvidno iz oblike krivulje, ki pomeni trenutno sliko preje. Kot θ se v spodnjem delu krivulje močno spremeni in krivulja se ovija okoli balona. Račun, pri katerem Coriolisove sile ne bi upoštevali, bi dal krivuljo, ki leži v ravnini (θ =*konst*). Tako bi podcenili dolžino preje, ki ustvarja balon, velika pa bi bila tudi napaka v izračunani napetosti *T*.

7 SKLEP

Izpeljali in utemeljili smo sistem parcialnih diferencialnih enačb, ki opisuje gibanje preje. Enačbe veljajo za gibanje preje med poljubnim tekstilnim postopkom in so povsem splošne. V drugem delu smo se osredotočili na odvijanje preje z vzdolžnega

a calculation depends on a single dimensionless parameter (p_o, the dimensionless coefficient of air friction) and on one boundary condition (the vertical distance z_{Dv} to the lift-off point). The parameter p_o is [8]

where c is the radius of the package, d the diameter of yarn, c_u the coefficient of air friction, ρ_{air} the density of air and μ_{yarn} the linear density of the yarn. We chose p_o =4 and z=12.

The surface of revolution thus obtained (the "balloon") has a belly-shaped protrusion due to the centrifugal force. A qualitatively similar picture could be obtained using a simpler model that neglects the Coriolis force and the air drag. Nevertheless, the effect of these forces is significant, as one can see from the form of the curve that represents the snap-shot of the yarn in motion. The angle θ undergoes a rapid change in the bottom part, where the curve spirals around the balloon. A calculation which does not take into account the Coriolis force and the air drag would give a plane curve (θ=*const*). In this case the length of the yarn would be underestimated and the error in the calculated value of the tension *T* would also be significant.

7 CONCLUSION

We have derived and justified a system of partial differential equations that describes the motion of the yarn. The derived equations are general and can be used to describe the yarn motion in any textile process. In the second part we focused on the over-end navitka in zapisali enačbe v vrtečem se koordinatnem sistemu, ki je bolj primeren za nadaljnjo obravnavo pri dejanskih primerih. Enačbe lahko na primer zapišemo v navidezno ustaljenem približku in jih rešimo numerično s strelsko metodo. V tem primeru se geometrijska oblika in način navitja preje na navitek kaže samo v robnih pogojih, zato je reševanje preprosto. Na ta način lahko izračunamo napetost v preji za poljubno zamišljene navitke, kar je v veliko pomoč pri iskanju navitka optimalne oblike za izbran tekstilni postopek.

unwinding of yarn from an axial package and we cast the equations in a form that is suitable for solving real problems by transforming them to a rotating coordinate system. The equations can be simplified using the quasi-stationary approximation and solved using the shooting method. In this case the geometry of the package and the type of winding appear in the boundary conditions and numerical solving is tractable. In this manner one can calculate the yarn tension for an arbitrary package design, which is helpful in optimizing the package shape for a chosen textile process.

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Izrazi za popis upogibnega nihanja palice nespremenljivega prereza

Equations for the Flexural Vibration of a Sample with a Uniform Cross-Section

Igor Štubňa - Anton Trník

V prispevku je predstavljen kratek pregled že znanih izrazov za popis upogibnega nihanja, uporabljenih za določitev Youngovega modula in hitrosti zvoka. Predstavljen je tudi nov izraz, ki velja za vztrajnost kroženja in vpliv strižnih sil z izrazom $i_z^2[2(1+\mu)/\kappa](\partial^4 y/\partial t^2 \partial x^2)$*, v katerem je* i_z *polmer vrtenja prereza,* μ *je Poissonovo razmerje in* κ *je oblikovni faktor, ki ga je uvedel Timošenko. Krivulje porazdelitve kažejo zelo dobro ujemanje splošno uporabljanega Timošenkovega izraza in novega izraza, ki sta ga razvila Štubňa in Majerník.*

(Ključne besede: upogibno nihanje, enačbe diferencialne, izraz Timošenkov, momenti upogibni)

A short review of the known equations of flexural vibration used for determining the Young's modulus and sound velocity is presented, as well as a new equation that accounts for the rotary inertia and the influence of the shear forces with the term $i_z^2[2(1+\mu)/\kappa](\partial^4 y/\partial t^2 \partial x^2)$*, where* i_z *is the radius of gyration of the cross-section,* μ *is Poisson's ratio, and* κ *is the shape coefficient introduced by Timoshenko. The dispersion curves show a very good fit between the commonly accepted Timoshenko's equation and the new equation derived by Štubňa and Majerník.*

(Keywords: flexural vibration, partial differential equation, Timoshenko's equation, bending moments)

0 INTRODUCTION

The most convenient type of vibration used for measurement is a flexural vibration. It is easy to excite it, and the magnitude of the vibration is sufficiently high. The resonant frequency of the flexural vibration is smaller than the resonant frequency of the longitudinal or torsional vibration of a sample of the same length and cross-section. These properties of flexural vibration make it preferable for measuring the elastic modulus (or velocity of sound propagation) at elevated temperatures.

The theory of the flexural vibration of prisms and rods is based on deriving and then solving a partial differential equation of vibration for the sample. The exact solution of a three-dimensional form of the equation is extremely difficult. Fortunately, the mathematical approach to the solution of the vibration of a sample with a simple and symmetrical form can be simplified, and a reasonably exact solution can be obtained. For this reason, only the vibration of the sample with a simple uniform cross-section (circular or rectangular) serves for a measurement of the elastic parameters of solid materials.

In this paper a short review of the equations of flexural vibration commonly used for a determination of the Young's modulus or sound velocity, as well as the new equation, is presented.

1 THEORY OF FLEXURAL VIBRATION

The simplified partial equation of flexural vibration of beams with a uniform cross-section is derived on the basis of the following assumptions ([1] and [2]):

a) The amplitude of vibration is small.
b) The mass element in the direction of vibration is in equilibrium (see Fig. 1), i.e.:

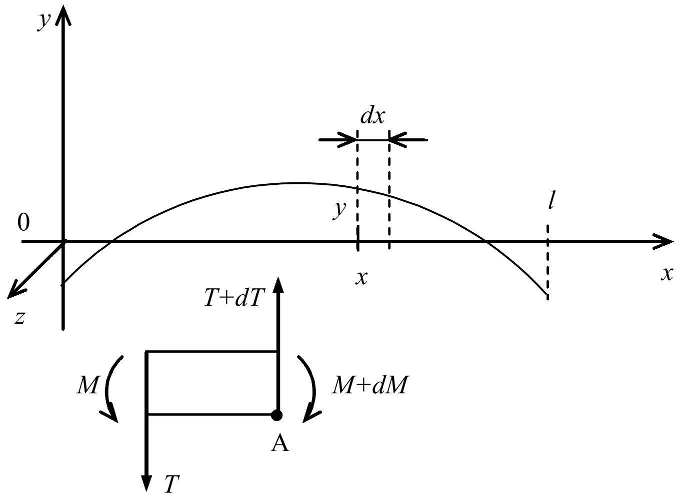

Fig. 1. *Bending line, forces and moments effecting the mass element*

$$\rho S dx \frac{\partial^2 y}{\partial t^2} = (T + dT) - T = \frac{\partial T}{\partial x} dx \quad (1)$$

where ρ is the density of the beam material, S is the area of the cross-section, T is the shear force, t is time and x, y are coordinates.

c) The equation of the elastic line holds:

$$EJ \frac{\partial^2 y}{\partial x^2} = -M \quad (2)$$

where M is the bending moment, E is the Young's modulus and J is the moment of inertia of the cross-section around the axis parallel with the z-axis.

d) The relationship between the shear force and the bending moment has the form:

$$\frac{\partial M}{\partial x} = T \quad (3).$$

Eliminating the shear force T from Eq. (1) with the help of Eqs. (2) and (3) we obtain:

$$\frac{\partial^2 y}{\partial t^2} + c_0^2 i_z^2 \frac{\partial^4 y}{\partial x^4} = 0 \quad (4)$$

where $c_0 = \sqrt{E/\rho}$ is the sound velocity (i.e., the velocity of the longitudinal wave propagation in the sample), $i_z = \sqrt{J/S}$ is the radius of gyration of the cross-section. Eq. (4) describes the vibrational motion of the sample with a sufficient exactness only when the ratio $l/d > 20$, where l is the length of the sample and d is the diameter of the cylindrical sample or thickness of the prismatic sample in the direction of vibration. The solution of Eq. (4) is the function:

$$y = y_m \exp\left[j\omega\left(t \pm \frac{x}{c} \right) \right] \quad (5)$$

where $j = \sqrt{-1}$, $\omega = 2\pi \; c/\lambda$ is the angular frequency, c is the phase velocity of the flexural wave and λ is the wavelength. Substituting Eq. (5) into Eq. (4) we obtain:

$$\frac{c}{c_0} = 2\pi\left(\frac{i_z}{\lambda}\right) \quad (6).$$

In Eq. (4) we anticipated only a displacement motion of the mass element in the direction of the y-axis. In the case of a fundamental mode vibration of a short sample (in which $l/d < 20$) the rotation of the mass element around the axis parallel with the z-axis must be taken into account. The rotation of the mass element must also be accounted for in the case $l/d > 20$ when the sample vibrates at a higher mode because the sample is divided into short parts by knots. The rotary motion of the mass element is described as (see Fig. 1):

$$\rho J dx \frac{\partial^2}{\partial t^2}\left(\frac{\partial y}{\partial x}\right) = \\ = T dx + M - (M + dM) = T dx - \frac{\partial M}{\partial x} dx \quad (7).$$

If we derive Eq. (7) according to x and eliminate T and M by means of Eqs. (1) and (2) we obtain an equation that includes the Rayleigh's correction (see e.g., [3]):

$$\frac{\partial^2 y}{\partial t^2} + c_0^2 i_z^2 \frac{\partial^4 y}{\partial x^4} - i_z^2 \frac{\partial^4 y}{\partial t^2 \partial x^2} = 0 \quad (8).$$

Substituting Eq. (5) into Eq. (8) we obtain:

$$\frac{c}{c_0} = 2\pi\left(\frac{i_z}{\lambda}\right)\frac{1}{\sqrt{1+4\pi^2\left(\frac{i_z}{\lambda}\right)^2}} \qquad (9).$$

As we can see from Fig. 2, the curves of the functions (6) and (9) correspond to the curve of function (15) only for a long wavelength.

Another step in the agreement between theory and experiment was made by Timoshenko [1], who proposed a correction for the effect of shear forces. Timoshenko made a hypothesis according to which the angle between the tangent to the elastic line and the x-axis is the sum:

$$\frac{\partial y}{\partial x} = \psi + \chi \qquad (10)$$

where the angles ψ and χ are connected with the shear force and the bending moment according to:

$$T = SG\kappa\chi \quad \text{and} \quad EJ\frac{\partial \psi}{\partial x} = -M \qquad (11)$$

and the moment condition of the equilibrium of the mass element is:

$$\rho J dx \frac{\partial^2 \psi}{\partial t^2} = T dx - \frac{\partial M}{\partial x} dx \qquad (12).$$

In Eq. (11) G is the shear modulus of elasticity and κ is a constant that depends on the shape of the cross-section. From Eqs. (12), (11), (10) and (1) we obtain Timoshenko's equation [1] by the sequential elimination of the values of M, T, ψ and χ:

$$\frac{\partial^2 y}{\partial t^2} + c_0^2 i_z^2 \frac{\partial^4 y}{\partial x^4} - i_z^2(1+p)\frac{\partial^4 y}{\partial x^2 \partial t^2} + \frac{i_z^2}{\kappa c_s^2}\frac{\partial^4 y}{\partial t^4} = 0 \qquad (13)$$

where $c_s = \sqrt{G/\rho}$ and $p = 2(1+\mu)/\kappa$, and where $\mu = (E/2G) - 1$ is Poisson's ratio. Timoshenko's equation describes the flexural vibration of the sample with a circular or square cross-section very well and in accordance with experimental results. For samples with a different form of cross-section Pickett proposed equation [4]:

$$\begin{aligned}&\frac{\partial^2 y}{\partial t^2} + c_0^2 i_z^2 \frac{\partial^4 y}{\partial x^4} - i_z^2(1+p)\frac{\partial^4 y}{\partial x^2 \partial t^2} + \\ &+(i_z^2 - i_y^2)\frac{\partial^4 y}{\partial x^2 \partial t^2} + \frac{i_z^2}{\kappa c_s^2}\frac{\partial^4 y}{\partial t^4} = 0\end{aligned} \qquad (14).$$

Eq. (14) transforms into Eq. (13) for a circular or square cross-section. However, the influence of the fourth term in Eq. (14) in the case of other cross-section shapes is very small. Substituting Eq. (5) into Eq. (13) we obtain:

$$\frac{c}{c_0} = +\sqrt{\frac{1}{2}\left(A - \sqrt{A^2 - \frac{4}{p}}\right)}$$

where:

$$A = \frac{1+4\pi^2(1+p)\left(\frac{i_z}{\lambda}\right)^2}{4\pi^2 p\left(\frac{i_z}{\lambda}\right)^2} \qquad (15).$$

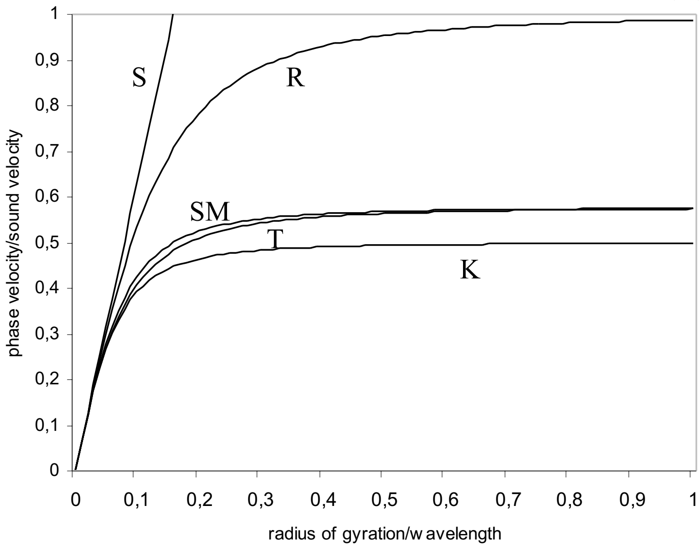

Fig. 2. *Disperse curves for the steel rod. S –for simplified equation (6), R - for equation with Rayleigh´s correction, Eq. (8), T – for Timoshenko´s equation (13), K – for Kuzmenko´s equation (16), SM – for equation derived by Štubňa and Majerník (20)*

A curve calculated from Eq. (15) is shown in Fig. 2.

From the analysis of Eq. (12) it is evident that on its left-hand side there is only an angular acceleration coming from the bending moment, and on its right-hand side there is a sum of all the moments of the forces effecting the mass element. The total angular acceleration is given by Eq. (7). Kuzmenko used Timoshenko's hypothesis (Eqs. (10) and (11)) together with Eqs. (7) and (1), [5]. Combining these equations we get:

$$\frac{\partial^2 y}{\partial t^2}+c_0^2 i_z^2\frac{\partial^4 y}{\partial x^4}-i_z^2(1+p)\frac{\partial^4 y}{\partial x^2\partial t^2}=0 \qquad (16)$$

and substituting Eq. (5) into Eq. (16) after mathematical modifications we obtain:

$$\frac{c}{c_0}=2\pi\left(\frac{i_z}{\lambda}\right)\frac{1}{\sqrt{1+4\pi^2(1+p)\left(\frac{i_z}{\lambda}\right)^2}} \qquad (17).$$

The result of Kuzmenko's attempt is shown in Fig. 2. The values c/c_0 for short wavelengths are different from those calculated by means of Eq. (15). The ratio c/c_0 for the short wavelengths must approach the value c_R/c_0, where c_R is the velocity of the propagation of Rayleigh's wave. For steel μ = 0.29 and c_R/c_0 = 0.577, [2]. To fulfil the physical requirement $c \rightarrow c_R$ when $\lambda \rightarrow 0$, it is necessary to change the coefficient from (1+*p*) in Eq. (17) to *p*. Then:

$$\lim_{\lambda\to 0}\frac{c}{c_0}=\lim_{\lambda\to 0}\frac{2\pi(i_z/\lambda)}{\sqrt{1+4\pi^2 p(i_z/\lambda)^2}}=\frac{c_R}{c_0} \qquad (18),$$

as can be seen in Fig. 2. After substituting *p* into Eq. (16) we obtain the equation:

$$\frac{c}{c_0}=2\pi\left(\frac{i_z}{\lambda}\right)\frac{1}{\sqrt{1+4\pi^2 p\left(\frac{i_z}{\lambda}\right)^2}} \qquad (19)$$

which gives a result very close to the curve of Eq. (15), see Fig. 2. We obtain the equation for phase velocity (19) from the new equation derived by Štubňa and Majerník [6]:

$$\frac{\partial^2 y}{\partial t^2}+c_0^2 i_z^2\frac{\partial^4 y}{\partial x^4}-i_z^2 p\frac{\partial^4 y}{\partial x^2\partial t^2}=0 \qquad (20)$$

which we obtain in the same way as Eq. (16) by using *p* instead of (1+*p*).

The solution for the differential equation of flexural vibration (20) can also be written in the form of a function of the type:

$$\begin{aligned} y(x,y)=Y(x)\Theta(t)=[\alpha\sinh ax+\beta\cosh ax+\\ +\gamma\sin bx+\delta\cos bx]\exp(j\omega t)\end{aligned} \qquad (21)$$

where:

$$\begin{aligned} a&=\frac{\omega}{c_0}\sqrt{-\frac{p}{2}+\sqrt{\frac{p^2}{4}+\left(\frac{c_0}{i_z\omega}\right)^2}}\\ b&=\frac{\omega}{c_0}\sqrt{+\frac{p}{2}+\sqrt{\frac{p^2}{4}+\left(\frac{c_0}{i_z\omega}\right)^2}}\end{aligned} \qquad (22)$$

The values for the bending moment and the shear force are:

$$\begin{aligned} M&=-EJ\left[\frac{d^2Y}{dx^2}+Yp\frac{\omega^2}{c_0^2}\right]\exp(j\omega t)\\ T&=-EJ\left[\frac{d^3Y}{dx^3}+\frac{dY}{dx}(1+p)\frac{\omega^2}{c_0^2}\right]\exp(j\omega t)\end{aligned} \qquad (23)$$

which together with the solution of Eq. (21) and its derivation with respect to *x* make it possible to compile the frequency equation for given boundary conditions.

2 CONCLUSION

The simplified Eq. (4) suffices for flexural waves with a long wavelength (i/λ < 0.03). For this case Eqs. (8) and (16) give identical results, but they are more complicated. For flexural waves with a shorter wavelength (i/λ > 0.03) Eq. (13) or Eq. (20) must be used. The dispersion curves show a very good agreement between the commonly accepted Timoshenko's equation (13) and the new equation (20) derived by Štubňa and Majerník.

Acknowledgement

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Prehodni pojavi pri postopku brušenja

Transient Phenomena in the Grinding Process

Vladas Vekteris

Lokalne stične premike, ki so posledica elastičnih deformacij orodja in obdelovanca, smo proučevali z uporabo končnih elementov in s preskusi. Izdelali smo grafične in analitične prikaze rezalne sile s harmoničnimi in stohastičnimi elementi.

Predhodno objavljene raziskave stika med brusilnim kolesom in obdelovancem temeljijo na predpostavki, da predstavljajo stične deformacije neposredno funkcijo normalnih in tangencialnih sil, ki med postopkom brušenja delujejo na kolo oz. njegova zrna, brez upoštevanja obrabe in lomljenja zrn. V prispevku smo, s pomočjo metode končnih elementov in preskusa krožnega polirnega brušenja z velikimi hitrostmi, opisali postopek raziskave in grafično prikazali prehodne pojave in vzorec uničenja brusilnih zrn znotraj stične zone kot posledico impulznih obremenitev. Prej omenjeno metodo lahko uporabimo pri prožnih, togih, plastičnih in drugih nelinearnih materialih, ki jih obdelujemo z brušenjem. Uporabo nelinearnih lastnosti materiala, modul prostornine in modul pomika v stični coni med brusilnim kolesom (vrsta 24A12ПCM28K5) in obdelovancem (jeklo 45), smo pri preskusu simulirali z uporabo tri-parametričnih elementov. S predstavljeno metodo lahko izračunamo prehodne napetosti in deformacije med krožnim polirnim brušenjem z velikimi hitrostmi ter proučujemo uničenje brusilnih zrn na dvorazsežnem modelu z nedoločenimi mejami in nelinearlnimi značilnostmi. Namen predstavljene razsikave je določitev vpliva prehodnih pojavov na sestavo rezalne sile med postopkom brušenja.

(Ključne besede: postopek brušenja, napetosti, deformacije, simuliranje, analize eksperimentalne)

Local contact displacements resulting from the elastic deformation of the tool and the blank, were studied using the finite-element and by experiments. Graphical and analytical expressions for the cutting force, with harmonical and stochastic components, were obtained.

Previously published research on the behaviour of the contact between the grinding wheel and the workpiece has been based, on the assumption that the contact deformations represent a direct function of both the normal and the tangent forces acting on the wheel or its grains during the grinding process, without taking into account the attrition and breaking of the grains. This paper covers the procedure for researching and graphically representating transient processes and the pattern of the abrasive grains' destruction within the contact zone under impulse loads, which is based on the method of finite elements and the results of a high-speed circular plunge-grinding experiment. The above-mentioned method can be applied to elastic, inelastic, plastic and other nonlinear materials machined by grinding. To introduce the nonlinear properties of the material in the experiment, the modulus of the volume and the modulus of the shift in the contact zone between the grinding wheel (grade 24A12ПCM28K5) and the workpiece (steel 45) are simulated by three-parametric elements. The presented method makes it possible to calculate transient stress and deformations during high-speed circular plunge grinding and to study the destruction of abrasive grains in a two-dimensional medium with indefinite boundaries and nonlinear characteristics. The present research is aimed at finding out the influence of transient phenomena on the structure of the cutting force during the process of grinding.

(Keywords: grinding process, stress, strain, simulation, experimental analysis)

0 INTRODUCTION

Factory-wide automation, the increase in machining precision and operational concentration, as well as the intensification of cutting processes, and other important factors for increasing the output and efficiency of adaptive production, constitute the objective rules of the development of technological equipment. On the whole, these trends in the development of industrial production bring forth new problems when developing grinding equipment, particularly of the spindle systems based on the intensification of cutting processes. The intensification of cutting processes is one of the basic methods of scientific and technical progress in the machine-tool building industry. An increase in the grinding speed up to 60 m/s (instead of 30 to 35 m/s) has drastically increased the efficiency of grinding equipment. Nowadays, there are all the necessary grounds for applying grinding speeds od up to 100 to 120 m/s ([1] to [3]). Despite this, a simple increase in the cutting speed by increasing the grinding wheel's velocity will not produce a tangible effect unless all the grinding system's reserves are used together, particularly the radial and circular feeds. Reference [4] shows that an increase in the circular feeding velocity of circular grinders is particularly effective when CBN grinding wheels are used. In such cases of high-speed grinding, as well as in cases of normal-velocity grinding, the quality of the work surface increases in proportion to the reduction of the cutting force. A large number of abrasive grains per unit time take part in the metal-cutting process during a high-speed grinding operation. This results in a decrease in the depth of cut-offs per abrasive grain and, consequently, in a lower stress on the grain, thus reducing its rate of wear.

At present the relative speed of the tool and the workpiece in metal machining is considered to be in the range from 25 to 500 m/s ([1] to [3]). Information is rather scarce about the phenomena occurring under such heavy-duty velocity and stress conditions. Here, theoretical physical investigations indicate that high-velocity grinding is characterized by the occurrence of the temperature field ([5] and [6]) and the field of forces during the grinding process.

At the present time there is a lot of activity to simulate the properties of abrasive tools with a particular grain and cutting-edge microgeometry in order to develop grinding wheels with new structures to operate under n-fold load and allow functional cutting speeds of up to 300-500 m/s ([1] to [3]). However the phenomena that take place during the interaction of the two elements with particular stochastic properties are still insufficiently studied. This includes the characteristics of the force field, generated during high-velocity cutting, and those of the field's stochastic components.

To make use of all the specific advantages of high-speed grinding it is necessary to clearly understand the mechanism of the wheel and workpiece interaction in the contact zone.

A number of researchers studied local elastic deformations in the contact zone between the grinding wheel and the workpiece by applying different approaches and methods. Reference [7] provides a review of this research. According to this research the deformation in the contact zone under the effect of normal and tangent forces is determined by the elastic properties of the tool and the elastoplastic properties of the workpiece.

The local elastic displacements of the abrasive grains inside an abrasive tool, caused by normal and tangent forces, are transferred to the adjacent grains thtough intergranular contacts (directly or through the binder). The intensity of these displacements depends on the geometry of an abrasive grain, the stress value, the amount and the properties of the intergranular contacts. It is common ([1], [2] and [7]) knowledge that abrasive grains have a random shape and geometry, they are also randomly oriented during the production of the abrasive tool, and the grains differ considerably from each other as regards shape, size, thickness and the number of binding ties ([2] and [7]). Because of this their displacement in the normal direction and the rotation in the tangent direction, resulting from the shock of their interaction with the billet, contributes to the activation of vibration in the cutting zone. The pulse stress waves generated in this zone spread over the material of the abrasive grains and binder ([1] and [2]). For this reason the material particles in the cutting zone vibrate at a very high frequency and produce a certain effect on the system's state and the chip-grinding process.

This paper presents a method for calculating the transient stress and the deformations in the contact zone between the grinding wheel and the workpiece, and the destruction of abrasive grains in the two-dimensional medium with indefinite boundaries and nonlinear characteristics. The suggested method and the program designed on the basis thereof ([16] and [17]) were verified with experimental data obtained during the process of grinding a steel workpiece (steel 45) with a grinding wheel (grade 24A12ПСМ28К5), which made it possible to substantiate the structure of the cutting force.

1 STRESS AND STRAIN

In order to understand the mechanism of the grinding processes and to determine the degree of system strain let us discuss local (contact) shifts resulting from the elastic deformation of the tool and workpiece during the penetration of the tool into the workpiece. Let us assume that the tools with determined geometry are not deformed whereas the grinding system undergoes eccentric deformation, though the cutting section later undergoes local thermoelastic deformations. The machining of materials using a tool with a stochastic micro-geometry is associated with local transient deformation at the contact of the interaction and the deformation of the grinding system ([1] and [8]). In the case of a rigid system the contact deformation changes the shape of the interacting bodies ([1], [8] and [9]).

If r_i is the radius of the non-deformed tools, then the change in the curvature determined by the force F_{ij} per unit of width and acting upon the contact will be as follows [10]:

$$\frac{1}{r_i}-\frac{1}{r_i^{'}}=\frac{F_{ij}}{C_n l_k^2} \quad (1)$$

where $r_i^{'}$ is the curvature of the deformed tool; l_n is the contact; C_n is a constant depending on the elastic properties of the tool ($C_n=\pi E_i/16\left(1-v_i^2\right)$), where ν_I is Poisson's ratio.

The dependence of the elasticity modulus on the temperature of a tool with a ceramic binder according to [11] is expressed with the exponential dependence $E_i=E_0\exp\left(\alpha_T T\right)$, where E_0 is the modulus of elasticity at room temperature ($E_0=\left(50...100\right)\cdot 10^3$ MPa), E_i is the modulus of elasticity at higher temperatures, α_T is a constant dependent on temperature ($\alpha_T=\left(3...6\right)\cdot 10^{-4}$), and T is the temperature. Then $r_i^{'}=r_i\left(1+F_{ij}/C_n l_k^2\right)$, where $l_k=\left(1+1/q^*\right)\sqrt{r_i^{'}t_0}$; $q^*=v_i/v_j$, v_i is the speed of the grinding wheel, v_j is the speed of the work piece, and t_0 is the real value of the depth of cut in one revolution. The transient force field F_{ij} is an unknown parameter in these expressions; it determines the degree of strain in the system. Control of the value of strain also guarantees appropriate control of the elasticity, the vibration resistance and the damping ability of the system. The shaping process strain and its field of forces are determined by the normal and tangent voltages caused by the changing characteristics of the integrating elements (instrument and part). The elastic displacements of abrasive grains at the point of interaction contact were determined by calculation and by experiment [7]. However, neither the strained state [12] nor the beginning of the transient processes with accompanying fracture of abrasive grains under the effect of impulse loads (Fig. 1) were observed. This can be explained by complicacy on account of lots of factors, particularly during the non-linear behavior of the instrument's and the part's material. The non-linear behavior of the material can be simulated by rheological equations on the basis of a three-parametrical model, including the model of Kelvin-Foight and spring (elastic materials, materials with Poisson's ratio and plastic flow). It is known from [7] that it is the removable layer that possesses the greatest elasticity, which is why it can be modulated as a spring and as a plastic flow of metal, it can also be modulated as a model of Kelvin-Foight. In this case the bulk modulus will be represented by a rigid spring, and the modulus of shear by a dashpot. Then the relation between the stress and the strain can be expressed as follows [13]:

$$\{\sigma\}=\left[\overline{C}\right]\{\varepsilon\}+\left[\overline{C_0}\right]\left\{\dot{\varepsilon}\right\}+\sum_{i=1}^{3}\left\{\left[\overline{C_i}\right]\int_0^t e^{-\left(\frac{t-\xi}{\tau_i}\right)}\{\varepsilon(\xi)\}d\xi\right\} \quad (2).$$

Where σ is the stress; $\bar{C}$, $\bar{C}_0$, and $\bar{C}_i$ are the matrixes characterising the material properties; ξ is the integration variable; and ε is the strain.

The application of the principle of conformity [13] makes it possible to automatically calculate the ratio of the stresses and strains (i.e., to calculate the values of the matrixes $\left[\overline{C}\right]$, $\left[\overline{C_0}\right]$, and $\left[\overline{C_i}\right]$).

The transient grinding process with the resulting ractures of abrasive grains during an impulse load (Fig. 1) belong to the type of problems for which no analytical solutions can be found. Therefore, in this case a widely known method of finite elements ([14] to [17]) to structurally idealize the continuous medium, to evaluate the rigidity of elements through the following node movement and

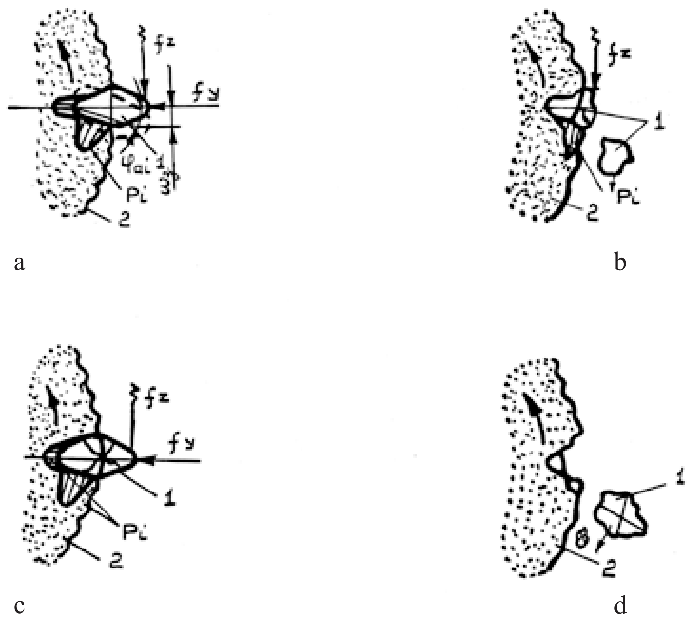

Fig. 1. *Basic types of destruction of abrasive grains: a – rotation and wear of grinding grains; b – crack-formation; c – destruction of grains with the separation of large particles; d – pull-out of grains from the binder; 1 – abrasive grain; 2 – binder of the grinding wheell;* φ_{ai} *- angle of rotation of the "i-th" grain in binder;* ω_j *– rotation value;* f_z, f_y *– forces;* p_i *– distribution of normal pressure*

velocity, to change the node movement in time and as an effective means of researching the strained state and the field of forces can be used.

2 FINITE-ELEMENT MODEL

In the model where finite elements are used every element is chosen so that a reasonable relation between load and movement (displacement) can be found. It is assumed here that the material characteristics of the element change in a known manner and the movement of any point of the element can be determined in the function of some system with generalized coordinates:

$$\{V(y)\} = [N(y)]\{q\} \tag{3}$$

and

$$\{V\} = [D]^{-1}\{q\} \tag{4}$$

where $\{V\}$ and $\{V_n\}$ are vectors of motion of the point located at "y" and the vector of nodal movement of the element; y is the vector of the position of the element point; $[N]$ is the matrix of the chosen function of displacement; $\{q\}$ is the vector of generalized coordinates; $[D]^{-1}$ is the matrix obtained after the substitution of the node vectors of the position into Equation (3).

Deformation at any point of the element is expressed by the following equation:

$$\{\varepsilon(y)\} = [B(y)]\{q\} \tag{5}$$

where the matrix $[B(y)]$ is obtainable from $[N(y)]$ by means of the equation (2). The use of the principle of virtual work and expression (2) leads to the following dynamics equation of grinding systems with non-linear materials:

$$[M]\{\ddot{\delta}\} + [C]\{\delta\} = \{F_\varepsilon(t)\} - [C_0]\{\dot{\delta}\} - \sum_j \left([C_j] \int_0^t \exp\left[-\left(\frac{t-\xi}{\tau_j} \right) \right] \{\delta(\xi)\} d\xi \right) \tag{6}$$

where $[M]$ is the diagonal matrix of concentrated masses; $F_\varepsilon(t)$ is the vector of node forces; $\{\delta\}$, $\{\dot{\delta}\}$ and $\{\ddot{\delta}\}$ are the vectors of node movement, velocity and acceleration, respectively; $[C]$, $[C_0]$ and $[C_j]$ are the matrixes of node rigidities of the system, associated with the matrixes $[C]$, $[C_0]$ and $[C_j]$.

The matrixes of rigidity included in Equations (6) can be obtained by summing up the matrix of element rigidity $[C_i] = [D]^T \int_s [B(y)]^T [\bar{C}][B(y)] ds [D]$, where s is the volume of the element. If an element fractured, its quality characteristics and node rigidities also get changed. A set of ordinary differential equations is solved by means of digital integration using the Hamming forecast and correction method. While solving Equation (6) the strain is being checked in every element and in the case when the maximum strain exceeds a critical value all the terms pending to this element are cancelled from the matrix of rigidity. If witnesses about the facture of the abrasive grain. As to the processed part, changing the characteristics of damping, modulus elasticity, etc., simulates the transition from an elastic band to a plastic one. The transition from one type of material behavior to another shows that all the following changes of the element's shape will be accompanied by new materials characteristics. In reference to the above-mentioned equation (6) it is considered in the increments on the step of integration Δt. It guarantees the absence of sudden load changes, typical of any

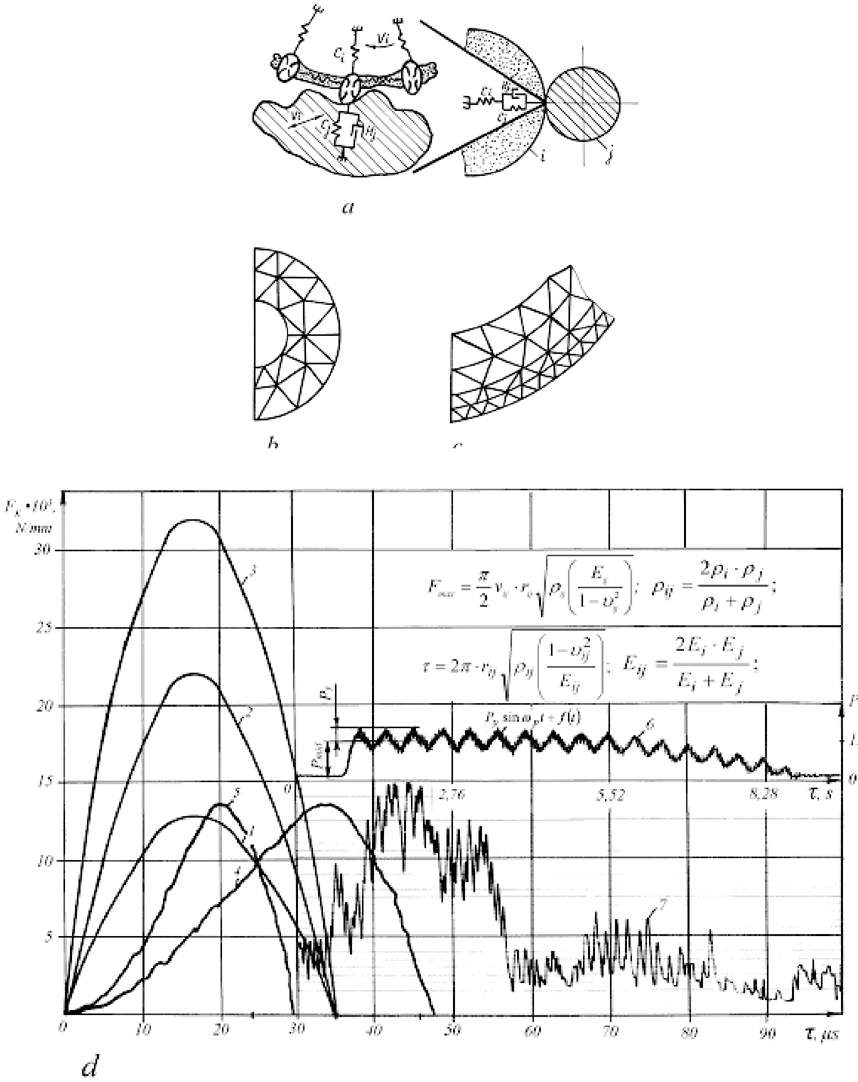

Fig. 2. *Numerical simulation and experimental results: a – a schematic diagram of the rheological model of the grinding process; b – partitioning of the grinding wheel and workpiece into final elements (39 nodes, 54 elements for contact zone); c – enlarged image of the contact zone; d – results of numerical simulation; 1,2,3 – according to the Hertz theory when* V_{ij} *– 30, 50 and 75 m/s, respectively; 4,5 – according to the rheological model; 6 – cutting force obtained from strain measurement; 7 – vibrations at the moment of cutting-in of the grinding wheel into the workpiece.*

element. A diagrammatic representation of the rheological model and the subdivision into the final elements of the grinding wheel, part and some results of the numerical simulation in a graphic view are shown in figure 2. However, the pulse of the force according to the static theory of grains is not show there, and the experimental results. It is worth mentioning that the static theory of Hertz does not reflect the free time of contact.

The time of contact depends on the velocity of the grinding process, and of the contact and the force of resistance against the grinding process. A high-frequency pulse force [2] is characteristic of the high-frequency grinding process, which is a vibration system of grinding, this is confirmed by experimental results (Fig. 2).

The cutting force will change according to the expression

$$P_y = P_{cp} + P \sin \omega_p t + f(t) \quad (7)$$

where P_{cp} is the average component of the cutting force; P is the amplitude of the variable component; ω_p is the frequency of the harmonic component of the cutting force; and f(t) is the zero average stochastic process of noise with dispersion σ_p^2.

3 EXPERIMENTAL ANALYSIS

The above-mentioned was proved by experimental analysis. Oscillograms of the cutting forces (Figs. 2, 3) and the high-frequency components show random oscillations, which can be noticed early while the fracture and the micro-fracture of the abrasive grains takes place during their wearing out.

These effects can be detected only in grinding systems with components that register and analyze the force field. Such components can be created if one has knowledge about the physical phenomena that occur during grinding and within grinding systems. Fig. 3a shows a diagram using physical phenomena for an estimation of the force field. The cutting forces are measured at the spindle, at the tensometric centers and directly at the sample mandrel by means of inductive converters. The contact between the workpiece and the sample mandrel is realized through a heat-insulation material. This arrangement is useful for avoiding any thermal expansion of the sample mandrel. The results obtained are presented in the form of an analogue oscillogram in Fig. 3b. A comparison of these results (Fig. 3b) shows that time changes in the force value are expressed by determined and stochastic components.

The cutting forces P_y and P_z were obtained by feeding the grinding wheel to a distance of 6.7 microns per revolution of the workpiece. The movements of the spindle with a grinding wheel in hydrodynamic bearings were obtained at a grinding depth of t_1 = 50 microns and t_2 = 20 microns. The vibrations of the sample chuck can reach approximately 10 microns. The obtained results show that the cutting force P_y is almost twice as large as the force P_z. The shape of the curves obtained from the spindle bearings corresponds to the shape of the cutting forces obtained by strain-gauging, but it is different as a result of the absence of the harmonic and stochastic components, which are damped by the oil film in the bearing. Such components are present in the oscillograms of the sample chuck.

These low-frequency and high-frequency components of the cutting force together with the vibrations in the system of the drive feed, and with oscillations of the spindle heats, lead to a transient radial shear of the axis rotating the spindle and the part, and to a low quantity of macro-geometry, micro-geometry and the structure of the surface layer of the processed part. The relationship between the radial shear and geometrical accuracy, the waviness and roughness of the surface under processing should be analyzed by considering the autoevaluational and cross-correlation functions and spectral densities of the processes. Therefore, it is necessary to carry out simultaneous measurements of all the above-mentioned factors. Such a treatment of the field of forces can help determine the influence of every component on the state of the system and in this case program-adaptive control of the strain of the system is indispensable. It also requires appropriate algorithms of control. However, algorithms of the program-adaptive control require a determined dependence between the cutting forces and temperatures that are occurring in the process of grinding. Analytical dependencies between the cutting force and contact temperature, arising in the process of grinding, show that the contact temperature reaches the melting temperature very soon when the specific intensity of material removal is increased. Analytical dependencies were determined on the basis of Kelvin's fundamental solution and half-empirical model [1]. This is identical

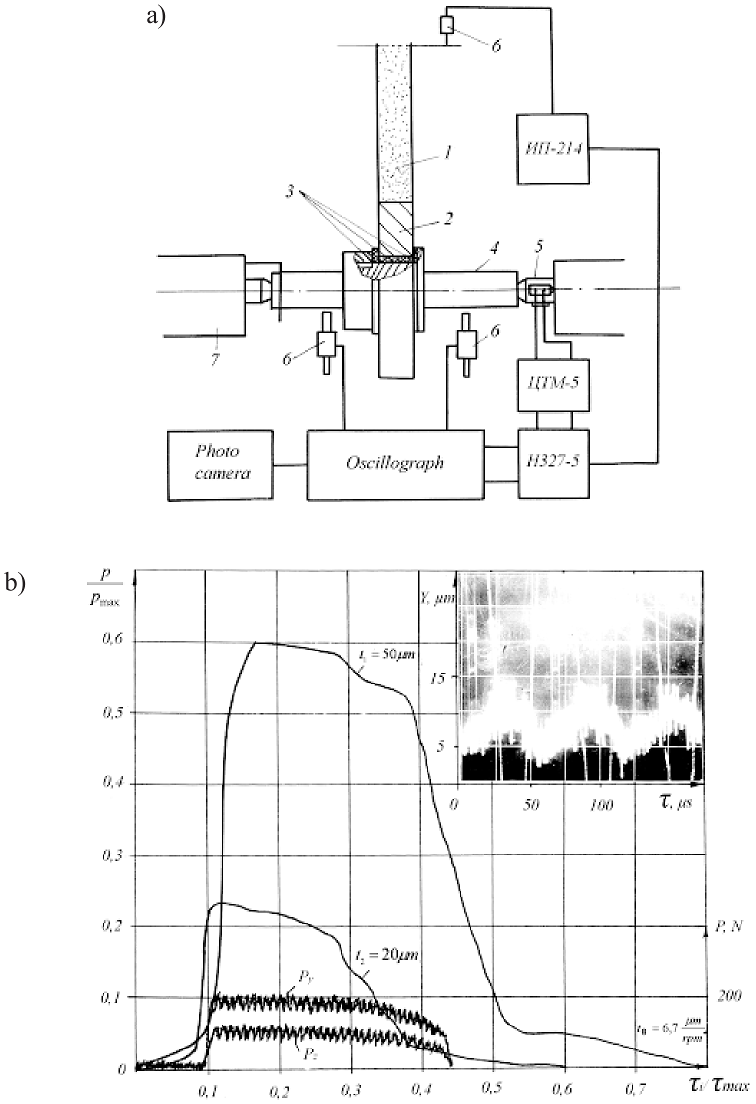

Fig. 3. *Diagram of the measurement of the force field (a) and results of the measurement (b): 1 – grinding wheel; 2 – workpiece; 3 – heat-insulation material; 4 – sample mandrel; 5 – strain-measuring centre; 6 – shift sensors; 7 – headstock.*

to the velocity change of the force pulse. Thus, it proves the expediency of measuring the cutting forces applied in flexible manufacture. Therefore, it is also necessary to analyze the influence of lubricants and cooling on the strained state of components of the grinding systems, stochastic state and the possibility of its application as a diagnostic and control means of the system. Thus, local stability mainly depends on revealing the lows and physical phenomena of the grease of the grinding process systems. The above-mentioned and other items will be discussed further in future papers.

4 CONCLUSION

Deterministic grinding systems change into deterministically stochastic ones. In this sense high-velocity grinding is rather important. Therefore, if it is clearly seen that the intensification of grinding modes requires appropriate decisions with reference to the major standards of accuracy and the quality of processing. It can be achieved by the implementation of various types of sensors, controlling the temperature and the field of forces in real-time and processing quality maintained by active control devices.

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Eksperimentalno numerična analiza kavitacijskega toka okoli lopatičnega profila

Experimental and numerical analyses of the cavitational flows around a hydrofoil

Ignacijo Biluš - Leopold Škerget - Andrej Predin - Matjaž Hriberšek

Namen prispevka je predstaviti analizo kavitacijskih tokovnih razmer okoli lopatičnega profila NACA. Predstavljen je fizikalno-matematični model v obliki Navier–Stokesovih enačb, zapisanih za fizikalne lastnosti zmesi voda – para in na podlagi prenosne enačbe za ohranitev mase vodne pare, s katero je bil modeliran nastanek, razširjanje in izginjanje vodne pare v toku zmesi.

Pri modeliranju fazne spremembe je bila uporabljena poenostavljena Rayleigh–Plessetova enačba, v kateri so upoštevani parametri, ki pomembneje vplivajo na dinamiko tokovnih pojavov v bližini osamljenega krogelnega parnega mehurčka v obdajajoči kapljevini.

Matematično fizikalni model je bil vključen v programski paket CFX 5.6, rezultati pa primerjani z rezultati preizkusa, izvedenega v kavitacijskem tunelu.

(Ključne besede: lopatice turbinske, tok kavitacijski, analize toka, simuliranje numerično)

In this paper we present an analysis of the cavitation flow conditions around a NACA hydrofoil. The mathematical model, in the form of Navier Stokes equations, based on the additional transport equation for vapour mass fraction inception, propagation and condensation is presented for the mixture's (water – water vapour) properties.

A simplified Rayleigh-Plesset equation is used when the phase change is modelled, where the parameters that influence the flow dynamics near the individual spherical bubble, surrounded by the liquid, are considered.

Mathematical/physical model is included in the CFD code CFX 5.6. Simulation results are compared with experimental results from the cavitation tunnel, where the tested hydrofoil (blade) was placed.

(Keywords: turbine blades, cavitation flow, water turbine flow analysis, numerical simulations)

0 UVOD

Kavitacija je pojav uparjanja vode in kondenzacije vodne pare v bližini lopatic v vodni turbini, ki je posledica neenakomernih razmer v tokovnem in temperaturnem polju tekočine. Opazovanje in razlage pojava kavitacije v vodnih turbinah so se začele že pred dvestopetdesetimi leti, ko je leta 1754 Euler prvi opisal omenjeni pojav. Od takrat se znanstveniki po svetu ukvarjajo s preučevanjem tega pojava, ki se pojavlja v hidravličnih strojih, ladijskih vijakih in hidravličnih napravah, vendar zaradi zapletenosti in številnih vplivnih parametrov kavitacija do danes fizikalno matematično še ni v popolnosti opisana in rešena.

0 INTRODUCTION

Cavitation is the water evaporation and condensation of water close to a turbine blade's surface that is a consequence of unequal conditions in the flow and the temperature field. Cavitation observations of water turbines started about 250 years ago, when in 1754 Euler described the cavitation phenomenon. Since then, scientists have studied this phenomenon, which appears in hydraulic machinery, ships' propellers and many hydraulic devices. However, the phenomenon is not clearly understood, either mathematically or physically, and many parameters are connected to the phenomenon.

Pojav kavitacije je tesno povezan z lokalnimi časovno spremenljivimi tokovnimi lastnostmi, kot so lokalne hitrosti in termodinamični tlak, ki je nižji od pripadajočega uparjalnega tlaka kapljevine pri delovni temperaturi sistema. Eksperimentalne študije kažejo na več vrst nestabilnosti, med katerimi je najbolj izrazito pulziranje kavitacijskega oblaka [1].

Temeljni raziskovalni projekti s področja kavitacije so osredotočeni na opis mehanizmov dinamike dvofaznih tokov in medsebojne interakcije med kapljevito in plinasto fazo. Dodatno je moč obravnavo razširiti tudi na interakcijo tok – trdnina, saj imajo lokalna nihanja tlaka lahko velik vpliv na trdne površine sestavnih delov turbinskočrpalnih sistemov.

S pospešenim razvojem merilnih metod in intenzivnim kopičenjem eksperimentalnih rezultatov je bilo v zadnjem času omogočeno tudi numerično modeliranje kavitacijskih tokov. Slednje izhaja s področja modeliranja večfaznih tokov, ki so bili razviti na temelju dvotekočinskega modela, torej na modelu Euler–Euler analize tokovnega polja v mirujoči prostorski točki, za vsako tekočinsko fazo posebej ([2] in [3]) .

Zaradi velike zahtevnosti obravnavanega sistema, tako z vidika fizikalno-matematičnega modeliranja kakor tudi z vidika učinkovitega numeričnega izračuna, je bil glavni motiv preučevanja kavitacijskih tokov fizikalno-matematični model, ki bi z zadovoljivo natančnostjo opisal prenosne pojave v primeru kavitacije in omogočil razmeroma kratke računske čase na dostopni računalniški opremi. Tako so bili v raziskavi izmed številnih vplivov, ki se pojavljajo pri kavitaciji, obravnavani le pomembnejši, torej fazna sprememba (nukleacija), rast in velikost mehurčkov, turbulentni tok, snovske lastnosti obeh faz in geometrijska oblika obtekane trdne površine (lopatice). Delež nečistoč in plinov, ki ne kondenzirajo, ter vplivi površinske napetosti in prenosnih pojavov na medfazni površini v prispevku niso obravnavani oziroma so obravnavani na makroskopskem integralnem nivoju. Prednost predstavljenega modela v primerjavi s podobnimi ([4] in [5]) je, da so vsi parametri eksperimentalno enostavno določljivi.

Omenjeni motiv je bil dosežen z uporabo matematično-fizikalnega modela v obliki Navier-Stokesovih enačb, zapisanih in rešenih za fizikalne lastnosti zmesi voda – para in na podlagi prenosne enačbe za ohranitev mase vodne pare, s katero smo modelirali nastanek, razširjanje in izginjanje vodne pare v toku zmesi.

The cavitation phenomenon is connected to locally time dependent flow properties, such as the local flow velocities and the thermodynamic pressure which is lower than vapour pressure at the given temperature. Experimental studies show a lot of instabilities sources, but the major one is in the strong cavitation cloud pulsation [1].

Basic research projects from the interesting area of cavitational flow deal with the dynamics of two-phase flow mechanisms that consider the interactions between the liquid and gas phases. It is possible to expand the analysed flow mechanics to the fluid–solid interaction studies, because local pressure oscillations have a large influence on the solid surfaces of parts of turbine/pump systems.

The intensive development of measuring methods and the large number of experimental results available, has enabled the numerical modelling of cavitational flows. The models are based on multiphase-flow modelling principles, developed for two fluids. This means the Euler-Euler model for flowfield analyses in the fixed point of 3D flow, for each individual phase ([2] and [3]).

Because of the analysed system's complexity from the physical/mathematical modelling point of view, as well as from the powerful simulation development aspect, the main aim of the cavitational flow study was an efficient flow model for transient cavitating conditions with a short calculation time using the available computer resources. To satisfy these limitations only the most important or influential parameters, i.e., the phase change (nucleation), bubble growth (bubble size), turbulent flow, fluid properties, and the geometry of the solid surface (blade surface) were considered. The impurities, the non-condensed gas and the surface tension's influence at the interfaces are not considered in this paper. The listed parameters are only considered from the macroscopic or integral point of view. Comparing to similar models ([4] and [5]), presented model has distinct advantage since it is easy to determine all included experimental parameters.

The aim was achieved by using a mathematical/physical model in the form of the Navier-Stokes equation, which was written and solved for the physical properties of water/vapour mixture based on the transient equation form for vapour continuity. Using this equation we modelled the appearance, growth and collapse of the vapour bubbles.

1 VODILNE ENAČBE ENOFAZNIH TOKOV

1.1 Zakon ohranitve mase

Zakon ohranitve mase je izpeljan iz ugotovitve, da je masa sistema nespremenljiva veličina. Integralsko obliko zapišemo z naslednjo enačbo:

1.2 Zakon ohranitve gibalne količine

Rezultirajoča sila okolice na prostornino je enaka časovnemu prirastku gibalne količine v prostornini in dotoku gibalne količine skozi njegovo površino. Integralska oblika zakona ohranitve gibalne količine je tako:

kjer so: v_i hitrostno polje, f_i prostorninska sila, p termodinamični tlak in τ_{ij} strižna napetost.

1.3 Zakon ohranitve turbulentne kinetične energije in raztrosa turbulentne kinetične energije

Model turbulentne kinetične energije k in raztrosne hitrosti turbulentne kinetične energije ε, oziroma model k-ε, je najpomembnejši dvoenačbni turbulentni model, ki temelji na postopku turbulentne viskoznosti. Turbulentne napetosti $\left(-\rho_0\widetilde{v_i'v_j'}\right)$ izrazimo z Boussinesqueovim približkom:

kjer sta k povprečna turbulentna kinetična energija turbulentnih odstopanj in $\upsilon_T=(\eta_T/\rho)$ turbulentna viskoznost. Člen $2\delta_{ij}k/3$ je razširitev osnovne Boussinesqueove podmene in ga lahko prištejemo statičnemu tlaku.

Značilne veličine so definirane z izrazi, npr. značilna hitrost je:

raztrosna hitrost turbulentne kinetične energije ε pa:

1 GOVERNING EQUATIONS FOR ONE-PHASE FLOW

1.1 Mass continuity equation

The continuity equation results from the fundamental physical principle that mass is conserved. In integral form it can be written as:

$$\frac{\partial}{\partial t}\int_V \rho\, dV + \int \rho\, v_j\, n_j\, dS = 0 \qquad (1).$$

1.2 Momentum equation

The resulting force on the volume element is equal to the time increment of the momentum in the volume and the flux across the element surface. The momentum equation in integral form can be written as:

$$\int_V \frac{\partial \rho v_i}{\partial t} dV + \int_S v_i \rho\, v_j n_j dS = \int_V \rho f_i dV + \int_S \left(-p\delta_{ij} + \tau_{ij}\right) n_j dS \qquad (2),$$

where v_i is the velocity flow field, f_i is the body force, p is the thermodynamic pressure, and τ_{ij} is the shear stress.

1.3 Conservation of turbulent kinetic energy and turbulent kinetic energy dissipation

The two-equation model for the turbulent kinetic energy k and the dissipation of turbulent kinetic energy ε, or the k - ε model, is the most important two-equation turbulent model that is based on the turbulent viscosity principle. The turbulent stresses $\left(-\rho_0\widetilde{v_i'v_j'}\right)$ are expressed with the Boussinesque approximation as follows:

$$\left(-\rho_0\widetilde{v_i'v_j'}\right) = \rho_0\upsilon_T\left(\frac{\partial\tilde{v}_i}{\partial x_j} + \frac{\partial\tilde{v}_j}{\partial x_i}\right) - \frac{2}{3}\delta_{ij}\rho_0 k \qquad (3),$$

where k is the averaged kinetic energy of the turbulent fluctuations, and $\upsilon_T=(\eta_T/\rho)$ the turbulent viscosity. The factor $2\delta_{ij}k/3$ is an extension of the Boussinesque hypothesis that can be added to the static pressure.

The characteristic properties are defined with the characteristic velocity

$$\hat{u} = \sqrt{k} \qquad (4),$$

and the dissipation velocity of the turbulent kinetic energy ε:

$$\varepsilon = \upsilon_0 \frac{\widetilde{\partial v_i' \partial v_i'}}{\partial x_j \partial x_j} \qquad (5)$$

podaja spremembo turbulentne energije toka v toplotno. Obe veličini k in ε določimo iz dodatnih posameznih parcialnih diferencialnih enačb, ki vsebujejo nove stalnice in funkcije. Za k velja enačba:

which defines the conversion of the turbulent energy into heat. Both the quantities k and ε are determined from additional, specific differential equations, which include new constants and functions. For k the following equation is valid

$$\frac{\partial k}{\partial t}+\tilde{v}_i\frac{\partial k}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(\upsilon_0+\frac{\upsilon_T}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+P-\varepsilon \qquad (6)$$

in podobno za ε

and similarly for ε

$$\frac{\partial \varepsilon}{\partial t}+\tilde{v}_i\frac{\partial \varepsilon}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\left(\upsilon_0+\frac{\upsilon_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}P-C_{2\varepsilon}\frac{\varepsilon^2}{k} \qquad (7),$$

kjer so stalnice modela C_μ=0,09, σ_k=1,0, σ_ε=1,3, $C_{1\varepsilon}$=1,44 in $C_{2\varepsilon}$=1,92 [6].

where the standard values of the constants are: C_μ=0.09, σ_k=1.0, σ_ε=1.3, $C_{1\varepsilon}$=1.44 in $C_{2\varepsilon}$=1.92 [6].

2 MATEMATIČNI MODEL

2 MATHEMATICAL MODEL

2.1 Dinamika krogelnega mehurčka

2.1 Bubble dynamic

Osamljen krogelni mehurček je najpreprostejša pojavna oblika parne faze v obdajajoči kapljevini, saj ne upošteva deformacij mehurčka, ki se pojavijo zaradi nehomogenosti tokovnega polja, niti medsebojnega vpliva mehurčkov. Kljub omenjenim poenostavitvam je dobra osnova za modeliranje prenosnih pojavov v dvofaznih kavitacijskih tokovih, ki se pojavljajo v turbinskih strojih.

Obravnavajmo iz tega razloga [7], krogelni mehurček polmera $R_B(t)$ v obdajajoči kapljevini temperature T_∞ in tlaka $p(t)$. Vrednost $p(t)$ naj bo znana, temperatura T_∞ pa nespremenljiva. Na začetku predpostavimo nestisljivo kapljevino ρ_L=konst. Vsebina mehurčka naj bo homogena, temperatura T_B in tlak $p_B(t)$ v mehurčku pa enakomerna. Dinamična viskoznost kapljevine η_L naj bo nespremenljiva.

Radialno lego v tekočini podamo z razdaljo r od središča mehurčka (sl. 1a), tlak v poljubni točki T zunaj mehurčka označimo s $p(r,t)$, radialna hitrost je $u(r,t)$ in temperatura $T(r,t)$.

Iz zakona ohranitve mase izhaja ([7] in [8]), da je zaradi spremembe površine mehurčka s kvadratom polmera r, hitrost $u(r,t)$ definirana kot:

An isolated, spherical bubble represents the simplest form of vapour surrounded by a liquid. This situation does not consider the bubble deformation that appears as a consequence of an non-homogenous flow field or the interaction between the vapour bubbles. However, in spite of these simplifying conditions, the mathematical model can be considered as a good basis for numerical modelling of the transient flow conditions for the two-phase flow that appears in turbine machines.

Consider a spherical bubble [7] of radius $R_B(t)$ (where t is the time) in an infinite domain of liquid, whose temperature and pressure far from the bubble are T_∞ and $p(t)$, respectively. The temperature is assumed to be constant and the pressure is assumed to be known. At the beginning it is also assumed that the fluid is incompressible (ρ_L=const.). The bubble contents are homogenous and the temperature T_B and pressure $p_B(t)$ within the bubble are uniform. The fluid dynamic viscosity η_L is constant.

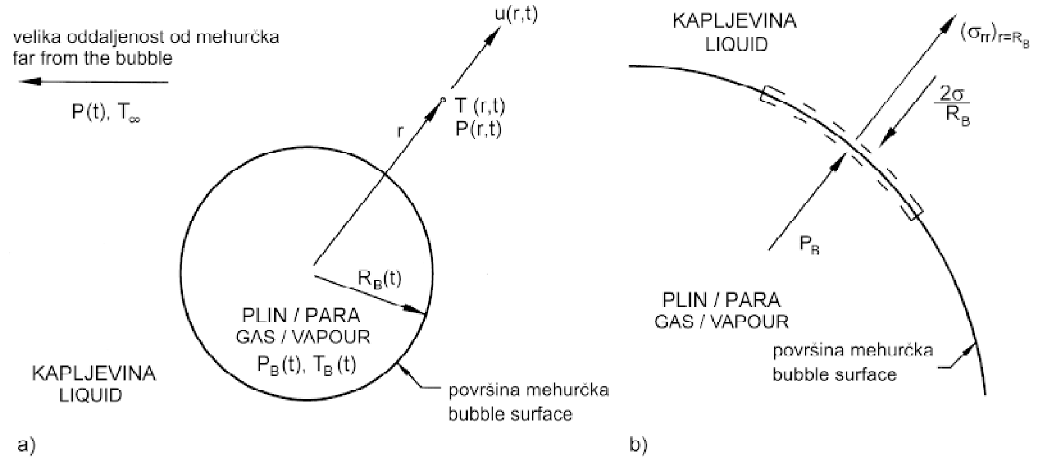
The radial position within the liquid will be denoted by the distance r from the bubble center (Figure 1.a). Let the pressure at an arbitrary point T be represented by $p(r,t)$, the radial outward velocity by $u(r,t)$, and the temperature by $T(r,t)$.

From the mass continuity equation ([7] and [8]) it follows that the spherical bubble's surface varies with the square of the radius r. Therefore, the flow velocity $u(r,t)$ can be defined by:

$$u(r,t)=\left[1-\frac{\rho_V}{\rho_L}\right]R_B{}^2\frac{dR_B}{dt}r^{-2}=\frac{F(t)}{r^2} \qquad (8).$$

Zapišimo gibalno enačbo [7] za smer r:

The momentum equation for the direction r [7] can be written as:



Sl. 1. *Krogelni mehurček v tekočini (a) in izsek iz površine krogelnega mehurčka (b) [7]*
Fig. 1. *Spherical bubble in a flow (a) and part of the spherical bubble surface (b) [7]*

$$-\frac{1}{\rho}\frac{\partial p}{\partial r}=\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}-\upsilon_L\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial u}{\partial r}\right)-\frac{2u}{r^2}\right] \qquad (9),$$

ker je $u=F(t)/r^2$ dobimo z ločitvijo spremenljivk in z integracijo v mejah $p\rightarrow p_{(r=R_B)}$ na površini mehurčka ($r\rightarrow R_B$):

where $u=F(t)/r^2$ can be defined with an integration between $p\rightarrow p_{(r=R_B)}$ on the bubble surface ($r\rightarrow R_B$):

$$-\frac{1}{\rho_L}\left(p_{(r=R_B)}-p\right)=-\frac{1}{r}\frac{\partial F}{\partial t}+\frac{1}{2}\frac{F^2}{r^4} \qquad (10).$$

Napetost na elementu površine krogelnega mehurčka podamo z izrazom:

The tension on the bubble surface element is

$$\tau=-p_{(r=R_B)}-\frac{4\eta_L}{R_B}\frac{dR_B}{dt}+p_B-\frac{2\sigma}{R_B} \qquad (11).$$

Za primer, ko ni masnega pretoka prek lupine, je τ=0, od koder izhaja:

In the case without mass flow over the bubble sphere we can write τ=0. From this we can derive the following:

$$p_{(r=R_B)}=p_B-\frac{4\eta_L}{R_B}\frac{dR_B}{dt}-\frac{2\sigma}{R_B} \qquad (12).$$

Z vstavitvijo izraza (11) v enačbo (9) dobimo:

Combining Equations (12) and (10) we obtain:

$$-\frac{1}{\rho_L}\left(p_B-\frac{4\eta_L}{R_B}\frac{dR_B}{dt}-\frac{2\sigma}{R_B}-p\right)=-\frac{1}{r}\frac{\partial F}{\partial t}+\frac{1}{2}\frac{F^2}{r^4} \qquad (13),$$

ker je $F=R_B^2(dr/dt)$, velja pri $r=R_B$:

where $F=R_B^2(dr/dt)$ for $r=R_B$:

$$\frac{1}{\rho_L}\left(p_B-p\right)-\frac{4\upsilon_L}{R_B}\frac{dR_B}{dt}-\frac{2\sigma}{\rho_L R_B}=R_B\frac{d^2R_B}{dt^2}+\frac{3}{2}\left(\frac{dR_B}{dt}\right)^2 \qquad (14).$$

Enačba (14) predstavlja končno obliko Rayleigh–Plessetove enačbe, kjer so na levi strani gonilni, viskozni in člen površinske napetosti, na desni strani pa vztrajnostni člen.

Z izpeljano Rayleigh–Plessetovo enačbo lahko zadovoljivo predstavimo dinamiko toka [8] v neposredni bližini osamljenega krogelnega parnega

Equation (14) represents the final form of the Rayleigh–Plesset equation. The first term is the driving term, the second term is the viscous term and the last term on the left-hand side of the equation is the surface-tension term. The inertia term is on the right-hand side of the equation.

With the derived Rayleigh-Plesset equation the flow dynamics [8] in the closest surroundings of mehurčka v kapljeviti okolici, zaradi česar je omenjena enačba podlaga za popis interakcije kapljevito – plinasto pri nastanku, razširjanju in izginjanju mehurčkov vodne pare.

an individual spherical vapour bubble in the liquid can be presented. In this case the equation describes the interaction between the liquid and gas phase by bubble growth and disappearance.

2.2 Homogeni dvofazni tokovni model

2.2 Homogenous two phase flow model

Definirajmo navidezno gostoto homogene mešanice voda – vodna para, ki je odvisna od masnega deleža parne faze (suhosti) f:

The density of a homogenous mixture of water and water vapour can be defined with:

$$\frac{1}{\rho}=\frac{f}{\rho_V}+\frac{1-f}{\rho_L} \qquad (15),$$

kjer je prostorninski delež parne faze:

where f represents the vapour mass fraction, connected with the volume fraction by the equation

$$\alpha = f\,\frac{\rho}{\rho_V} \qquad (16).$$

Za prenosno enačbo masnega deleža pare pišemo:

With this notation the vapour-phase mass-fraction transport equation can be written as follows:

$$\frac{\partial}{\partial t}(\rho f)+\vec{\nabla}\cdot\left(\rho\vec{V}f\right)=\vec{\nabla}\cdot\left(\rho\Gamma\vec{\nabla}f\right)+R_e-R_c \qquad (17),$$

kjer sta R_e in R_c izvirna člena oziroma stopnja uparjanja in stopnja kondenzacije, ki sta funkciji tokovnih veličin (tlak, hitrost) in snovskih lastnosti (gostote kapljevite in plinaste faze, uparjalnega tlaka, površinske napetosti), medtem ko je Γ kinematična difuzivnost spremenljivke f. Enačba (16) izhaja iz teorije homogenega dvofaznega toka, kar pomeni primerno poenostavitev iz naslednjih razlogov:

- v inženirski praksi se kavitacija pojavlja v področjih nizkega tlaka, kjer so hitrosti razmeroma visoke in ni zdrsa med tekočo in plinasto fazo;
- po navadi je faza pare v obliki drobnih mehurčkov. Ker pa je v okolici le-teh treba izbrati ustrezni fizikalni model za izračun velikosti (polmera mehurčka) in sile upora, kar pomeni velik problem, saj splošnega in zanesljivega modela še ni, je postopek po teoriji homogenega dvofaznega toka uporabna rešitev.

Pričujoči model je omejen na izpeljavo izraza za fazni premeni R_e in R_c ([9] in [10]), z dodanim difuzivnim členom v prenosni enačbi (17).

V kapljevinskem toku brez zdrsa na medfazni površini in brez upoštevanja vpliva plinov v mehurčku, dinamiko mehurčka podamo s spremenjeno Rayleigh–Plessetovo enačbo (14):

where R_e and R_c represent the source terms or the evaporation/condensation rate. They are functions of the flow parameters (flow pressures and velocities) and the fluid properties (density, evaporation pressure, surface tension). Γ represents the kinematic diffusivity of the variable f. Equation (17) derives from the theory of homogenous two-phase flow, which represents a good simplifying approach for the following reasons:

- In engineering practice cavitation appears in the low pressure areas, where the relative flow velocities are high, and therefore no slip between the liquid and gas phases exists.
- The vapour phase usually has the form of small bubbles. In the bubble proximity we have to use a suitable models for bubble radius and drag determination, which causes the problem. Therefore, the homogenous two-phase model is the suitable solution.

The presented homogenous two-phase flow model is limited to the derivation of the source terms (R_e and R_c) ([9] and [10]), with the addition of the diffusion term (17).

Bubble dynamics, without slip on the interfaces and without considering the gas effects in the bubble, can be defined with the modified Rayleigh–Plesset equation (14), written in the following form:

$$R_B\frac{d^2R_B}{dt^2}+\frac{3}{2}\left(\frac{dR_B}{dt}\right)^2=\left(\frac{p_B-p}{\rho_L}\right)-\frac{4\upsilon_L}{R_B}\dot{R}_B-\frac{2\sigma}{\rho_L R_B} \qquad (18).$$

Da bi izračunali neto stopnjo uparjanja $R=R_e-R_c$, zapišimo spremenjen zakon ohranitve mase za:
- fazo pare:

To calculate the net evaporation rate $R=R_e-R_c$ the mass continuity equation can be written as:
- vapour phase:

$$R = \frac{D}{Dt}\left[\alpha\rho_V\right] + \alpha\rho_V\vec{\nabla}\cdot\vec{v} \tag{19},$$

- fazo kapljevine:

- liquid phase:

$$-R = \frac{D}{Dt}\left[\left(1-\alpha\right)\rho_L\right] + \left(1-\alpha\right)\rho_L\vec{\nabla}\cdot\vec{v} \tag{20},$$

- homogeno mešanico:

- homogenous mixture:

$$0 = \frac{D}{Dt}\rho + \rho\vec{\nabla}\cdot\vec{v} \tag{21}.$$

S kombinacijo enačb izpeljemo odvisnost:

By combining the equations, the following dependency can be written:

$$\vec{\nabla}\cdot\vec{v} = \frac{-\frac{D}{Dt}\left(\left(1-\alpha\right)\rho_L + \alpha\rho_V\right)}{\left(\left(1-\alpha\right)\rho_L + \alpha\rho_V\right)} \tag{22}$$

oziroma:

and:

$$\frac{D}{Dt}\rho = -\rho\frac{\frac{D}{Dt}\left(\left(1-\alpha\right)\rho_L + \alpha\rho_V\right)}{\left(1-\alpha\right)\rho_L + \alpha\rho_V} \tag{23}.$$

Če ni spremembe gostote pare, niti spremembe gostote kapljevine in ob predpostavki, da je sprememba prostorninskega deleža pare zaradi konvekcije zanemarljiva, lahko zapišemo totalni odvod gostote mešanice kot:

If the vapour and liquid densities are constant, and with the assumption that the volume phase of vapour caused by convection can be neglected, the total derivation of the mixture density can be written as:

$$\frac{D\rho}{Dt} = -\left(\rho_L - \rho_V\right)\frac{d\alpha}{dt} \tag{24}.$$

Prostorninski delež plinaste faze je definiran s številsko gostoto mehurčkov n in polmerom mehurčka R_B, in v kombinaciji z (21) izpeljemo:

The volume fraction of the gas phase with the bubble number density n and with the bubble radius R_B. Combining this with Equation (21), the following equation results:

$$\frac{D\rho}{Dt} = -\left(\rho_L - \rho_V\right)\left(4\pi n\right)^{1/3}\left(3\alpha\right)^{2/3}\frac{dR_B}{dt} \tag{25}.$$

S kombinacijo Rayleigh–Plessetove enačbe brez viskoznega člena in brez člena površinskih napetosti ter z uporabo zgoraj zapisanih zvez lahko, ob upoštevanju $\left(\vec{V}\cdot\vec{\nabla}\right)\alpha = 0$ in predpostavki $D\rho_v/Dt=0$, izpeljemo odvisnosti:

With the combination of the Rayleigh–Plesset equation without the viscous term and the term of surface tension and $\left(\vec{V}\cdot\vec{\nabla}\right)\alpha = 0$, the following dependency can be written (with the assumption $D\rho_v/Dt=0$),

$$R = \frac{\rho_V\rho_L}{\rho}\left(4\pi n\right)^{1/3}\left(3\alpha\right)^{2/3}\frac{dR_B}{dt}$$

$$R = \frac{\rho_V\rho_L}{\rho}\left(4\pi n\right)^{1/3}\left(3\alpha\right)^{2/3}\left(\frac{2}{3}\left(\frac{p_B - p}{\rho_L}\right) - \frac{2}{3}R_B\frac{d^2R_B}{dt^2}\right)^{1/2} \tag{26}.$$

Če zanemarimo drugi odvod polmera mehurčka v zgornjem izrazu (pomemben samo v začetni pospešeni fazi rasti mehurčka), velja

If we neglect the second derivative of the bubble radius in the equation above (important only in the first bubble-growing phase), the simplified poenostavljena prenosna enačba (16) za paro v naslednji obliki:

transport equation (16) for the vapour phase in the following form can be written as:

$$\frac{\partial}{\partial t}(\rho f)+\vec{\nabla}\cdot(\rho f\,\vec{v})=\vec{\nabla}\cdot\left(\rho\Gamma\vec{\nabla}f\right)+\frac{\rho_V\rho_L}{\rho}(4\pi n)^{1/3}(3\alpha)^{2/3}\left(\frac{2}{3}\left(\frac{p_B-p}{\rho_L}\right)\right)^{1/2} \quad (27).$$

Drugi člen na desni strani zgornje enačbe pomeni uparjalni (izvirni) člen. Čeprav razmere ob uparjanju niso identične tistim ob kondenzaciji, poenostavljeno vzamemo, da je enačba enaka za oba postopka fazne premene.

V zgornji enačbi so vsi členi, razen n, znane stalnice ali odvisne spremenljivke. Iz tega razloga bomo zapisali enačbo za izvirna člena v spremenjeni obliki [9]:

The second term on the right-hand side of the above equation is the vapour source term. It is known that the process during water evaporation is not equal to the water condensation process, but it can be simplified, i.e. Equation (27) is the same for both processes.

In the above Equation (27) all the terms except n are constants or dependent variables. This is the reason why the source terms are written in changed form [9]:

$$R_e=C_e\frac{V_{ch}}{\sigma}\rho_L\rho_V\left[\frac{2}{3}\frac{p_v-p}{\rho_L}\right]^{1/2}(1-f) \quad (28)$$

$$R_c=C_c\frac{V_{ch}}{\sigma}\rho_L\rho_L\left[\frac{2}{3}\frac{p-p_v}{\rho_L}\right]^{1/2}f \quad (29),$$

kjer sta C_e in C_c stalnici, V_{ch} pa določa lokalno relativno hitrost med kapljevino in paro in jo lahko ocenimo z enačbo $V_{ch}=\sqrt{k}$. Zgornje enačbe temeljijo na naslednjih predpostavkah:

- v mehurčastem toku je stopnja fazne spremembe sorazmerna V_{ch}^2, za večino praktičnih dvofaznih tokov pa lahko predpostavimo linearno odvisnost od hitrosti;
- relativna hitrost med kapljevito in plinasto fazo je reda velikosti 1 do 10% povprečne hitrosti toka, kar v večini turbulentnih tokov ustreza redu velikosti lokalnih turbulentnih sprememb. Tako lahko za prvi približek zapišemo $V=\sqrt{k}$.

where C_e and C_c are constants, and V_{ch} defines the local relative velocity between the liquid and the vapour, and it can be assumed by $V_{ch}=\sqrt{k}$. Equations (28) and (29) are based on the following assumptions:

- The rate of phase change is proportional to V_{ch}^2 in bubbly flow, but the linear dependency on velocity can be predicted for conventional two-phase flows.
- The relative velocity between the liquid and gas phases is in the range from 1 up to 10% of the average flow velocity, which is suitable for the local turbulent fluctuations in most turbulent flows. For the first approximation, $V=\sqrt{k}$ can be used.

3 NUMERIČNA ANALIZA TOKA OKOLI LOPATE

Numerično simulacijo obtekanje lopate smo s predstavljenim matematičnim modelom izvedli s programom CFX 5.6. Programski paket temelji na metodi končnih prostornin (MKP). Predstavljen matematično-fizikalni model smo vključili v običajni sistem Navier Stokesovih enačb v obliki dodatne konvektivno difuzivne prenosne enačbe za masni delež pare.

Računsko območje je 3D prostornina velikosti 1200×1000×5 mm, z vseh strani zaprt s ploskvami. Območje računanja je razdeljeno na tetraedre. Take tetraedre imenujemo pretočni elementi, njihova oglišča pa so vozlišča. Opisane mreže imenujemo nestruktuirane. Lokacija vozlišča v

3 ANALYSES OF THE NUMERICAL FLOW AROUND THE BLADE

The numerical simulation for the flow around the blade profile using the presented mathematical model was performed by CFX 5.6. The numerical code is based on the finite-volumes method (FVM). The presented mathematical/physical model is included in the conventional system of the Navier Stokes equation in the form of an additional convective-diffusion transport equation for the vapour mass fraction.

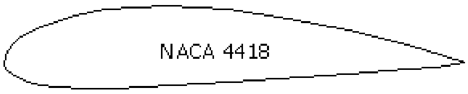
The calculation area is a 3D volume with a size of 1200 x 1000 x 5 mm, closed from all sides. The area is divided into tetrahedrons. Such a tetrahedron is called a flow element, and its edges represent the calculating nodes. This type of mesh is an unstructured mesh. The location of the nodes is prostoru je določena s kartezičnimi koordinatami x, y in z. V vsakem vozlu pretočnega elementa dobimo z numeričnim izračunom vrednosti odvisnih spremenljivk: tlaka, hitrosti, turbulentne kinetične energije, raztrosa turbulentne kinetične energije in masnega deleža pare.

Testni izračun brez kavitacije smo izvedli pri različnih gostotah računske mreže okoli lopatičnega profila NACA 4418, prikazanega na sliki 2a. Iz diagrama na sliki 2b je razviden potek tlaka pod in nad lopatico za štiri različna števila vozlišč (preglednica 1).

determined by the Cartesian coordinates x, y, and z. For each node of the flow element the dependent variables pressure, velocity, turbulent kinetic energy, dissipation of the turbulent kinetic energy and the vapour fraction are calculated.

A test calculations without cavitation was performed for different calculation mesh densities and shown in Figure 2.a. The pressure distributions along the suction side and the pressure side of the blade for different mesh-refinement factors (Table 1) is evident in the diagram (Figure 2.b).

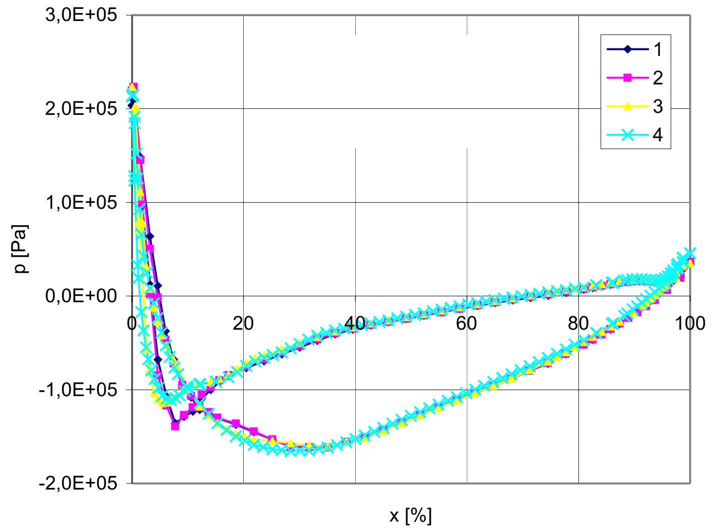
a)



Algoritem izračuna:
1. Reševanje osnovnega sistema NS enačb za turbulentni tok.
2. Določitev R_e in R_c po enačbah (27) in (28).
3. Rešitev enačbe (16).

Solver algorithm:
1. Solving the fundamental system of NS equations for turbulent flow
2. Determining the source terms R_e and R_c .
3. Solving the additional transport equation.

b)



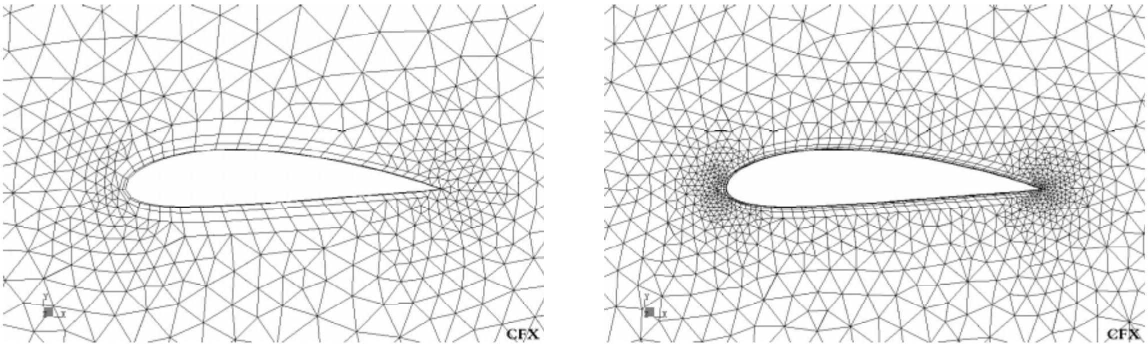
Sl. 2. *Lopatični profil (a) in potek tlaka (b) vzdolž lopatice pri različnih gostotah računske mreže za režim $\alpha=0°$, $Re=1\cdot10^6$, $\sigma=3$*

Fig. 2. *Blade profile (a) and pressure distribution (b) around the blade profile for different mesh-refinement factors for regime $\alpha=0°$, $Re=1\cdot10^6$, $\sigma=3$*

Preglednica 1. *Podatki o računski mreži*

Table 1. *Mesh data*

Zap. štev. Case no.	NACA 4418	
	Št. vozlišč Number of nodes	Št. elementov Number of elements
1	2846	8362
2	4394	12608
3	13372	39824
4	29511	93061



Sl. 3. *Gostota računske mreže v neposredni bližini profila NACA 4418*
Fig. 3. *Mesh density near blade profile surface (profile NACA 4418)*

Iz diagrama je razvidno, da med primerom 3 in rezultati za gostoto računske mreže, označeno z zaporedno številko 4, ni bistvenih razlik. Z namenom hitrejšega računanja smo zato v nadaljevanju računali z mrežo s približno 40.000 elementi (zap. št. 3).

Na sliki 3 sta prikazani računski mreži št.1 in št. 3 v neposredni bližini lopatičnega profila. Informacije o toku na mejnih ploskvah računskega območja smo definirali z naslednjimi robnimi pogoji:
- stenski pogoj,
- vstopni pogoj,
- izstopni pogoj,
- simetrični robni pogoj.

Na steni ni bilo zdrsa, na vstopu smo predpisovali masni pretok, na izstopu pa termodinamični tlak.

3.1 Računski parametri in konvergenca

Za ustaljeni izračun je bil uporabljen običajni turbulentni model k-ε. Za diskretizacijo konvektivnega člena prenosne enačbe je bila uporabljena shema "upwind", analiza pa je bila izvedena pri različnih vrednostih kinematične difuzivnosti Γ. Difuzivnost pomeni hitrost razširjanja skalarne veličine v primeru brez konvekcije in je v splošnem odvisna od lastnosti nosilne (kapljevite) faze in lastnosti faze, za katero rešujemo dodatno prenosno enačbo. Iz tega razloga smo numerično simulacijo ponovili pri različnih vrednostih Γ.

Ciljni ostanek je bil $r = 10^{-5}$, za odvisne spremenljivke (tlak, hitrost, turbulentna kinetična energija, raztros turbulentne kinetične energije in masni delež pare).

From the diagram (Figure 2) it is evident that the calculation results do not deviate remarkably. From this fact it can be concluded that the density does not significantly affect the calculation results in this case. For this reason a mesh with approximately 40.000 elements (mesh type 3, table 1) was used.

Figure 3 shows the mesh type 1 and 3 for the blade profile surface area. The information about the boundary layers of the calculating domain is defined by the following boundary conditions:
- wall condition,
- inlet condition,
- outlet condition,
- symmetry condition.

No flow slip on the wall is considered. The mass flow rate is defined at the inlet. The thermodynamic pressure is defined at the outlet.

3.1 Calculation parameters and convergence

The conventional k - ε was used for the stationary calculation. For the convective term discretisation the "upwind" scheme was used. The calculation was performed for different values of the kinematic diffusion Γ. The diffusion represents the velocity of the scalar quantity propagation. In the case of no-convection, this in general depends on the liquid properties and/or on the properties of the phase that is currently calculated by the transport equation. For this reason the calculation is repeated for different values of Γ.

The target residual was $r = 10^{-5}$, for dependent values (pressure, velocity, turbulent kinetic energy, dissipation of the turbulent kinetic energy, and the vapour-phase mass fraction).

4 EKSPERIMENTALNA RAZISKAVA TOKA OKOLI LOPATE

Eksperimentalna raziskava je bila izvedena v tunelu za preizkušanje Kaplanovih turbin v Turboinštitutu v Ljubljani [11]. Najpomembnejše notranje mere tunela so: B=150 mm in H=400 mm, kjer je ravni del tunela dolg $L^*=21L$ (sl. 4). Dolžina polirane lopate iz brona je L=150 mm in vpliva na vrednost Reynoldsovega števila:

4 EXPERIMENTAL INVESTIGATIONS OF FLOW AROUND THE BLADE PROFILE

The experimental analysis was performed in the tunnel for the Kaplan turbine testing at the Turboinstitute in Ljubljana [11]. The general dimensions of the tunnel are as follows: width, B=150 mm; and height, H=400 mm. The straight tunnel part is long, up to 21 times the blade profile lengths $L^*=21L$, as shown in Figure 4. The length of the profile with a polished surface is made from brass L=150 mm. The Reynolds number is determined by:

$$\mathrm{Re} = \frac{v \cdot L}{\upsilon} \qquad (30).$$

Na vstopu v tunel je izveden konfuzor, na izstopu pa difuzor za upočasnitev toka in rekuperacijo kinetične energije. Tunel je opremljen z mehanizmom za spreminjanje nagibnega kota lopate ter oknom iz poliakrilnega stekla, za vizualno opazovanje. Potek in način meritev je podrobneje opisan v [11].

Spreminjanje termodinamičnega tlaka in s tem kavitacijskega koeficienta:

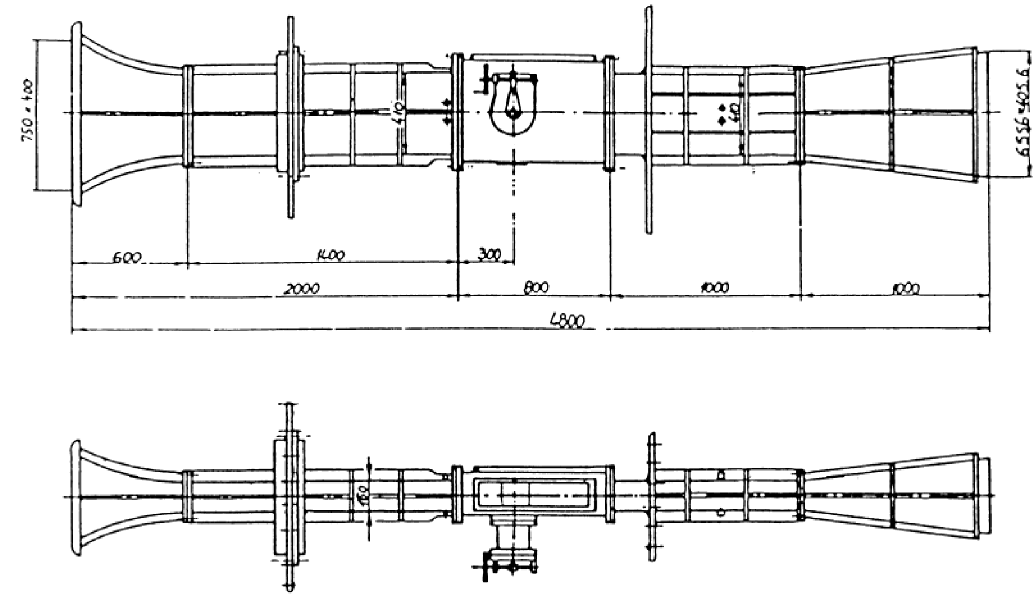
For the tunnel intake an entrance tube was used, similar to the diffuser at the tunnel exit. At the exit part of the tunnel (in the diffuser) the flow velocities decrease; this allows recuperation. The tunnel was equipped with a mechanism to change the blade attack angle and a transparent Plexiglas window for the flow visualisation.

The thermodynamic pressure variation was achieved with a vacuum pump. In this way the variation of the cavitation coefficient:

$$\sigma = \frac{p - p_V}{\frac{1}{2}\rho v^2} \qquad (31)$$

je omogočeno s sistemom z vakuumsko črpalko. V zgornji enačbi je p statični tlak, ki ga merimo v tunelu pred lopato na razdalji 350 mm pred vrtiščem lopate.

is achieved. p in the Equation (31) presents the statical pressure measured in the cavitation tunnel 350 mm in front the blade rotating point.



Sl. 4. *Kavitacijski tunel [11]*

Fig. 4. *Cavitation tunnel [11]*

Nagibni kot lopate α je mogoče spreminjati v obe smeri, pri čemer pomeni kot α =0° vodoravno lego tetive profila, pozitivni koti pa dvigovanje vstopnega roba lopatice.

5 PRIMERJAVA REZULTATOV

Na slikah 5 do 8 je podana primerjava rezultatov za tri različne tokovne režime, definirane z brezrazsežnima številoma σ in Re.

Na sliki 5 so razvidni zametki pare na sliki, ki prikazuje rezultate numerične simulacije in na fotografiji preizkusa. Območje, kjer se pojavi para, je v primeru numerične simulacije nekoliko večje.

Na sliki 6 je razvidno, da pride do pojava kavitacije tudi v primeru tokovnega režima definiranega z α=16°, Re=$1\cdot10^6$, σ=2. Izračunan

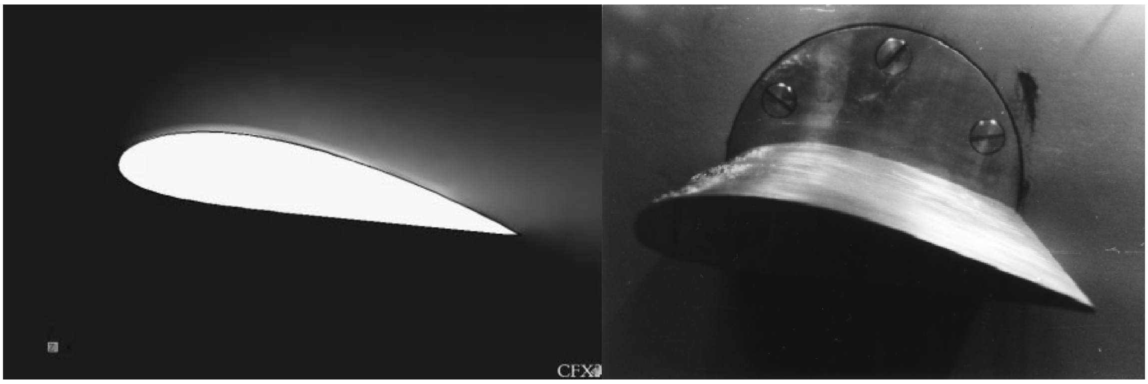
The blade inclination angle α can be changed on both sides (positive and negative). The zero value α =0° corresponds to the horizontal blade chord position and positive angles mean lifting of the leading edge.

5 COMPARISON OF THE RESULTS

In Figures 5 to 8 is a results comparison for three different flow regimes, defined by the non-dimensional numbers σ and Re.

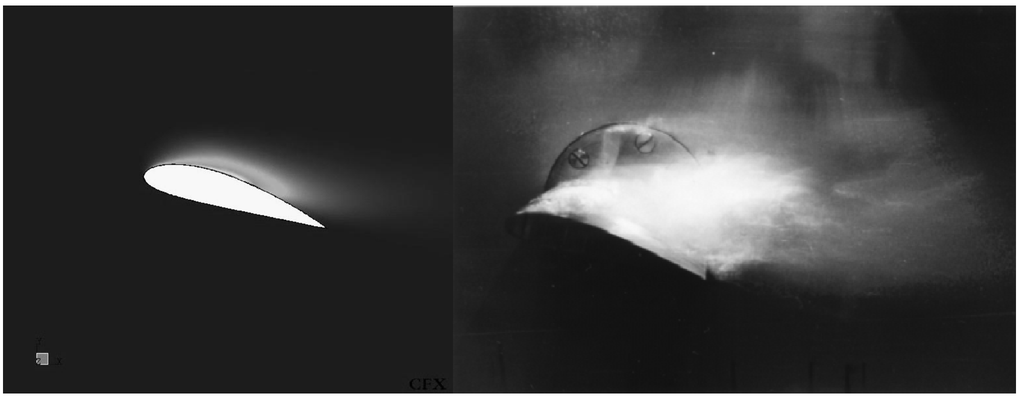
In Figure 5 the starting cavitation is evident from the both results (experimental (b), and numerical (a)). The area where the cavitation occurs is larger in the case of the numerical simulation than with the experimental result.

In Figure 6 it is evident that the cavitation phenomenon also occurs in the case of the flow defined by, α=16°, Re=$1\cdot10^6$, σ=2. The calculated cavita-



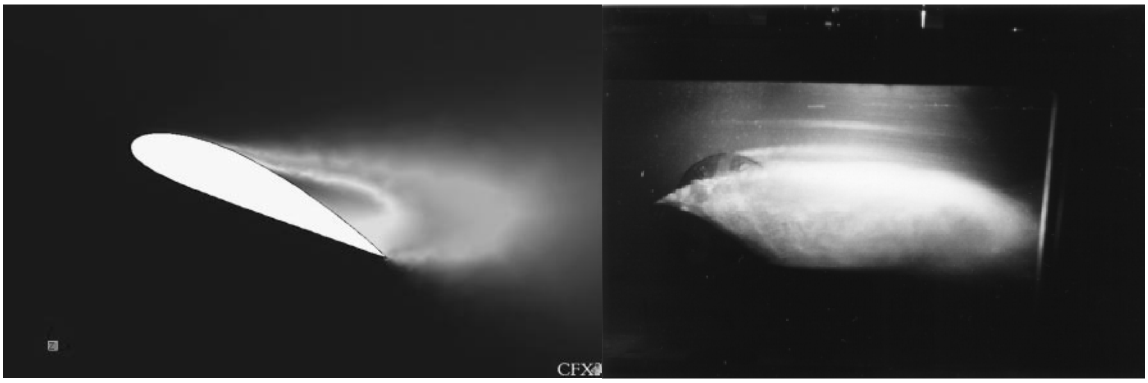
Sl. 5. *Primerjava eksperimentalnih (a) in numeričnih (b) rezultatov za spremenljivko f za režim α=10°, Re=$8\cdot10^5$, σ=3*

Fig. 5. *Comparison of the experimental (a) and numerical (b) results for value f in regime, α=10°, Re=$8\cdot10^5$, σ=3*



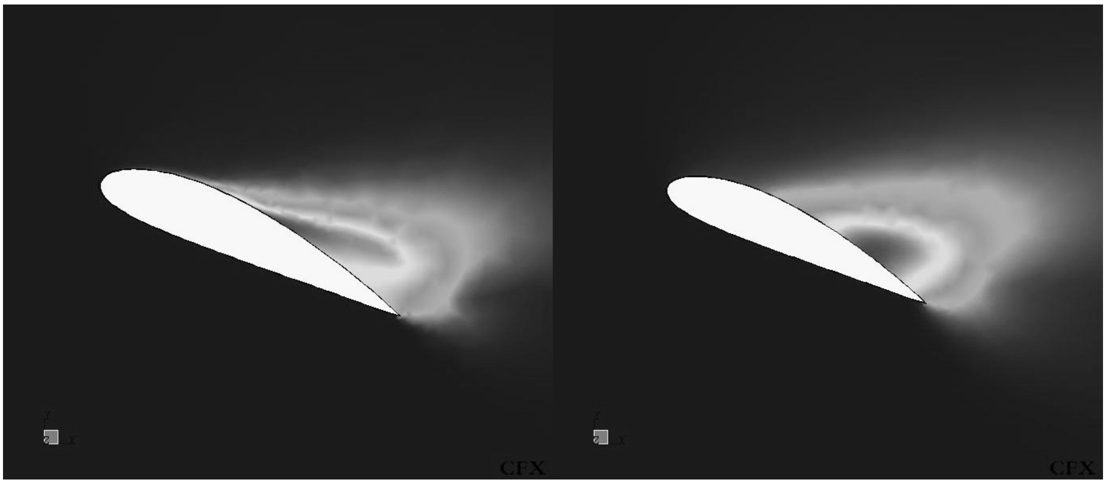
Sl. 6. *Primerjava eksperimentalnih (a) in numeričnih (b) rezultatov za spremenljivko f za režim α=16°, Re=$1\cdot10^6$, σ=2*

Fig. 6. *Comparison of experimental (a) and numerical (b) results for value f in regime, α=16°, Re=$1\cdot10^6$, σ=2*



Sl. 7. *Primerjava eksperimentalnih (a) in numeričnih (b) rezultatov za spremenljivko f za režim* $\alpha=24°$, $Re=1\cdot 10^6$, $\sigma=1$

Fig. 7. *Comparison of experimental (a) and numerical (b) results for value f in regime,* $\alpha=24°$, $Re=1\cdot 10^6$, $\sigma=1$



Sl. 8. *Primerjava numeričnih rezultatov za spremenljivko f pri različnih koeficientih difuzivnosti*

Fig. 8. *Numerical result comparison for the value f with different diffusion coefficients*

kavitacijski oblak je nekoliko manjši od kavitacijskega oblaka, prikazanega na fotografiji, verjetno zaradi vpliva difuzivnosti Γ.

Na sliki 7 je prikazana primerjava rezultatov za režim, pri katerem se je pri preizkusu kavitacijski oblak zelo razširil v tokovno brazdo. Iz primerjave je razvidno neujemanje oblike kavitacijskega oblaka. Razlika je verjetno posledica premajhne difuzivnosti, zaradi česar smo povečali vrednost na $\Gamma=10^{-3}$.

Iz rezultatov na sliki 8 je razviden vpliv difuzivnosti Γ na prenos masnega deleža pare f za primer $\alpha=24°$, $Re=1\cdot 10^6$, $\sigma=1$. Sklenemo lahko, da je ujemanje z rezultati preizkusa na sliki 7 v primeru večjega prispevka difuzivnega člena v enačbi (27) boljše.

tion cloud is smaller than the cavitation cloud in the experiment. This is probably the effect of diffusion Γ.

In Figure 7 is the comparison of the results in the operating regime where the cavitation cloud is propagated into the blade wake. A little disagreement of cavitation swirl form is evident from this comparison. The difference is probably caused by a too small diffusion coefficient. This is the reason why the diffusion coefficient is increased to $\Gamma=10^{-3}$.

From the results given in Figure 8 we can see the influence of diffusion on the mass flow part of the vapour phase f can be seen for the case, $\alpha=24°$, $Re=1\cdot 10^6$, $\sigma=1$. It can be concluded that the agreement between the experimental and numerical results, given in Figure 8, is better when the diffusion part in Equation (27) is considered.

6 SKLEPI

Na temelju slik 6 do 8 lahko zapišemo, da predstavljeni homogeni dvofazni model zadovoljivo popiše kavitacijske razmere pri obtekanju lopatičnega profila pri različnih natočnih kotih.

Primeren je za napovedovanje pojava kavitacije in v razširjeni (konvektivno difuzivni) obliki zadovoljivo popiše tudi obliko kavitacijskega oblaka.

V prenosni enačbi masnega deleža (suhosti) pare difuzivni člen vpliva na obliko kavitacijskega oblaka, saj z njim skušamo zajeti razširjanje kavitacijskega polja zaradi razlik v koncentracijah v mehurčku.

Uporabljen običajni dvoenačbni turbulentni model k-ε, je primeren za popis turbulentno kavitacijskih razmer pri obtekanju lopatičnih profilov.

Predpostavljena nespremenljiva gostota pare in kapljevine ne pomeni prevelike napake.

Konvekcija na medfazni površini ne vpliva na deleža pare.

Predstavljeni homogeni kavitacijski model je dobro orodje za napovedovanje kavitacije v turbinskih strojih, saj so predstavljeni rezultati numerične simulacije časovno povprečene vrednosti, fotografije eksperimenta pa prikazujejo trenutno strukturo kavitacijskega oblaka, zaradi česar je primerjava omejena.

Zahvala

Avtorji se zahvaljujejo osebju podjetja Turboinštitut iz Ljubljane za vse rezultate meritev.

6 CONCLUSIONS

Based on Figures 6 to 8 we can conclude that the presented homogenous two-phase model gives good results for the flow pattern around the blade profile at different flow attack angles.

The presented mathematical model is suitable for the prediction of the cavitation cloud around a hydrofoil (shape, position and dimensions).

The mass part of the vapour phase in the transportation equation influences the shape of the cavitation cloud. With this approach we try to consider the concentration change in the bubbles.

The conventional two-equation turbulent model k - ε is suitable for a determination of the turbulent cavitation flow conditions when the flow around blade profiles is calculated.

The assumed constant density of the vapour and the liquid do not cause important mistakes.

The convection at the bubble interface does not influence the vapour phase fraction.

The presented homogenous cavitation model presents a good tool for cavitation prediction turbo machines, since averaged numerical simulation results agree to the instant cavitation cloud structure at the photos.

Acknowledgement

The authors would like to thank the personnel of the Turboinštitut, Ljubljana, for all the measurement results.

7 SIMBOLI
7 SYMBOLS

širina kavitacijskega tunela	B	cavitation tunnel width
stalnica	C_c	constant
stalnica	C_e	constant
stalnica	C_μ	constant
stalnica	$C_{1\varepsilon}$	constant
stalnica	$C_{2\varepsilon}$	constant
masni delež pare (suhost mešanice)	f	vapour mass fraction
gostota prostorninske sile	f_i	body force
funkcija	F	function
višina kavitacijskega tunela	H	cavitational tunnel height
turbulentna kinetična energija	k	turbulent kinetic energy
dolžina lopatice	L	blade length
številska gostota mehurčkov	n	bubble number density
normala na površino	$\vec{n}, n_j$	surface normal

nastanek turbulentne kinetične energije	P	turbulent kinetic energy production
termodinamični tlak	p	thermodynamic pressure
tlak v mehurčku	p_B	pressure in the bubble
uparjalni tlak	p_V	vapour pressure
razdalja od središča mehurčka	r	distance from the bubble center
neto fazna sprememba	R	net phase change
stopnja kondenzacije	R_c	condensation rate
stopnja uparjanja	R_e	evaporisation rate
polmer parnega mehurčka	R_B	bubble radius
površina kontrolne prostornine	S	surface of control volume
čas	t	time
temperatura obdajajoče kapljevine	T_∞	surrounding fluid temperature
temperatura v mehurčku pare	T_B	temperature in bubble
radialna hitrost	u	radial velocity
značilna hitrost	$\hat{u}$	characteristic velocity
časovno povprečen vektor hitrosti	$\tilde{v}_i$	time averaged velocity vector
nadzorna prostornina	V	control volume
volumski delež parne faze	α	vapour volume fraction,
Kroneckerjeva delta funkcija	δ_{ij}	Kronecker delta function
kinematična difuzivnost	Γ	kinematic difusivity
raztrosna hitrost turbulentne kinetične energije	ε	disipation velocity of turbulent kinetic energy
kinematična viskoznost	υ	kinematic viscosity
turbulentna kinematična viskoznost	υ_T	turbulent kinematic viscosity
dinamična viskoznost	η	dynamic viscosity
gostota mešanice	ρ	mixture density
gostota kapljevite faze	ρ_L	liquid density
gostota plinaste (parne) faze	ρ_V	gas (vapour) density
površinska napetost, kavitacijsko število	σ	surface tension, cavitation number
napetostni tenzor	σ_{ij}	stress tensor
napetost na elementu izseka iz krogelne površine	τ	tension on the bubble surface element
tenzor strižnih napetosti	τ_{ij}	shear stress tensor

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Kotiček za tehniko in tehnologijo v vlogi razpoznavanja in razvijanja nadarjenosti predšolskega otroka
Small Corner for Technics and Technology in Function Identification and the Development of Talents in Children under School Age

UVOD

Nadarjenost v ožjem pomenu besede je vsekakor "nadpovprečna inteligenčna sposobnost. Inteligentnost je v večji meri prirojena sposobnost " [13].

O nadarjenosti ni splošno sprejete definicije. Vendar "konsenzualno velja, da je nadarjenost vsota danih in pridobljenih dejavnikov, ki omogočajo nadpovprečne stvarne ali latentne, osebno ali družbeno koristne stvaritve na enem ali več toriščih ljudske dejavnosti, specifična organiziranost živčevja, nagnjenj, interesov in motivov nadarjenih pa daje pečat tudi njihovi osebnosti. S pojmom nadarjenosti je povezanih več vidikov, med njimi zlasti odnos med družbenim in osebnim pomenom nadarjenosti, poreklo, graduacija in obseg nadarjenosti" [13].

Postavlja se vprašanje, ali imamo pri dejavnostih s področja tehnike in tehnologije v vrtcih opraviti s splošno ali z delno nadarjenostjo. Za splošno nadarjenost je značilno, da omogoča nadpovprečne rezultate v več ali v večini dejavnosti. "Psihološka teorija korelacije jo utemeljuje z visoko občo inteligentnostjo in z močjo njenega transfera na različna psihofizična področja. Veliko več je parcialne nadarjenosti oziroma talentiranosti na ožjem področju" [13].

Pristali bi lahko pri ugotovitvi, da se tudi na zgoraj omenjenem področju izkazuje delna nadarjenost z visoko stopnjo odvisnosti in prenosa na področje narave, družbe, gibanja, jezika, umetnosti in tudi matematike.

Zelo se tudi strinjam z naslednjo ugotovitvijo: "Kljub temu, da se parcialno nadarjeni učenci kasneje v življenju in delu običajno izkažejo zelo inovativno, je obča družbena klima in tudi šolska praksa, z večinoma verbalno naravnanostjo, bolj v prid univerzalni nadarjenosti kot učencem z delnimi, zlasti bolj praktičnimi sposobnostmi" [13].

Za uveljavitev dejavnosti na področju tehnike in tehnologije so pomembne te-le misli: "Če se omejuje šola na nadarjenosti, ki se morajo uveljaviti le pri klasičnih, večinoma verbalno klasičnih učnih predmetih, potem bo mnoge zgrešila. Nujno je, da razširi svoj učni repertoar tudi na druga spoznavna področja, ki niso zastopana v klasičnem učnem predmetniku, zlasti na raznovrstne praktične in tehnične zmožnosti učencev" [13].

Postavlja se vprašanje, kaj naj razumemo s pojmom tehniška nadarjenost?

"Tehniška nadarjenost – pri tej nadarjenosti niso mišljene ročne spretnosti, ampak izrazit smisel in sposobnost za tehniko, dojemanje prostora, zapažanje detajlov, podobnosti in razlik ter podobno" [5].

Predšolski otrok z igro in drugimi dejavnostmi spoznava svet okoli sebe, svet, v katerem se vsak dan srečuje tudi s tehniko in njenimi stvaritvami. Pri svojih dejavnostih opazuje, prepoznava in posnema tehnične stvaritve iz svojega okolja. Z mimiko in glasom posnema stroje in vozila, prepoznava jih po obliki, velikosti, značilnih zvokih in gibanju. V svojih igrah oblikuje in gradi, pa tudi razstavlja. Tako si pridobiva prva spoznanja, izkušnje in vpogled v svet tehnike in tehnologije. Praktično dejavnost pri tehniki in tehnologiji v vrtcih "moramo pojmovati kot kompleksno aktivnost, pri kateri so otroci in vzgojitelji postavljeni v aktiven in ustvarjalen odnos do preoblikovanja začetnega stanja materiala" [7].

Kot oblika opravilne dejavnosti je praktično delo povezano z intelektualno in s sprejemno dejavnostjo in le v tej zvezi ima svoj pomen v okviru ustvarjanega delovnega postopka, kjer se izkazuje "skupina kot tim" [2] in v takšni skupini gre za sodelovalno učenje, "kjer v manjših skupinah doživljajo socialne izkušnje in prek njih gradijo svoje znanje" [14].

Ustvarjalni delovni postopek razumemo kot model in za razvijanje ustvarjalnih tehniških sposobnosti in kot možnost in priložnost za spremljanje in razpoznavanje nadarjenih za tehniko in tehnologijo.

Faze tega postopka so mikroelementi oziroma koraki vzgojne dejavnosti, pri kateri gre za uporabo in povezanost specialno didaktičnih, pedagoško-psiholoških, tehniških, tehnoloških, ergonomskih, oblikovnih in organizacijskih vidikov.

Pri tehniki in tehnologiji spoznavajo materiale, orodja, naprave in obdelovalne tehnike, pri tem ugotavljajo, preizkušajo, sestavljajo, razstavljajo, gradijo, primerjajo in vrednotijo ter si pridobivajo spretnosti, delovne navade, izkušnje, ustvarjalne sposobnosti in si razvijajo delno nadarjenost za tehnične in tehnološke naloge, postopke, zakonitosti, probleme in rešitve.

Za vse te dejavnosti pa je treba priskrbeti posebno osnovno opremo, orodja in naprave, ki jih stabiliziramo, namestimo in uporabljamo v okviru kotička za tehniko in tehnologijo. Takšen kotiček smo razvili na oddelku za proizvodno-tehnično vzgojo na Pedagoški fakulteti Univerze v Mariboru in jo v obliki raziskovanja preizkusili v eksperimentalnem kabinetu za predšolsko tehniko.

OPREDELITEV PROBLEMA

Odkrivanje nadarjenosti in razpoznavanje vrste in stopnje otrokove nadarjenosti za tehniko in tehnologijo

Najprimernejše obdobje za razpoznavanje delne nadarjenosti je predšolsko obdobje in zgodnje otroštvo.

"Pri odkrivanju iščemo indikacije nadarjenosti, medtem ko pri identifikaciji določamo vrste in stopnje nadarjenosti. Cilji identifikacije so zelo pragmatični, nujno povezani z edukativnim programom. Oblike identifikacije so zato drugačne, kadar želimo razvijati splošne sposobnosti, posebne sposobnosti, spretnosti" [1].

Praktično usmerjeni identifikacijski in izobraževalni vodič

Praktično usmerjeni identifikacijski in izobraževalni vodič za delo na področju zgodnjega uvajanja v tehniko in tehnologijo naj se prične z diagnostičnim profilom značilnosti in potreb nadarjenih otrok za to področje.

V okviru ustvarjalnega delovnega postopka lahko evidentiramo in identificiramo značilnosti in potrebe nadarjenih otrok za ukvarjanje s tehnično in tehnološko vsebino. Ta postopek mora vsebovati problemske situacije, ki jih otrok v organizirani vzgojni dejavnosti odkriva in razrešuje. "Takšen način dela pa predpostavlja raznovrstno angažiranje otrok in vzgojitelja" [9].

Vzgojitelj mora vnaprej načrtovati ustvarjalno produktivnost in določiti možnosti za ustvaritev tehničnih predmetov (z obdelovanjem materialov ali s konstrukcijskimi zbirkami). Pri tem gre postopek spoznavanja, ki ga pojasnjujemo z dvema ločenima postopkoma prilagajanja in vključevanja. "To je proces ekvilibracije. Neravnotežje ali disekvilibrum vsebuje neprijetne notranje konflikte med nasprotujočimi si razlagami in predstavlja motivacijo za iskanje rešitve. Ta rešitev vzpostavi intelektualno ravnotežje in notranje zadovoljstvo" [6].

V okviru ustvarjalnega delovnega postopka se izkazujejo naslednje značilnosti, ki jih lahko pripišemo nadarjenemu otroku, in sicer:

- "zmožnost intenzivne in dalj časa trajajoče koncentracije na preučevalnem problemu,
- sposobnost miselne analize, sinteze, abstrakcije in generalizacije,
- hitro in uspešno odkrivanje vzročno posledičnih odnosov, zvez med predmeti in pojavi,
- osebna splošna poučenost,
- določenim, interesno problemskim nalogam se predajajo zagrizeno,
- prizadevajo si do popolnosti izpolniti naloge,
- pri delu so vztrajni, vestni in skrbni" [1].

Hitro napredovanje in kakovosten razvoj nadarjenosti za tehniko in tehnologijo dosežemo v okviru postopka, pri katerem v okviru načrtovanih vsebin gre za usklajenost pridobivanja, razvijanja in poglabljanja posebnih sposobnosti, intenzivnega interesa, za uporabo ustreznih strategij vzgojno-izobraževalnega dela za tehniko in tehnologijo [10], za nadrobne strategije za pridobitev novega znanja (poskus – napaka, prilagodljivost, preverjanje hipotez, sklepanje), metode izkustvenega učenja (simulacije, igre vlog, načrtovalne igre, interakcijske igre) in osebne stile vodenja in spodbujanja.

Ustvarjalni delovni postopek naj se praviloma odvija v delovnem kotičku, ki ponuja in zagotavlja optimalne možnosti za razvijanje ustvarjalnosti (s poudarkom na tehnični ustvarjalnosti).

Ustvarjalnost lahko proučujemo z različnih vidikov. Za naše področje jo najbolje določujeta naslednja kriterija:

- ustvarjalni dosežek in
- ustvarjalni postopek.

Na "polju tehnike in tehnologije" je nam ustrezna tista opredelitev, ki izhaja iz posameznikovega dosežka in ga skuša določiti kot nekaj, kar je novo. "Nov je vsak tisti dosežek, ki se je prvič pojavil v zgodovini ali pri posamezniku. Po tej

Preglednica 1. *Zasnovna razsežnost tehnike in tehnologije*

USMERJEVALNI IN CELOSTNI CILJI TEHNIKE IN TEHNOLOGIJE V PREDŠOLSKEM OBDOBJU	⟷	**USTVARJALNI DELOVNI POSTOPEK**

VIDIKI:

1. specialnodidaktični,
2. pedagoško – psihološki,
3. tehnični, tehnološki, fizikalni, ergonomski, oblikovni, organizacijski in ekonomski.

↓

ETAPNI CILJI:

Spoznavanje materialov in obdelovalnih tehnik	**Spoznavanje in uporaba orodja in naprav**	**Oblikovanje, razvijanje spretnosti in ustvarjalnih sposobnosti**

↓

Usmerjenost dejavnosti:

UGOTAVLJAJO	**PRESKUŠAJO**	**SESTAVLJAJO**
RAZSTAVLJAJO	**GRADIJO**	**PRIMERJAJO**
VREDNOTIJO		

↓

IZDELEK NI NAMEN, AMPAK LE SREDSTVO ZA OBLIKOVANJE USTVARJALNE IN CELOVITE OSEBNOSTI [9]

opredelitvi je ustvarjalen vsakdo, ki je rešil neki problem tako, da rešitve ni priklical iz spomina, ampak jo je za ta problem na novo izdelal" [3].

OMEJITEV PROBLEMA

Miselni vzorec

Zasnovna razsežnost tehnike in tehnologije (delovno tehnične vzgoje) v predšolskem obdobju

Z miselnim vzorcem bom nadrobno prikazal kategorije, sestavine in elemente, ki predstavljajo zasnovno razsežnost delovno-tehnične vzgoje na predšolski stopnji.

"V okviru ustvarjalnega delovnega postopka z opredeljenimi usmerjevalnimi oziroma globalnimi cilji je treba upoštevati **specialnodidaktične, pedagoško - psihološke, tehnične, tehnološke, ergonomske, oblikovne, organizacijske in ekonomske vidike.**

V tem procesu otroci spoznavajo materiale in delovne tehnike, uporabo orodja in naprav, konstruirajo in si razvijajo spretnosti in ustvarjalne sposobnosti" [11].

Nekaj ciljev, ki pomenijo zasnovo za razvoj nadarjenosti

Otrok naj:

- spozna namen in pomen tipičnih predmetov, pojavov in postopkov;
- primerja in razlikuje objekte, vozila, stroje, orodja in pripomočke, ki jih srečuje v svojem okolju;
- odkriva osnovne tehnične funkcije (npr. prevažanje, dviganje, poganjanje, vrtenje, kroženje itn.);
- spoznava različne materiale (npr. papir, karton, lepenko, različne vrste embalaže, les, usnje, furnir, žico, plastične materiale itn.);
- oblikuje iz različnih materialov in tako si razvija svoje tehnične ustvarjalne zmožnosti;
- pri oblikovanju s sestavljankami si pridobiva tehnično-fizikalna znanja in izkušnje ter si razvija sposobnost za ustvarjalnost in oblikovanje;
- pridobiva si zanimanje za tehnične izdelke, pojave in postopke;
- razvija in bogati si svoje govorne sposobnosti in občutek za pravilno uporabo slovenskih imen za tehnična sredstva, orodja, predmete, pojme, pojave in postopke [11].

Iz preglednice 2 je mogoče ugotoviti, da je poznavanje nekaterih možnosti za tehnične dejavnosti v obdobju intuitivne inteligence pomembno zato, da se lahko pripravi specialnodidaktično, pedagoško – psihološko in tehnično – tehnološko (predmetno – vsebinsko) raznolik in bogat program, v katerem si bodo nadarjeni otroci pridobivali, poglabljali in utrjevali nova teoretična in praktična znanja, si

Preglednica 2. *Nekatere možnosti za tehnične dejavnosti v obdobju intuitivne inteligence*

Obdobje	**Oblike dejavnosti**	**Metode dela**	**Pričakovani rezultati**
Faza intuitivne Inteligence (2 do 7 let) Razvoj predstavljanja je pomemben mejnik v razvoju sposobnosti spoznavanja in označuje prehod v novo - intuitivno oziroma predoperativno fazo mišljenja, ki traja do 7. leta. Pri 6 do 7 letih začenja otrok kazati vrsto sposobnosti, ki jih [12] imenuje konkretna opravila. Vsa ta opravila so sedaj že obrnljiva.	Nove funkcije igre, razvijanje sposobnosti za opazovanje narave, predmetov in ljudi. Pridobivanje tehničnih izkušenj, logično matematičnih predstav, spretnosti in delovnih navad [8].	Igralne dejavnosti. Pogovor, opazovanje, posnemanje, izdelovanje, oblikovanje s sestavljankami, sestavljanje in razstavljanje tehničnih predmetov, zbiranje tehničnih predmetov.	Razgovor, igranje vlog, risba, izdelek, zbirka (npr.: kamenje, plodovi, listje, ploskovne podobe tehničnih predmetov).

razvijali učni in metakognitivni stil ter osebnostne lastnosti.

Pri tem pa je treba upoštevati načela uspešnega učnega razvoja, to so:
- "aktivna raba pridobljenega znanja,
- samostojnost in samousmerjanje,
- doživljanje naraščajočega občutka samoizpolnitve" [1].

SKLEP

1. **V tem letu (2005) bomo te in še nove predpostavke raziskovalno preučevali na vzorcu otrok 1. razreda 9–letke in večjo skrb namenili usmerjenosti v smeri razpoznavanje in razvijanja splošne in delne nadarjenosti šolskega otroka.**
2. Zgoraj naštete (in druge) kategorije bomo vključili v strukturo modela, s prepričanjem, da sta področji tehnike in tehnologije izredno pomembni veji pri rasti in razvoju mlade ustvarjalne in nadarjene osebe. Pri tem pa se zavedamo, da otroci niso posode, ki jih je treba enkrat za vselej napolniti z znanjem, ampak bakle, ki jih je treba prižgati. To pomeni, da v pravem času potrebujejo kakovostne in pravilne spodbude v praktični, pisni, slikovni in grafični obliki. Prav ta spoznanja so vtkana v model kotička za tehniko in tehnologijo, ki pomeni optimalni temelj za odkrivanje in razvijanje delne nadarjenosti za tehnične predmete, dejavnosti, postopke, zakonitosti, probleme in rešitve.

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Darilo Fakulteti za strojništvo v Ljubljani
Donation to the Faculty of Mechanical Engineering in Ljubljana

Nemško združenje raziskovalcev (Deutsche Forschungsgemeinschaft - DFG) je podarilo knjižnici Fakultete za strojništvo več kot 120 knjig večinoma s področja Tehnične akustike, črpalk, kompresorjev in ventilatorjev. To je že tretje darilo, po dveh iz leta 1998 in 2000. Literatura je pretežno z nemškega govornega področja (65%) in v angleškem jeziku, ki je bila izdana v eni od založb nemškega jezikovnega področja. Knjižno gradivo je na voljo v knjižnici Fakultete za strojništvo v Ljubljani. Dostop do literature je prost vsem zainteresiranim. Ob tej priložnosti se v imenu prejemnika, knjižnice Fakultete za strojništvo in Laboratorija za energetske delovne stroje in tehnično akustiko, darovalcu (DFG) iskreno zahvaljujem.

Prof. dr. Mirko Čudina
Predstojnik laboratorija za energetske delovne stroje in tehnično akustiko

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Prof. dr. Mirko Čudina
Head of the Laboratory of Power Engineering and Technical Acoustics

Strojniški vestnik - Journal of Mechanical Engineering 51(2005)2, 119-124

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DOMAČE REVIJE

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2004, 4
Martinc, P., Gerbec, J.: Sodobni absorpcijski hladilni agregati (2. del)
Čretnik, J.: Obratovalni monitoring oziroma sistemi trajnih meritev in sistemi avtomatskega vrednotenja – 2. del
Barbir, F.: Razvoj gorilnih celic – stanje in izgledi

Informatica, Ljubljana
2004, 2
Ayaz Isazadeh: Software engineering: The Trend
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A.Karim El-Jabali: Development of diabetes mellitus mathematical models from patient's clinical database

Les, Ljubljana
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Šernek, M., Jošt, M.: Konstrukcijski kompozitni les

Livarski vestnik, Ljubljana
2004, 3
Wolf, G., Wolf, H.: Proces integriranega ekološkega nadzora v livarnah – strategija in ukrepi za zmanjšanje emisije ter recikliranje uporabljenih materialov

Materiali in tehnologije, Ljubljana
2004, 3-4
Lazić, L., Črnko, J.: Finite-element thermal analysis of a new cooler design
Vasevska, T.: Utrjevanje aluminija in zlitin pri vzdolžnem hladnem valjanju

2004, 5
Grozdanić, V.: A 3-D mathematical model of solidification of feeding distances of cast-steel bars
Založnik, M., Šarler, B., Gobin, D.: Simulation of macrosegregation in the DC casting of binary aluminium alloys
Vertnik, R., Perko, J., Šarler, B.: Solution of temperature field in DC cast aluminium alloy billet by the diffuse approximate method

2004, posebna številka
Farrar, J.C.M., Marshall, A.W.: Smartweld – an overview
Brown, S.GR., Fourlaris, G., Gater, A.JP., Ooi, S.W., Khoo, C.A.: Direct computer modelling methods for simulating precipitate behaviour in steels
Ule, B., Jenko, M., Šturm, R.: Accelerated small-punch creep testing

Obzornik za matematiko in fiziko, Ljubljana
2004, 4
Pisanski, T., Žitnik, A.: Incidenčne strukture, grafi in volitve v parlament EU
Strnad, J.: Novi Millikanov poskus

Vakuumist, Ljubljana
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Žitko, R., Muševič, I.: Tunelski mikroskop kot nanotehnološko in analitično orodje
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Varilna tehnika, Ljubljana
2004, 3
Rihar, G.: Zlepi v zvarih – karakterizacija ultrazvočnih indikacij
Markelj, F.: Matematično modeliranje toplotnih in strukturnih procesov pri TIG varjenju feritnega nerjavnega jekla

TUJE REVIJE

Aerospace America, Reston
2004, 9
Croft, J.: Engineering through the sound barrier

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CDA
Condizionamento dell'aria Riscaldamento Refrigerazione, Milano
2004, 8
Boccacci, C.: Riscaldamento autonomo e centralizzato
Campanati, F.: Telefonia mobile: Raffreddamento ad alte prestazioni

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Lazzarin, R., Nalini, L.: Controllo dell' umidificazione
Zattoni, R.: Travi fredde

Engineering, Tallinn
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Jobbágy, Á.: Using photoplethysmographic signal for incresing the accuracy of indirect blood pressure measurement
Lass, J., Meigas, K., Kattai, R., Karai, D. Kaik, J., Rossmann, M.: Optical and electrical methods for pulse wave transit time measurement and its correlation with arterial blood pressure
Talts, J. Estimation of the finger arterial pressure-volume relationship and blood pressure waveform from photoplethysmographic signals

2004, 10/3
Parve, T., Land, R.: Improvement of lock-in signal processing for applications in measurement of electrical bioimpedance

Journal of Theoretical and Applied Mechanics, Sofia
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Abadjiev, V., Abadjieva, E.: The conic convolute helicoids generation for active flanks of the spiroid pinion threads
Dong, F., Hsui, A.T., Riahi, D.N.: A stability analysis and some numerical computations for thermal convection with a variable buoyancy factor

2002, 3
Petrov, V., Georgiev, N., Kurths, J.: Determining phase space dimension of a dynamical system from analytic time series
Atten, P., Koulova-Nenova, D.: Time evolution of a viscous liquid jet by one-dimensional model
Savova, R.: Energy-flux vectors in thermoelasticity

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Kazakoff, Al. B.: Characteristics of mechanical filters incorporating viscoelastic materials (Part I)
Valeva, V., Ivanova, J., Mróz, Z.: Parametric analysis of the decay rate of end effects in heat conduction for multi-layered semi-infinite sandwich structures
Dzhupanov, V.A., Dzupanova, D.V.: Statement ruses of the problem on the dynamic stability of cantilevered pipe conveying liquid and lying on elastic foundation (Part I)
Kisliakov, D.: Coupled 3-D analysis of the axial and transversal earthquake-induced vibrations of a pressure pipeline on frictional support columns

2003, 1
Kazakoff, Al. B.: Characteristics of mechanical filters incorporating viscoelastic materials (Part II)
Polyanin, A.D., Zhurov. A.I.: Structure of the solutions of linear nonhomogeneous heat and mass transfer problems
Dzhupanov, V.A., Lilkova-Markova Sv.V.: Statement ruses of the problem on the dynamic stability of cantilevered pipe conveying liquid and lying on elastic foundation (Part II)
Haghi, A.K.: Experimental evaluation of the microwave drying of natural silk

2003, 2
Lilkova-Markova, S.V.: Influence of variable middle elastic support to the dynamic stability of a cantilevered fluid conveying pipe with two additional elastic supports

2003, 3
Abadjiev, V., Petrova, D.: On the synthesis and computer design of spiroid gears: A review of the Bulgarian approach
Nikolova, Y.D., Nikolov, N.D.: Application of an ultrafiltration module with screw mixers

2003, 4
Gospodinov, G.: Boundary element thermoelastic stress analysis with crack opening

2004, 1

Tsvetkov, Ch.: Spherical hydrostatic bearing without clearance

Baltov, A.: Materials sensitive to the type of the process: a review

2004, 2

Vladikov, I.: Free vibration of skew plates

Nedev, A., Nikolov, N., Altaparmakov, I.: Blank diameter analysis for different metals during deep drawing process

2004, 3

Lebon, G., Baltov, A., Krmela, M.: Extended thermodynamics of thermo-elasticity, visco-elasticity and visco-plasticity

Klimatizacija, grejanje, hlađenje, Beograd

2004, 3

Benišek, M., Batinić, B., Batinić, R.: Aerodinamičko oblikovanje razdelilnih T-račvi u cilju smanjena gubitaka jedinične energije u ventilacionim i klimatizacionim postrojenjima

Bulard, K.: Transkritički sistemi sa CO_2 – skorašnji napredak i novi izazovi

Naučimo – podsetimo se (priredio prof. Emin Kulić)

Magdeburger, Magdeburg

2004, 1

Deters, L.: Grundsätzliches zu Reibung und Verschleiss in der technischen Anwendung

Mechanical Engineering, Budapest

2004, 48/1

Csernák, G., Stépán, G.: Fractal dimension as measure of control time

Kocsis, L., Kiss, R.M., Kocsis, L. and Knoll, Z.: Biomechanical models and measuring techniques for ultrasound-based measuring system during gait

Pálfalvi, A., Mashimo, K.: Non-linear finite element analysis of a polymer-made machine part

Strojarstvo, Zagreb

2003, 4-6

Kostović, D.: Ocjena primjenljivosti nekih metoda nelinearne analize linijskih sustava na konzolu

Veljačić, Z., Domazet, Ž.: Utjecaj toplinske obradbe na dinamičku izdržljivost legiranih čelika

Živić, M., Virag, Z., Galović, A.: Analiza utjecaja prirodne konvekcije pri taljenju leda

Godec, Z.: Procjena nesigurnosti mjerenja duljive mjerilima za opću i posebnu namjenu

Osebne vesti - Personal Events

Doktorati, magisteriji, diplome - Doctor's, Master's and Diploma Degrees

DOKTORATI

Na Fakulteti za strojništvo Univerze v Mariboru je z uspehom zagovarjal svojo doktorsko disertacijo:

dne 7. januarja 2005: **mag. Ignacijo Biluš**, z naslovom: "Homogeni dvofazni prenosni modeli kavitacije v turbinskih strojih".

S tem je navedeni kandidat dosegel akademsko stopnjo doktorja znanosti.

MAGISTERIJI

Na Fakulteti za strojništvo Univerze v Ljubljani je z uspehom zagovarjal svoje magistrsko delo:

dne 27. januarja 2005: **Sašo Prijatelj**, z naslovom: "Analiza tokovnih pojavov v ventilu motorja z notranjim zgorevanjem".

S tem je navedeni kandidat dosegel akademsko stopnjo magistra znanosti.

DIPLOMIRALI SO

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv univerzitetni diplomirani inženir strojništva:

dne 31. januarja 2005: Denis BULJAN, Marko HROVAT, Matevž KOSTANJŠEK, Miha ZUPANČIČ.

Na Fakulteti za strojništvo Univerze v Mariboru je pridobil naziv univerzitetni diplomirani inženir strojništva:

dne 27. januarja 2005: Robert VASLE.

*

Na Fakulteti za strojništvo Univerze v Ljubljani so pridobili naziv diplomirani inženir strojništva:

dne 13. januarja 2005: David KRŠEVAN, Robert PRELEC, Breda ŠPRAJCAR, Jože TAVČAR, Marko TISOVIC;

dne 14. januarja 2005: Petar BOGDANIĆ, Urban BRADEŠKO, Rudi MALAVAŠIČ, Anton ORAŽEM, Gregor VRTAČNIK, Matija ZAJEC;

dne 17. januarja 2005: Sebastjan FIŠER, Mihej KOBLAR, Robert LUKEŽIČ, Zdenko TALJAT.

Na Fakulteti za strojništvo Univerze v Mariboru sta pridobila naziv diplomirani inženir strojništva:

dne 27. januarja 2005: Peter GOŠNJAK, Stanislav ŠTERN.

Navodila avtorjem - Instructions for Authors

Članki morajo vsebovati:
- naslov, povzetek, besedilo članka in podnaslove slik v slovenskem in angleškem jeziku,
- dvojezične preglednice in slike (diagrami, risbe ali fotografije),
- seznam literature in
- podatke o avtorjih.

Strojniški vestnik izhaja od leta 1992 v dveh jezikih, tj. v slovenščini in angleščini, zato je obvezen prevod v angleščino. Obe besedili morata biti strokovno in jezikovno med seboj usklajeni. Članki naj bodo kratki in naj obsegajo približno 8 strani. Izjemoma so strokovni članki, na željo avtorja, lahko tudi samo v slovenščini, vsebovati pa morajo angleški povzetek.

Za članke iz tujine (v primeru, da so vsi avtorji tujci) morajo prevod v slovenščino priskrbeti avtorji. Prevajanje lahko proti plačilu organizira uredništvo. Če je članek ocenjen kot znanstveni, je lahko objavljen tudi samo v angleščini s slovenskim povzetkom, ki ga pripravi uredništvo.

Papers submitted for publication should comprise:
- Title, Abstract, Main Body of Text and Figure Captions in Slovene and English,
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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.

For papers from abroad (in case that none of authors is Slovene) authors should provide Slovenian translation. Translation could be organised by editorial, but the authors have to pay for it. If the paper is reviewed as scientific, it can be published only in English language with Slovenian abstract, that is prepared by the editorial board.

VSEBINA ČLANKA

Članek naj bo napisan v naslednji obliki:
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- Povzetek, ki naj bo skrajšana oblika članka in naj ne presega 250 besed. Povzetek mora vsebovati osnove, jedro in cilje raziskave, uporabljeno metodologijo dela,povzetek rezulatov in osnovne sklepe.
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Besedilo članka naj bo pripravljeno v urejevalnilku Microsoft Word. Članek nam dostavite v elektronski obliki.

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Enačbe naj bodo v besedilu postavljene v ločene vrstice in na desnem robu označene s tekočo številko v okroglih oklepajih

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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).

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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.

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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] Tarng, Y.S., Y.S. Wang (1994) A new adaptive controller for constant turning force. *Int J Adv Manuf Technol* 9(1994) London, pp. 211-216.

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

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

Podatki o avtorjih

Članku priložite tudi podatke o avtorjih: imena, nazive, popolne poštne naslove in naslove elektronske pošte.

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Uredništvo Strojniškega vestnika si pridržuje pravico do odločanja o sprejemu članka za objavo, strokovno oceno recenzentov in morebitnem predlogu za krajšanje ali izpopolnitev ter terminološke in jezikovne korekture.

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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.).

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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.

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References should be collected at the end of the paper in the following styles for journals, proceedings and books, respectively:

[1] Tarng, Y.S., Y.S. Wang (1994) A new adaptive controller for constant turning force. *Int J Adv Manuf Technol* 9(1994) London, pp. 211-216.

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

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

Author information

The information about the authors should be enclosed with the paper: names, complete postal and e-mail addresses.

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