© Strojniški vestnik 46(2000)6,330-341
ISSN 0039-2480
UDK 532.5:530.16
Izvirni znanstveni članek (1.01)
© Journal of Mechanical Engineering 46(2000)6,330-341
ISSN 0039-2480
UDC 532.5:530.16
Original scientific paper (1.01)

Analiza kinematike toka za utripajočim profilom spremenljive geometrijske oblike z uporabo računalniške vizualizacije

Analysis of the Flow Kinematics Behind a Pulsating Adaptive Airfoil Using Computer-Aided Visualisation

Brane Širok - Erik Potočar - Matej Novak

V polnorazvitem zračnem toku podzvočnega vetrovnika je bila z uporabo računalniške vizualizacije ter metode digitalnega procesiranja serije posnetkov izvedena analiza kinematike toka vzdolž deformljivega profila (NACA 4416) spremenljive oblike pri hitrostnih razmerah Re =1000.

V prvem delu raziskave je bila izvedena študija preoblikovanja strukture toka ob profilu pri ustaljenih spremembah oblike profila, v drugem delu pa smo se osredotočili na opazovanje sprememb struktur toka pri periodično utripajoči obliki profila. Obliko poprej geometrično umerjenega profila smo spreminjali s periodičnimi tlačnimi utripi zraka, uvajanega v notranjost profila. Osnovna frekvenca vrtinčne sledi za profilom se pod vplivom utripov oblike profila opazno spremeni. Na zaporednih posnetkih tokovnih struktur vrtinčne sledi za utripajočim profilom, posnetih z video kamero, je bila izvedena količinska analiza časovnih vrst s simultano digitalizacijo nivojev sivine v izbranih področjih (oknih) sekvenc posnetkov. Za tokovno polje vzdolž profila so značilne različne vrednosti spektralnih gostot nivojev sivine in pripadajočih standardnih odmikov. Z metodo računalniške vizualizacije so bile raziskane strukturne tokovne spremembe v vrtinčni sledi v odvisnosti od frekvence vzbujanja geometrijske oblike profila. Rezultati kažejo, da periodične spremembe oblike profila vplivajo na tokovno strukturo vzdolž profila oziroma na njeno frekvenco in amplitudo ter na položaj točke odlepljanja na opazovanem profilu. Pojavlja se možnost prilagodljivega spreminjanja tokovne kinematike vzdolž profila.

(Ključne besede: kinematika toka, analize tokov, strukture tokov, vizualizacija računalniška)

In the fully developed airflow of a non-return subsonic wind tunnel using flow visualization and a digital image-processing method, an experimental study of the flow kinematics along and behind a hollow NACA 4416 adaptive airfoil at Reynolds number Re = 1000 was performed.

The study was performed in two parts: first the observation of flow transformation at temporal stationary changes of the airfoil shape was performed, and the second part of the analysis focused on the transformation of the flow at periodic time-pulsating airfoil deformations. The shape of a previously geometrically calibrated airfoil was modified with periodic pressure changes inside the airfoil. The basic frequency of the vortex street behind the airfoil is changed under the influence of the pulsating frequency of the airfoil. A CCD camera was used to capture smoke visualization images of the turbulent airflow wake, illuminated by the light sheet. A quantitative analysis was made on time series, obtained by simultaneous digitization of the grey level in several small areas (windows) of the overall image. The flow field along and behind the airfoil exhibited various frequency spectra and standard deviations. With the help of the computer-aided visualization method, structural flow changes were investigated, i.e. variations of the wake frequency response and respective amplitudes depending on the airfoil pulsation frequency. Results show that periodic changes of the airfoil shape have an affect on the flow structure along and behind the airfoil, i.e. the amplitude and frequency of the wake, and the location of a separation point. There may exist possibilities for adaptive flow kinematics variation along and behind the airfoil.

(Keywords: flow kinematics, flow analysis, flow structure, computer aided visualization)

0 UVOD

Zaradi dolgoletnih prizadevanj za vse boljšimi aerodinamičnimi lastnostmi profilov in zato večjim izkoristkom strojev so ustaljene oblike profilov

0 INTRODUCTION

As a result of the continuous drive for better aerodynamic profile quality, and as a consequence, more efficient machinery, the imdandanes v sklepni fazi razvoja. V zadnjih tridesetih letih je prišlo do napredka na področju raziskav pretočnih razmer vzdolž profilov, ne samo zaradi uvedbe novih materialov in vključevanja novih eksperimentalnih metod analize toka, ampak tudi spričo hitrega razvoja računalniško podprtih numeričnih modelov toka ob profilih. Pretežni del študij je bil usmerjen v analizo aerohidrodinamičnih karakteristik časovno nespremenljivih oblik profilov v polno razvitem turbulentnem toku. Iz literature je znano, da so se analize tokovnih karakteristik vzdolž nihajočih profilov osredotočale bodisi na interakcijo vrtinec/profil [1] ali na razvoj samega vrtinca pri sunkovito pospešenem krilu [2]. Omenjeni problem je bil raziskan tako numerično kakor tudi eksperimentalno [3]. Vendar pa rezultati raziskav spremembe geometrijske oblike profila, o katerih poroča razpoložljiva literatura, niso zelo obsežni. Tako so v preteklosti na profilih izvajali statično preoblikovanje obrisa profila [4] ter pri nekaterih tipih letal uporabljali kombinacijo dveh različnih geometrijskih oblik profila [5].

Če spreminjamo obliko profila, se tokovna sestava za njim značilno spremeni. S časovnimi spremembami oblike profila krila se lahko tako ustvarja povsem različna tokovna sestava, ki jo je, kakor kaže tudi pričujoča študija, mogoče nadzirati z različnimi načini preoblikovanja profila. Na tokovno sestavo za profilom je mogoče vplivati bodisi s spremembami oblike celotnega profila ali le posameznih delov profila.

1 NARAVA TOKA OKOLI PROFILA V STVARNI TEKOČINI

V stvarni tekočini prihaja do pojava cirkulacije toka zaradi viskoznih sil. Pri študiji tokovnega polja okoli profila je najprej treba preučiti razmere, v katerih nastajajo vrtinci v opazovanem toku tekočine. Vrtinci nastajajo na obrisih telesa v toku tekočine celo pri telesih brez ostrih robov zaradi naraščanja tlaka v smeri toka in velikih hitrostnih gradientov ob površinah trdnih teles. Pri obtekajočih telesih, kakor je profil krila v tokovnem polju, nastajajo vrtinci v področju prehoda mejne plasti v polno razviti tok tekočine. Razvoj vrtincev je tako odvisen od časovnih in krajevnih sprememb hitrostnega polja ob profilu, od širine vrtinčne sledi in hrapavosti površine.

Na stični površini neoviranega in vrtinčnega toka ob telesu profila deluje trenje. Pri tem nastale hidrodinamične sile težijo k trganju vrtincev in njihovemu prenosu vzdolž toka. V trenutku, ko se gradient tlaka, ki zadržuje opazovani vrtinec v vrtinčni coni zmanjša, se vrtinec odtrga iz mejne plasti in potuje s tokom v področje vrtinčnega toka na izstopnem robu profila. Tako imenovani začetni vrtinec na mestu izstopnega roba profila se razvija navidez periodično. Energijo za svoj obstoj, rast in dinamiko črpa iz razvitih vrtincev vzdolž toka ob profilu. Glede na vpadni kot α neoviranega toka na profil se lega in oblika

provement of the airfoil form has been taken almost to the limit. Over the past thirty years, progress has been made not only in the discovery of new materials, but also in connection with use of computer techniques and other relevant methods. The analyses of flow characteristics around the airfoil have focused on the flow structure over an oscillating airfoil during vortex/airfoil interaction [1]. The study of vortex evolution on an impulsively started airfoil has also been discussed [2]. This problem has been treated in a mathematical and experimental way [3], however, the results of research into airfoil-shape modification are, according to our knowledge, not very extensive. Investigations report on the static shape control of an adaptive airfoil [4], and the use of two different airfoils for a plane glider [5].

When the airfoil profile is modified, the flow structure behind the airfoil is completely changed. With the dynamic airfoil profile changes, it can create a completely different flow structure behind the airfoil, a structure which we can control with different methods of dynamic modification to the airfoil shape. It is possible to alter the shape of the entire airfoil, or only the shape of a certain airfoil section.

1 DEVELOPMENT OF CIRCULATION AROUND THE AIRFOIL IN A REAL FLUID

In a real fluid the circulation develops because of the viscous forces. When considering a flow field around an airfoil, it is primarily the conditions under which the vortices are formed in the actual fluid flow that have to be studied. Vortices are formed on the edges of bodies in the fluid flow. Even for bodies that are round and do not have sharp edges, the vortices appear due to a pressure rise in the flow direction and because of large velocity gradients along the profile structure. At bluff bodies, e.g. at the profile in the flow field, vortices are generated in the regions of transfer of the boundary layer into the fully developed fluid flow. The development of vortices depends on time and space changes of the velocity field along the profile, and on the width of the boundary layer and roughness of the surface.

On the contact surface of free and vortex flows along the profile structure friction occurs. The hydrodynamic forces generate vortex separation and vortex transport along the flow. When the pressure gradient, which holds the observed vortex in the vortex zone, decreases, the vortex is separated from the boundary layer and transported by the flow into the vortex street. The so-called initial vortex that appears near the trailing edge develops quasi-periodically. The energy for its existence, growth, and dynamics is generated from vortices along the profile. According to the value of the incidence angle α of the free flow začetnega vrtinca spreminjata. Zaradi tega se tudi zajemanje razvitih vrtincev vzdolž telesa profila spremeni in vpliva na asimetrično naravo toka ob profilu. Trganje začetnega vrtinca na izstopnem robu profila in gibanje tega vzdolž toka v vrtinčni sledi za profilom je podobno kakor pri vrtincih na mikro skali, odvisno od razmerij hidrodinamičnih sil na vrtincu. Nastanek tako imenovanih svobodnih vrtincev ob telesu in na izstopnem robu ima za posledico raztros kinetične energije in pripelje do uporov v tokovnem polju. Izhajajoč iz tega lahko pričakujemo, da oblika vrtinčnega polja okoli profila in v vrtinčni sledi neposredno vpliva na hidrodinamične karakteristike profila, vključno z raztrosnimi karakteristikami.

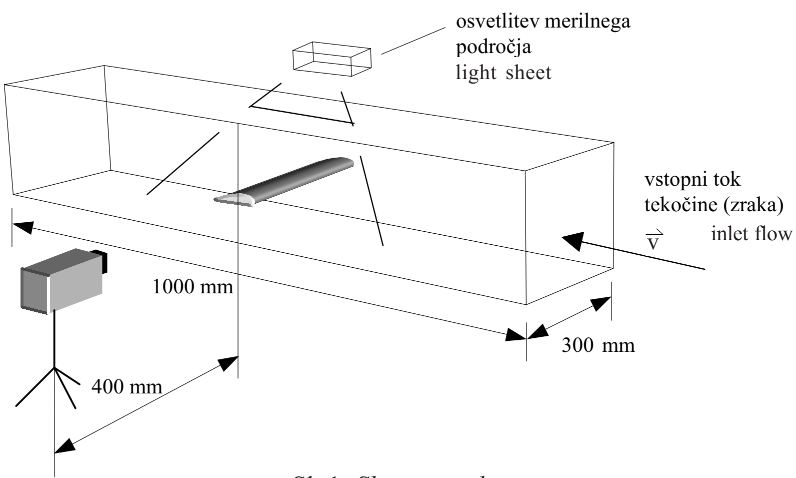
2 PRESKUS

Preskusi so bili izvedeni v podzvočnem vetrovniku odprtega tipa. Hitrost toka v vetrovniku se spreminja s spreminjanjem frekvence vrtenja ventilatorja z uporabo frekvenčnega regulatorja, ki omogoča spreminjanje frekvence od 0 do 50 Hz v korakih po 0,01 Hz. Preskusni del iz poliakrilnega stekla je kvadratnega prereza s stranico 300 mm in dolžino 1000 mm. Koeficient zožitve vetrovnika znaša 16,5 : 1. Nivo turbulentnosti vetrovnika pri preizkusnih hitrostnih razmerah znaša 2,8%. Profil (NACA 4415) dolžine vzdolž toka 89 mm in višine 14 mm je bil pritrjen v preskusni del vetrovnika po njegovi celotni širini. Profil je izdelan iz vzmetne pločevine CK 60, ki je bila ustrezno termično obdelana. Na konceh profila je bil le ta zaprt s silikonskima čepoma. S tem je omogočena ob napihovanju profila njegova enakomerna sprememba oblike po celotni širini ob ustrezni tesnosti. Profil je bil, tako kakor tudi zadnja stena vetrovnika, prebarvan s črno barvo, kar zagotavlja kar največje zmanjšanje odboja svetlobe pri vizualizaciji tokovnega polja ob profilu. Natočni kot zraka na profil med preskusi je znašal 12^0.

onto the profile, the position and shape of the initial vortex changes. Consequently, the capturing of oncoming vortices along the profile structure is changed, and this influences the non-symmetric flow nature along the profile. The separation of the initial vortex that appears on the profile trailing edge and its movement along the flow in the vortex street is similar to phenomena on a micro scale, and depends on the relationship between the hydrodynamic vortex forces. Generation of the so-called “free vortices” along the profile structure and at the trailing edge causes the dissipation of kinetic energy and consequently generates the resistance in the flow field. Therefore it can be expected that the vortex field shape around the profile and in the vortex street directly influences the hydrodynamic and dissipation characteristics of the profile.

2 EXPERIMENTAL FACILITY

The tests were performed in a non-return subsonic wind tunnel. The wind tunnel fan speed is controlled by a frequency regulator with a range from 0 to 50 Hz in steps of 0.01 Hz. The test section has a square cross-section, made of plexi-glass, with a width of 300 mm and a length of 1000 mm. The wind-tunnel contraction ratio is 16.5:1. The turbulence level is 2.8%. The NACA 4415 airfoil was mounted so that it spanned the tunnel working section. The airfoil has an 89 mm stream-wise length and a thickness of 14 mm. It was mounted so that it spanned the tunnel working section. It was made from spring-tin plate CK 60, which had undergone a sufficient thermal treatment. The tips were filled with silicone, which enabled the airfoil to change its form symmetrically throughout its length. The airfoil was painted black, as was the back tunnel wall, to reduce the reflection of light during visualisation of the flow field around the profile. The angle of attack of the airfoil during the experiments in the wind tunnel was 12^0.



Sl. 1. *Shema preskusa*
Fig. 1. *The experimental configuration*

Vrtinčna sled vzdolž profila je bila vizualizirana z uporabo polutanta - dima parafinskega olja, ki smo ga uvajali v vetrovnik na oddaljenosti 20 mm pred profilom skozi cevko notranjega premera 1,5 mm.

Vrtinčna sled je bila osvetljevana od zgoraj s halogensko lučjo z močjo 1000 W. Širina svetlobnega snopa je znašala približno 2 mm. Zaporedni posnetki vrtinčne sledi so bili posneti z video kamero s frekvenco 25 posnetkov v sekundi, ki je bila usmerjena pravokotno na smer toka v osi profila (sl. 1). Resolucija vsakega posnetka je bila 736 x 560 točk, pri čemer je bila velikost točke pri danem eksperimentu 0,4 mm. Nivo sivine v času in prostoru ustvarja skalarne vzorce, ki jih z uporabo računalniške vizualizacije lahko opazujemo. Z zaporedno digitalizacijo gradientov sivine v opazovanih območjih (oknih) dobimo simultane skalarne časovne vrste.

Za določitev količinskih lastnosti tokovnih vzorcev za opazovanim profilom vpeljemo celoštevilčno spremenljivko $A(k, t)$ [6]:

In order to visualise the vortex street behind the airfoil, paraffin oil smoke was injected into the wind tunnel in front of the airfoil through a specially modified hose with a 1.5 mm internal diameter. The hose was 20 mm away from the airfoil and directed onto the half thickness of the airfoil.

The visualised streak lines were illuminated from above by continuous lighting supplied by a 1000 W halogen lamp. The light-sheet was approximately 2 mm wide. The successive images of the visualised vortex street were captured by a CCD camera, aimed along the spanwise axis of the airfoil, with 25 frames/s (Fig. 1). The resolution of each of the frames was 736 x 560 pixels. The spatial resolution of a pixel is about 0.4 mm for this experiment. The grey level in time and space generates scalar patterns, which can be observed with the help of a computer-aided visualization. Quantitative analysis was made on a time series, obtained by simultaneous digitization of the grey level in several small areas (windows) of the overall image.

For the assessment of the quantitative behaviour of the patterns of the flow behind the airfoil, an integer-type scalar's variable $A(k, t)$ was introduced [6]:

$$A(k,t) = \sum_{l=1}^{L}\sum_{m=1}^{M} E(l,m) \qquad E(l,m) = \{0,1,2,3.....255\} \tag{1}$$

S skalarno spremenljivko $A(k, t)$ je podana prostorsko povprečena intenzivnost sivine v opazovanem oknu k v času t. Opisani model povezuje intenzivnost svetlobe z navzočnostjo delca v opazovanem oknu. Časovni interval je definiran s frekvenco zajema slik na kameri in s številom zaporednih slik poljubno izbranega časovnega intervala.

Intenzivnost svetlobe $E(l, m)$, zaznavamo v 256 nivojih sivine, od popolnoma črne pri 0 do popolnoma bele pri 255. Časovne vrste lokalno krajevno povprečenega nivoja sivine so bile dobljene za vsakega od opazovanih oken.

Standardni eksperimentalni odmik lokalnega nivoja intenzivnosti sivine v posameznem oknu je bil izračunan po naslednji enačbi:

$A(k, t)$ is the space averaged light intensity (grey level) of an observed window k at time t, and corresponds to the instantaneous smoke concentration in the observed window. This is obtained by summing each individual pixel brightness $E(l, m)$ over the entire window. The time interval of the observation is defined by the camera speed and by the number of sequentially taken pictures in an optional time interval.

The light intensity can vary from complete blackness with a zero value, to complete whiteness with a value of 255. The time series of local space-averaged grey intensity level at our disposal were obtained for each observed window.

The standard deviation of the local grey intensity level in the window is defined as:

$$\sigma = \sqrt{\frac{1}{n}\sum_{k=1}^{n}\left\langle \left(A(k,t) - \langle A(k,t)\rangle \right)^2 \right\rangle} \tag{2}$$

kjer $\langle A(k,t)\rangle$ pomeni časovno povprečeno vrednost krajevno povprečene intenzivnost sivine $A(k, t)$:

where $\langle A(k,t)\rangle$ is the time-averaged value of the space averaged light intensity $A(k, t)$:

$$\langle A(k,t)\rangle = \frac{\sum_{k=1}^{n} A(k,t)}{n} \tag{3}$$

kjer je $A(k, t)$ trenutna prostorsko povprečena intenzivnost sivine.

Za podrobno analizo fluktuacij intenzivnosti sivine $A(k, t)$ uporabimo 1024 zaporednih digitaliziranih posnetkov za vsakega od analiziranih oken. Spektre moči izračunamo iz osnovnih časovnih vrst s standardno Fourierjevo transformacijo osnovnih časovnih vrst:

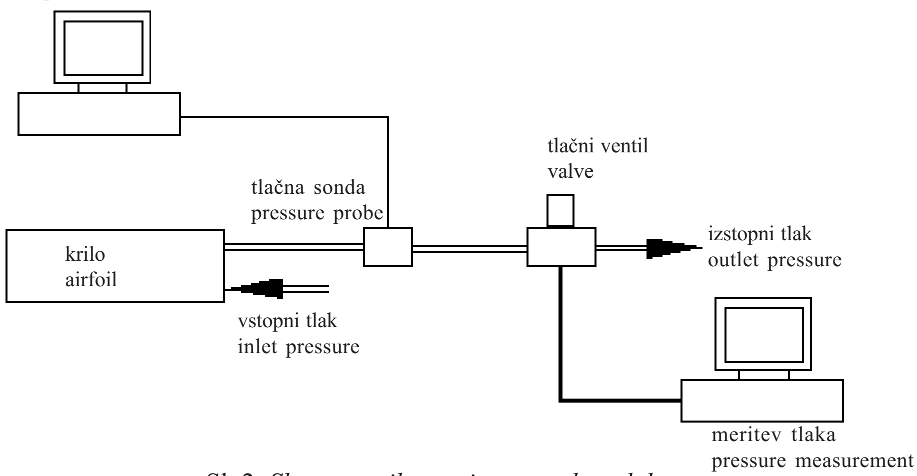
and $A(k, t)$ is the instantaneous space-averaged light intensity.

For detailed studies of the fluctuations in the light intensity $A(k, t)$, 1024 successive frames were digitised for each window analysed. The power spectra of the time series may be obtained using the Fourier transform:

$$A(k,\omega)=\frac{1}{2\pi}\sum_{t}A(k,t)e^{-i\omega t} \qquad (4).$$

Obliko profila, ki je bila poprej geometrično umerjena, smo spreminjali s periodičnimi tlačnimi utripi z zrakom, ki smo ga uvajali v notranjost profila. Meritve fluktuacij toka so bile izvedene v dveh sklopih. Najprej pri različnih tlakih v notranjosti profila, ki so imeli za posledico različno časovno ustaljeno obliko profila in nato pri periodičnih časovnih utripih geometrijske oblike profila. Tlak v profilu smo nadzirali s tlačnim ventilom, povezanim prek kartice z računalnikom. Merilna veriga z računalniškim nadzorom vzbujanja (sl. 2) je bila sestavljena iz utripnega generatorja, merilnika sunkov in izpisa časovnega stanja krmilnega ventila. Na drugem računalniku pa je bilo mogoče prebrati tlačne spremembe na opazovanem profilu s tlačnim pretvornikom KISTLER Kristal tip 4285A5 v frekvenčnem področju do 1 kHz.

The airfoil shape was modified with periodic pressure changes inside the airfoil. For the geometrically calibrated airfoil, measurements of airflow kinematics were performed at stationary integral parameters, and at periodic time-pulsating airfoil deformations. The pressure in the airfoil was controlled with the aid of a pressure valve. The valve was controlled by a computer with a Visual Designer data-acquisition board. The measurement chain for pressure-valve control in the Visual Designer program is composed of pulse generator, impulse meter, and of a pulsation function display. Pressure changes were displayed on a second computer, measured by a KISTLER type 4285A5 pressure probe with a frequency range up to 1 kHz. A schematic of the pressure-control measuring set-up is shown in Fig. 2.



Sl. 2. *Shema merilne verige za nadzor tlaka*
Fig. 2. *Schematic of the pressure control measuring set-up*

Tlačna sprememba v profilu spremeni obliko profila v profil z bistveno drugačnimi aerodinamičnimi karakteristikami. Nenapihnjeni profil je imel obliko profila NACA 4416. Ko se je tlak znotraj profila zvišal na največjo vrednost 2,4 bar, se je višina profila povečala za 4,19 mm, tako da se je oblika tlačno deformiranega profila približala obliki profila tipa NACA 4421.

A pressure change in the airfoil modifies its shape to an airfoil with completely different aerodynamic characteristics. The non-deformed airfoil has the shape of the NACA 4416 airfoil. When the pressure inside the airfoil was increased up to a maximum of 2.4 bar, and as a result the airfoil thickness increased by 4.19 mm, the shape was modified to that of the airfoil NACA 4421.

3 PREDSTAVITEV REZULTATOV

3.1 Kinematika vrtinčne sledi pri ustaljenih parametrih

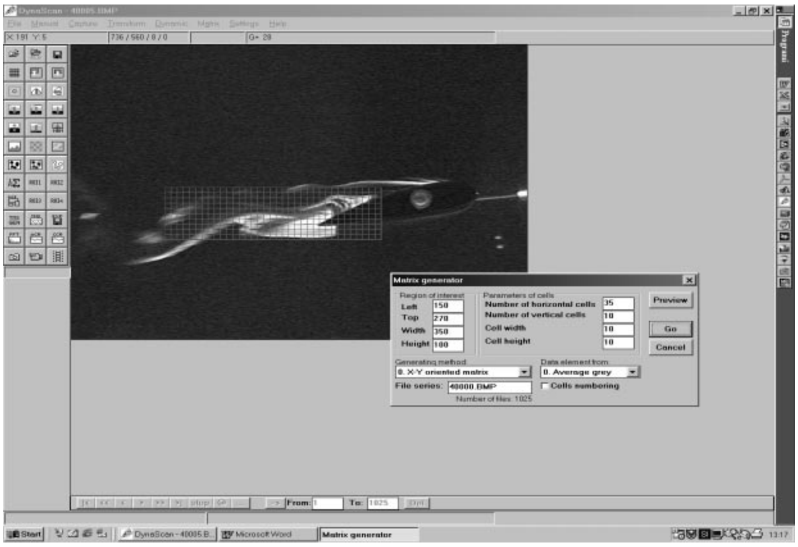
V vetrovniku je bila najprej izvedena analiza kinematike vrtinčne sledi pri ustaljenih integralnih parametrih oblike profila za nedeformiranim in deformiranim profilom. Območje opazovanja, prikazano

3 RESULTS AND DISCUSSION

3.1 Vortex street kinematics at stationary integral parameters

The first analysis in the wind tunnel was of the vortex street kinematics at stationary integral parameters behind a non-deformed and deformed airfoil. The observation area, shown in na sliki 3, je bilo izbrano tako, da omogoča analizo toka okoli zadnjega roba profila ter vrtinčne sledi za profilom. Predpostavljamo namreč, da so spremembe dinamike toka v omenjenem območju najintenzivnejše. Velikost opazovanega območja je znašala 350 x 100 točk (1 točka znaša 0,4 mm za obravnavani preskus). Opazovano območje je bilo razdeljeno v 350 oken velikosti 10 x 10 točk. Reynoldsovo število za osnovni profil je znašalo v času trajanja eksperimenta Re = 1016. Na slikah 4 in 5 sta predstavljeni topološki sestavi standardnega eksperimentalnega odmika lokalnega nivoja intenzivnosti sivine $\sigma(x,y)$ v tokovnem polju za osnovnim in deformiranim profilom.

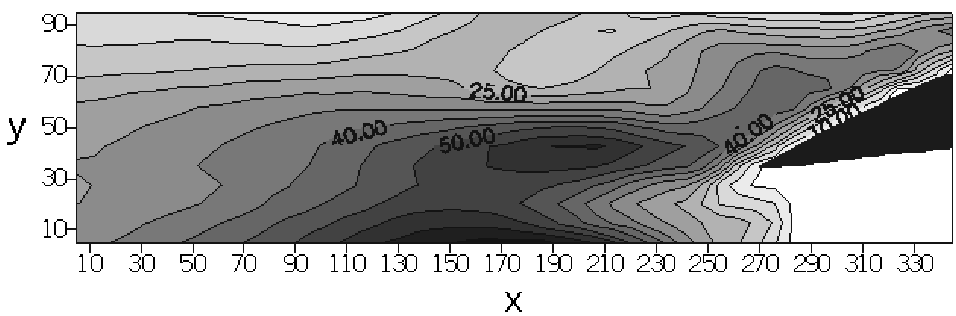
Fig. 3, was chosen in a manner that enables observation of the rear end of the airfoil and of the vortex street. We assumed that the changes are the most significant in the chosen area. The size of the observation area was 350 x 100 pixels (1 pixel was about 0.4 mm), and was divided into 350 windows, 10 x 10 pixels in size. The Reynolds number, based on a profile during the experiments, was Re = 1016. In Figs. 4 and 5 the topological standard deviation maps of the average grey intensity $\sigma(x,y)$ in the flow field behind a non-deformed and deformed airfoil are presented.



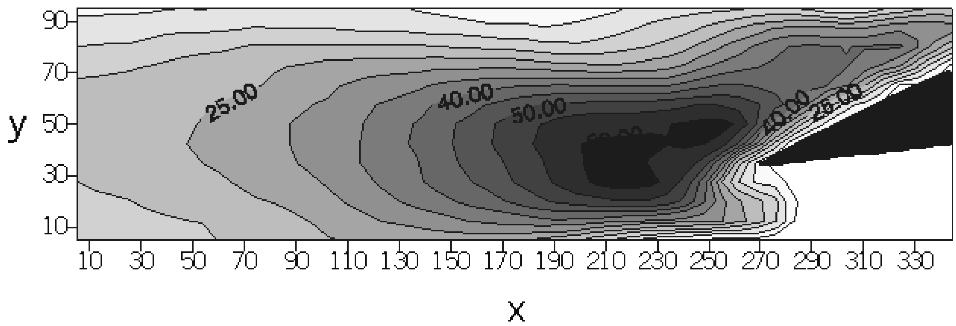
Sl. 3. *Opazovano območje za profilom*
Fig. 3. *Location of the observation area behind the airfoil*

V diagramu standardnega eksperimentalnega odmika nivoja sivine nedeformiranega - osnovnega profila NACA 4416 (sl. 4) lahko opazimo, da je vrednost standardnega eksperimentalnega odmika večja (nad 50) v območju, kjer se polutant dalj časa zadržuje, kar kaže na pojav vrtinčenja. To območje je po abscisni osi pri vrednosti x = 200 točk in po ordinatni okoli y = 40 točk in je podolgovate oblike. Na zgornjem delu zadnjega roba profila se vidi področje z višjo vrednostjo spremenljivke σ (nad 25), kar je povezano s povratnim tokom ob lopatici.

In the diagram of the standard deviation of the average grey intensity of a non-deformed basic airfoil NACA 4416 (Fig. 4), one can see that the value of the standard deviation is larger (over 50) in the region where smoke particles persist and denote whirling. The maximum value of the area is around the value of 200 on the x-axis, and around 40 on the y-axis, and has an oblong shape. On the upper part of the airfoil edge, where the flow is recurrent, an area with a larger standard deviation value σ (over 25) can be sensed.



Sl. 4. *Standardni odmik nivoja sivine za nenapihnjeno lopatico (NACA 4416)*
Fig. 4. *Standard deviation of the average grey intensity of a non-deformed airfoil (NACA 4416)*



Sl. 5. *Standardni odmik nivoja sivine za napihnjeno lopatico (NACA 4421)*
Fig. 5. *Standard deviation of the average grey intensity of a deformed (blown) airfoil (NACA 4421)*

V diagramu standardnega odmika povprečnega nivoja sivine deformiranega profila NACA 4421 (sl. 5), lahko opazimo, da se je območje za lopatico, ki predstavlja začetni vrtinec, pomaknilo bliže zadnjemu robu profila (x = 220 točk, y = 45 točk), kar je pri debelejšem profilu pričakovano. Pri tem se je nivo standardnega odmika povečal in razširil proti zgornjemu delu krila (povratni tok ob krilu se pomika nazaj proti toku). Pri deformiranem profilu se tokovnice slabše prilagajajo obrisu profila. Iz primerjave obeh primerov vidimo, da s spremembo oblike profila dobimo različne tokovne sestave ob krilu in v vrtinčni sledi.

3.2 Kinematika vrtinčne sledi pri periodičnem utripnem spreminjanju geometrijske oblike profila

V drugem delu je bila izvedena analiza kinematike vrtinčne sledi za profilom, kateremu smo z uporabo tlačnih utripov periodično spreminjali obliko. Na sliki 6 je predstavljen del sekvence zaporednih posnetkov vrtinčne sledi profila pri Re = 1016.

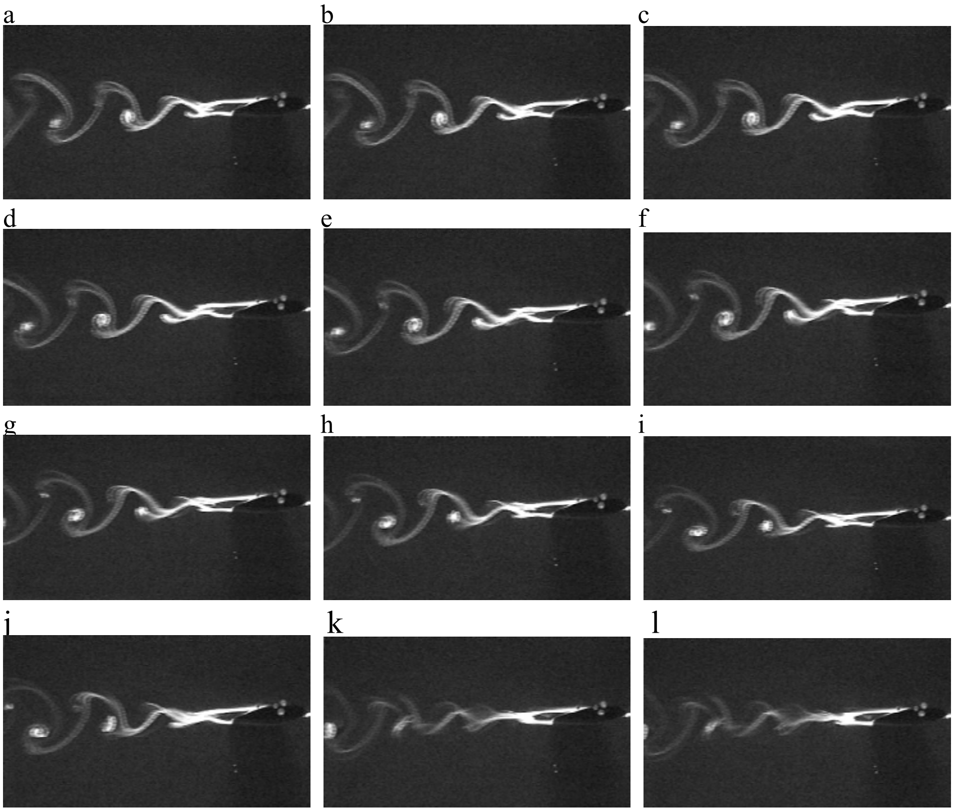
Iz zaporednih posnetkov Karmanove vrtinčne sledi, dobljene pri frekvenci tlačnih utripov 0,25 Hz lahko opazimo, da se na zgornji površini profila razmeroma hitro odtrga mejna plast in ustvari sled, ki se neposredno za profilom združi s sledjo s spodnje površine profila. Tu nato prihaja do nastanka polno razvite vrtinčne sledi za profilom. Spodnja in zgornja slednica se izmenoma združujeta ena v drugo in delata Karmanovo vrtinčno sled. V njej se oblikujejo v enakem časovnem zaporedju, manjši vrtinci, ki se pomikajo s tokom. Ti vrtinci se pojavljajo v enakem zaporedju izmenoma na zgornji in spodnji strani. Razdalja med njimi se vzdolž toka povečuje. Pri slikah k in l (sl. 6) lahko vidimo značilen pojav nenadne porušitve v vrtinčni sledi, ki je posledica tlačnega vzbujanja profila in nelinearne interakcije med vrtinci. Pri tem prihaja do naključne aperiodične vzpostavitve popolnoma nove navidez periodične vrtinčne sledi. Za količinsko analizo toka pri utripajočem profilu je bilo v vrtinčno sled nameščenih 12 oken opazovanja, katerih položaj je prikazan na sliki 7. V nadaljevanju bodo predstavljeni rezultati analize časovnih vrst nivoja sivine v 11. oknu.

In the diagram of the standard deviation of the average grey intensity of a deformed, i.e. blown airfoil NACA 4421 (Fig. 5), one can observe that the area of the maximum vorticity behind the airfoil is moved closer to the trailing edge (with the centre at x = 220, y = 45) as was expected for the thicker airfoil. Moreover, the magnitude of the area has increased and moved towards the upper airfoil surface, i.e. the recirculated flow above the airfoil has lifted. The qualitative inspection of both non-deformed and deformed airfoil image sequences showed that the streamlines above the upper surface of the airfoil for the deformed airfoil are straighter. Therefore, the difference between both respective airfoil shapes can be seen and as a consequence, they have various influences on the vortex street.

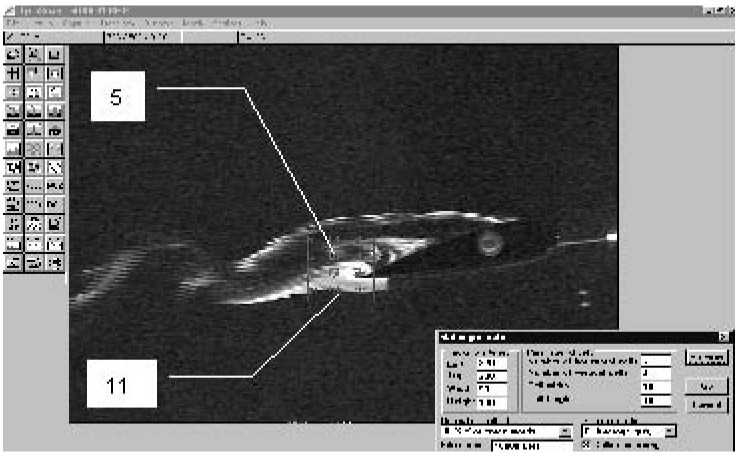
3.2 Vortex street kinematics at periodic time-pulsating airfoil deformations

The next stage was to analyse the vortex street kinematics for periodic time-pulsating airfoil deformations. In Fig. 6 a part of the successive image sequence is shown for the airfoil vortex street obtained at Re = 1016.

In the successive images the Karman vortex street can be observed, obtained at an airfoil pulsation frequency of 0.25 Hz. The flow is separated at the upper airfoil surface and generates a streamline which is behind the airfoil amalgamated with the lower streamline. The connected streamline oscillates, and vortices are shed alternately from each side of the airfoil and persist for some distance downstream, forming a double row, typical of a Karman vortex street. In images k and l of Fig. 6 a sudden brake of the vortex street shape occurs, caused by the airfoil pulsation. Consequently, a new type of the vortex street is formed. For the quantitative analysis of the flow behind the pulsating airflow the 12 observation windows were located in the vortex street behind the airfoil (Fig. 7). In continuation the results of the grey level intensity time series analysis for the 11^{th} window are presented.



Sl. 6. *Zaporedje posnetkov vrtinčne sledi za utripajočim profilom*
Fig. 6. *Image sequence of the pulsating airfoil vortex street*



Sl. 7. *Lega posameznih območij opazovanja*
Fig. 7. *Position of the observed windows in the pulsating airfoil vortex street*

Opravili smo analizo časovnih vrst krajevno povprečenega nivoja sivine v izbranem oknu ter pripadajočih spektrov moči pri različnih frekvencah utripanja profila v razponu od 0,25 do 10 Hz. Na slikah 8 in 9 lahko vidimo, da se pri povečevanju frekvence utripanja profila vrednost osnovne frekvence vrtinčne sledi in pripadajočega višjega harmonika spreminja. Pri tem lahko glede na stopnjo naraščanja celotno območje utripnih frekvenc pri nespremenjenem Re številu razdelimo na dve ločeni področji, prvo do frekvence utripanja profila 2,5 Hz in drugo nad njim.

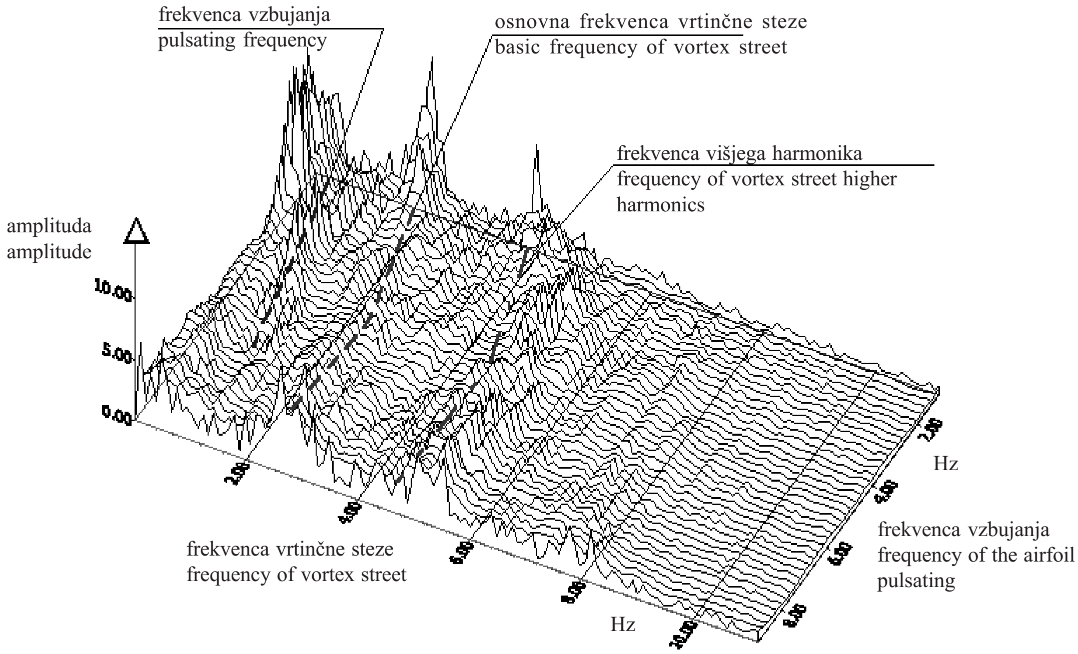
The grey level intensity time series and their spectra were observed at different airfoil pulsation frequencies, varying between 0.25 and 10 Hz. From Figs. 8 and 9 one is able to recognise that when increasing the pulsation frequency, the characteristic frequency of the vortex street along with its higher harmonics changes. There are basically two regions of the gradient of increase, the first below the airfoil pulsation frequency of 2.5 Hz, and the second above it. In the first part, the dynamic reply of a vortex street is significant. In the area of pulsating frequencies

V prvem področju je odgovor dinamike vrtinčne sledi na vzbujanje vpliven. V frekvenčnem področju od 0 do 0,5 Hz, je gradient spreminjanja frekvence vrtinčne sledi največji. V drugem območju s frekvenco utripanja profila nad 2,5 Hz pa je dinamični odziv vrtinčne sledi majhen.

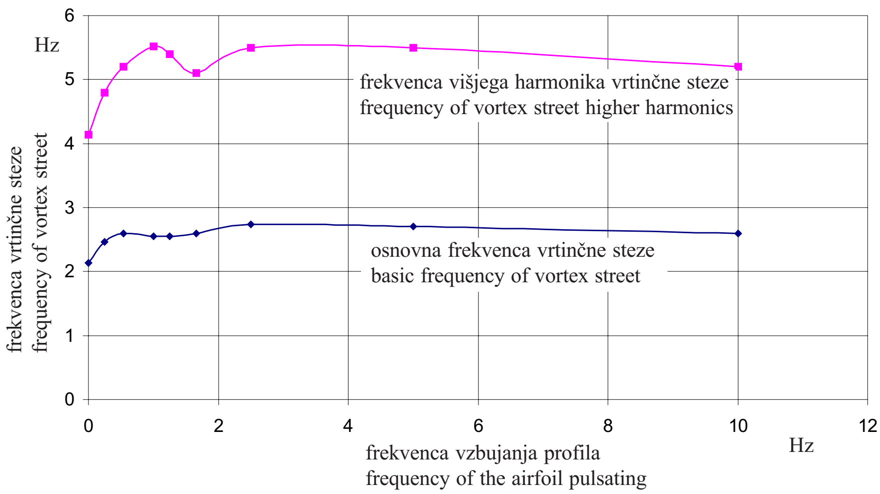
Iz navedenega lahko povzamemo, da vsiljeno utripanje profila povzroča nastajanje vedno večjega števila vrtincev v vrtinčni sledi, kar pripelje do povečanja frekvence vrtinčne sledi. Pri frekvenci utripov, ki je blizu karakteristični frekvenci vrtinčne sledi nenapihnjenega profila, vrednost karakteristične frekvence vrtinčne sledi vzbujanega profila doseže svoj vrh. Ko je omenjeno frekvenčno območje preseženo, povečevanje frekvence utripov ne vpliva bistveno na osnovno frekvenco vrtinčne sledi.

between 0 and 0.5 Hz, the gradient of the vortex street frequency change is the highest. In the second region, with pulsation frequencies above 2.5 Hz, the dynamic reply of a vortex street, however, is minimal.

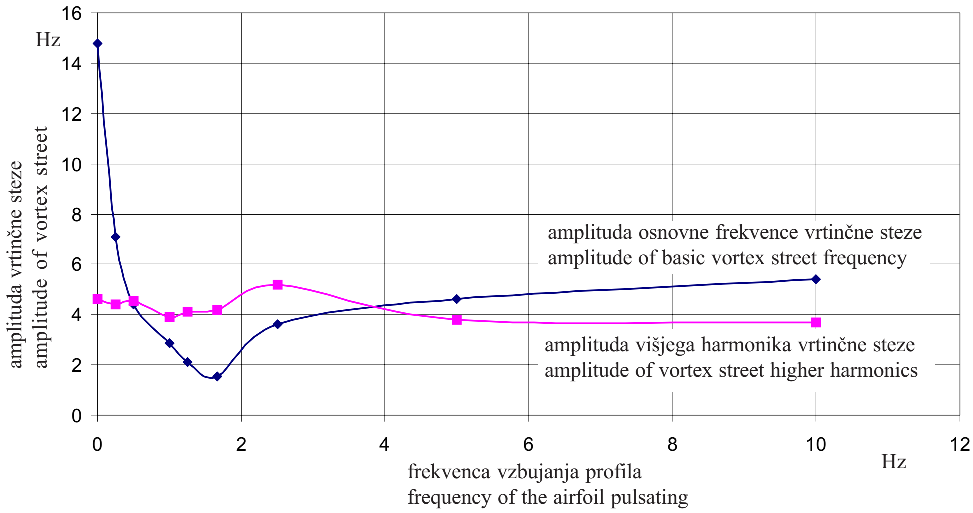
From the above mentioned it can be concluded that the growth of the pulsation frequency generates more vortices in the vortex street, which consequently leads to the growth of the vortex street frequency. At the frequency of pulsation close to the characteristic frequency of the vortex street for the non-blown profile, a vortex street frequency behind the pulsating airfoil reaches its maximum. After that point, the increase in pulsation frequency does not influence significantly the basic frequency of the vortex street any more.



Sl. 8. *Diagram frekvenčnih spektrov vrtinčne sledi za 11. okno za vse frekvence vzbujanja profila*
Fig. 8. *3D diagram of a frequency spectra of different pulsation frequencies of the 11th window*



Sl. 9. *Osnovna frekvenca in višji harmonik vrtinčne sledi v odvisnosti od frekvence vzbujanja profila*
Fig. 9. *Basic vortex street frequency and higher harmonics vs. the airfoil pulsation frequency*



Sl. 10. *Amplitudi osnovne frekvence in višjega harmonika vrtinčne sledi v odvisnosti od frekvence vzbujanja profila*
Fig. 10. *Amplitude of basic vortex street frequency and higher harmonics versus the airfoil position frequency*

Amplituda osnovne frekvence vrtinčne sledi (sl. 10) se pri povečevanju frekvence nihanj znatno zmanjšuje do frekvence vzbujanja 1,7 Hz in se zatem začne ponovno povečevati. Amplitude v območju frekvence višjega harmonika pa se pri različnih frekvencah vzbujanja ne spreminjajo značilno in se stabilizirajo v področju nad lastno frekvenco vrtinčne sledi, podobno kakor amplituda osnovne frekvence.

Bistveno pri periodičnem spreminjanju oblike profila je, da utripi znatno vplivajo na frekvenco in obliko fluktuacij toka v vrtinčni sledi in je mogoče s pulzacijami oblike profila frekvenco vrtinčne sledi ter njeno amplitudo spreminjati. Ta vpliv je močan v področju vzbujanja pri frekvenci vzbujanja, nižji od lastne frekvence sprememb v vrtinčni sledi opazovanega profila.

4 SKLEP

Namen pričujočega prispevka je bila analiza sprememb v vrtinčni sledi okoli utripajočega profila v vetrovniku. Spremembe v vrtinčni sledi smo opazovali z uporabo računalniško podprte vizualizacije. Želeli smo odgovoriti na vprašanje, ali se tokovne razmere spremenijo in v kakšni meri, če s periodičnimi utripi spreminjamo obliko profila. Pri analizi smo opazovali povezavo med dinamiko spreminjanja oblike profila in sestavo toka za in okoli profila.

Rezultati so razdeljeni v dve osnovni skupini: v prvem delu so predstavljeni rezultati razlik v toku pri dveh različnih oblikah profilov brez dinamičnega vzbujanja. Skladno s pričakovanji se velikost vrtincev pri debelejšem profilu poveča in vrtinčni tok se pomakne bliže k zadnjemu robu profila.

V drugem delu raziskave je bila izvedena analiza tokov za periodično vzbujanim profilom v

The amplitude of the basic frequency of the vortex street, when increasing the pulsating frequency, decreases to a pulsating frequency of 1.7 Hz and then slowly begins to increase again (Fig. 10). The amplitude of the higher harmonic however does not change significantly with the pulsating frequency. It stabilises in the region above the basic frequency of the vortex street, like it does for the amplitude of the basic frequency.

The most distinctive phenomenon of the periodic changes of profile shape is the significant influence of pulsation on the frequency and shape of vortex street fluctuations. With aid of profile shape pulsation, the frequency and amplitude of the vortex street can be altered. The influence is significant mainly in the pulsating frequency region lower than the basic frequency of the vortex street of the non-deformed profile.

4 CONCLUSION

The purpose of this study was the observation of changes in the vortex street behind and around the pulsating adaptive airfoil in a wind tunnel. Modifications in the vortex street were observed with the help of a computer-aided visualisation. We tried to answer the question, whether the flow conditions behind the airfoil can be changed, and to what extent, by the shape-altering pulsation of the airfoil. We focused as well on the connections between the dynamics of the airfoil shape and the flow structure behind and around the airfoil.

The results are divided into two parts: in the first part, the results from the observation of flow transformation at temporal stationary changes of the airfoil's shape are presented. In accordance with expectations, the size of the vortices is enlarged when the airfoil is thicker and the flow moves closer to the rear edge of the airfoil.

In the second part, the analysis was focused on the transformation of the flow at the pulsating airdoločenem razponu tlačnih utripov. Opazimo lahko, da je s periodičnim preoblikovanjem profila mogoče spreminjati obliko tokovne sestave za profilom in da je le ta različna od oblike pri časovno ustaljenih razmerah. Osnovna frekvenca vrtinčne sledi se pod vplivom utripov profila spremeni. Pri zviševanju vrednosti frekvence utripov se vrednost osnovne frekvence vrtinčne sledi povečuje, vrednost amplitude v področju osnovne frekvence pa zmanjšuje. Pri frekvenčnih vrednostih utripov, ki so blizu osnovni frekvenci vrtinčne sledi nenapihnjenega profila, je amplituda osnovne frekvence vrtinčne sledi za profilom najnižja in frekvenca največja. Z nadaljnjim povečevanjem frekvence pulzacij profila se učinek utripne frekvence na vrtinčno sled naglo zmanjšuje.

Bistveno pri utripanju oblike profila je, da utripanje znatno vpliva na frekvenco vrtinčne sledi in je mogoče z utripanji oblike profila frekvenco vrtinčne sledi ter njeno amplitudo spreminjati. Na ta način je mogoče spreminjati sestavo toka za profilom, kar odpira nove možnosti uporabe oziroma uporabe aerodinamičnih lastnosti profila. Prav tako pa je z omenjeno metodo mogoče povečati uporabno območje posameznega profila, kar navaja na možnost prilagodljivega krmiljenja tokovnih razmer na različnih tehničnih uporabah.

foil. The flow structure behind the airfoil can be altered by periodic pulsation of the airfoil's shape and it differs from the stationary one. The basic frequency of the vortex street behind the airfoil is changed under the influence of the pulsating frequency of the airfoil. As the pulsating frequency is increased, the value of the basic vortex street frequency rises, and its amplitude in the region of the basic frequency decreases. At pulsating frequencies close to the basic frequency of the stationary non-deformed airfoil shape, the amplitude of the basic frequency of the vortex street behind the pulsating airfoil is the lowest, and the frequency is a maximum. However, with the continual growth of the pulsating frequency, the effect of the pulsating frequency on the vortex street rapidly decreases.

The most notable change when pulsating the airfoil shape is that the pulsation influences the basic frequency of the vortex street to a great extent, and that the frequency of the vortex street and its amplitude can be altered. In this way the structure of the flow behind the airfoil can be significantly modified. This opens up new possibilities for the exploitation of aerodynamic properties of the airfoil. It can also increase the operational range for which the airfoil is adequate and opens up new possibilities for future adaptive control of flow conditions in various technical applications.

5 SIMBOLI
5 NOMENCLATURE

celoštevilčna skalarna spremenljivka – nivo sivine	$A(k, t)$	integer-type scalar variable – level of greyness
amplituda	$A(k, \omega)$	amplitude
intenzivnost svetlobe	$E(l, m)$	light intensity
opazovano okno	k	observed window
celo število	L	integer number
število vrstic	l	number of rows
celo število	M	integer number
število stolpcev	m	number of columns
število vzorcev	N	number of samples
Reynoldsovo število	Re	Reynolds number
čas	t	time
vodoravna lega v točkah	x	horizontal position in pixels
navpična lega v točkah	y	vertical position in pixels
standardni eksperimentalni odmik lokalnega nivoja intenzivnosti sivine	σ	standard deviation of the local grey level intensity

6 LITERATURA
6 REFERENCES

[1] Cheng – Hsiung Kuo, J.K.Hsieh (1998) Flow structure over an oscillating airfoil during vortex/airfoil interaction, 8Th Internationnal symposium on flow visualization.

[2] P. Ghosh Choudhuri, D.D. Knight (1994) Two-dimensional unsteady leading – edge separation on a pitching airfoil, AIAA Journal.

[3] Isogai, K. and Y. Shinmoto (1999) Numerical simulation and visualization of unsteady viscous flow around an oscillating tandem airfoil in hovering mode, Proceedings of PSFVIP-2.

[4] Austin, F., Michael J. Rossi (1994) William Van Nostrad and Gareth Knowles, Static shape control for adaptive wing, AIAA Journal, vol.32, No.9.

[5] Streather, R.A. (1982) Variable geometry aerofoils as applied to the Beatty B-5 and B-6 sailplanes.

[6] Novak, M., Širok, B., Hočevar, M., Philpott, D.R., P. R. Bullen (1999) Analysis of turbulent mixing flow of a bluff body wake using a computed vision system, 3rd ASME/JSME JointFluid Engineering Conference July 18 – 22, San Francisco, California.

Naslovi avtorjev: doc.dr. Brane Širok
Fakulteta za strojništvo
Univerze v Ljubljani
Aškerčeva 6
1000 Ljubljana

Erik Potočar
Ministrstvo za znanost in tehnologijo
1000 Ljubljana

Matej Novak
Turboinštitut
1000 Ljubljana

Authors' Addresses: Doc.Dr. Brane Širok
Faculty of Mechanical Eng.
University of Ljubljana
Aškerčeva 6
1000 Ljubljana, Slovenia

Erik Potočar
Ministry of Science and Tech.
1000 Ljubljana, Slovenia

Matej Novak
Turboinstitute
1000 Ljubljana, Slovenia

Prejeto:
Received: 20.4.2000

Sprejeto:
Accepted: 2.6.2000