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Gonilni mehanizmi kavitacijskega vrtinca v vstopnem vodu radialne črpalke

The Driving Mechanisms of the Cavitation Swirl in the Entrance Pipe of a Radial Pump

Andrej Predin - Ignacijo Biluš

V prispevku je podana analiza gonilnih mehanizmov in tlačnih utripanj povezanih s pojavom kavitacijskega vrtinca v vstopnem vodu radialne črpalke.

Kavitacijski vrtinec je rezultat interakcije številnih zapletenih sekundarnih tokovnih pojavov, ki nastopijo kot posledica obratovanja s podoptimalnimi pretoki v kavitacijskem obratovalnem režimu.

Izvedene in predstavljene so tudi meritve tlačnih utripanj v vstopnem vodu radialne črpalke na različnih razdaljah od rotorskega ustja na sklenjeni kavitacijski merilni progi. Meritve so izvedene pri različnih vrtilnih hitrostih in različnih tlakih nad spodnjo vodno gladino. Podani so tudi rezultati frekvenčne analize posnetih tlačnih utripanj.

(Ključne besede: črpalke radialne, vrtinci kavitacijski, režimi obratovanja, meritve tlačnih utripov)

Analyses are given of the driving mechanisms and pressure pulsations relating to the cavitation swirl in the entrance pipe of a radial pump.

The appearance of cavitation swirl is a result of a complicated secondary flow interaction, which appears as a consequence of the pump operating at small, under-optimum capacities in the cavitation operating regime.

Results of the flow pressure pulsation measurements in the entrance pipe of the radial pump are reported. These measurements were made at different distances from the impeller eye, in the upstream direction at the closed cavitation measuring test ring, with the pump operating at different impeller speeds and at different values of gas (air) pressure over the lower liquid (water) position. Results are also given for the frequency analyses of the measured flow pressure.

(Keywords: radial pumps, cavitation, swirl, operating regime, pressure pulsation measurements)

0 UVOD

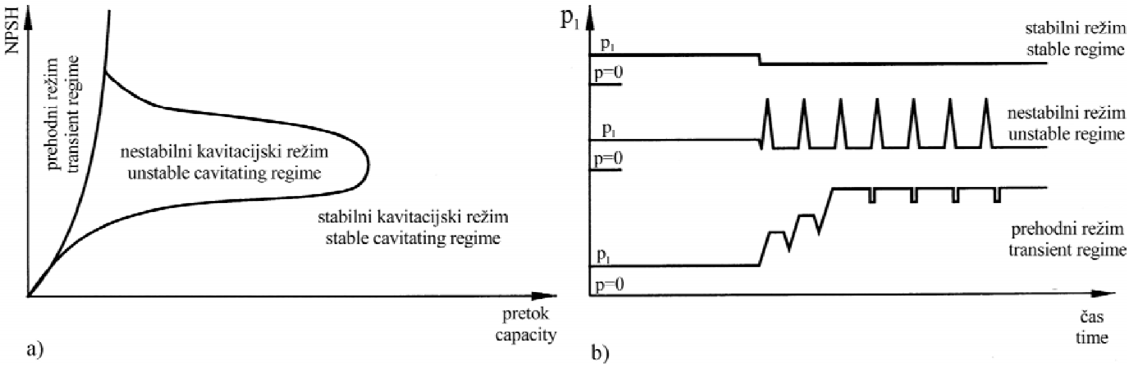
Pri manjšanju prostorninskega pretoka skozi črpalko, lahko pri obratovanju v kavitacijskem obratovalnem režimu v področju podoptimalnih pretokov opazimo tri različne kavitacijske režime, ki jih imenujemo stabilni, nestabilni in prehodni kavitacijski obratovalni režim [1].

Najpomembnejši je stabilni obratovalni režim, v katerem praviloma obratujejo vse črpalke. Če pa je črpalka ali sistem v katerega je črpalka vključena, nepravilno dimenzioniran, se lahko trenutna obratovalna točka, definirana s presečiščem osnovne karakteristike (dušilne

0 INTRODUCTION

Using a decreased volume flow rate through a pump at under-optimum capacities, three different cavitation regimes, stable, unstable and transient, can be observed [1].

The most important of these is the stable operating regime, within which most pumps operate. If the pump is incorrectly connected to the pipe system the other two cavitation regimes could appear. Temporary operating point, which is determined as a cross-section of pumps and pipe characteristic curves, is shifted to the area



Sl. 1. *Kavitacijski obratovalni režimi*
Fig. 1. *Cavitation operating regimes*

krivulje) črpalke in karakteristike sistema, premakne v področje podoptimalnih pretokov, kjer nastopi možnost pojava ostalih dveh kavitacijskih režimov. Na sliki 1a so obratovalni režimi prikazani v odvisnosti od pretoka skozi črpalko, kjer je presežek vstopne višine nad višino, ki ustreza uparjalnemu tlaku črpane kapljevine, enak:

of under optimum capacities, where the other two cavitating operating regimes could appears. In Figure 1 a, the three different cavitation regimes are presented. The excess of intake head over head of the water evaporation head pressure is given as:

$$NPSH = \frac{p_1}{\rho_1\, g} + \frac{v_1^2}{2g} - \frac{p_v}{\rho_l\, g} \quad (1).$$

0.1 Stabilni kavitacijski obratovalni režim

V stabilnem obratovalnem režimu (slika 2) mehurčki nastajajo in implodirajo v rotorskem kanalu, zaradi česar je rotor izpostavljen udarnemu delovanju in kavitacijski eroziji. Tok skozi rotorski kanal je pretežno enosmeren, kar pomeni, da se v opazovanem segmentu prostornina mehurčkov ne spreminja s časom.

Makroskopsko gledano je tekočinski tok v takem obratovalnem režimu stabilen, saj je časovno nespremenljiv tlak na ustju črpalke (slika 1 b).

0.2 Nestabilni kavitacijski obratovalni režim

Nestabilni kavitacijski režim oziroma hidrodinamično vzbujene spremembe toka nastopijo ponavadi kot posledica premajhnih pretokov, lahko

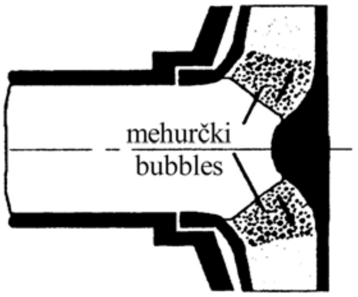
0.1 Stable cavitation operating regime

During the stable cavitation operating regime (Fig. 2) bubbles appear and implode in the impeller channels. As a result, the impeller is exposed to significant “micro water-hammer” effects and, therefore, to cavitation erosion. The flow across the impeller channels is mainly uni-directional, which means that for any particular water volume the bubble volume is timed independently.

In such an operating regime the flow is stable from the macroscopic point of view, while the flow pressure course in the time domain is constant (Fig. 1 b).

0.2 Unstable cavitation operating regime

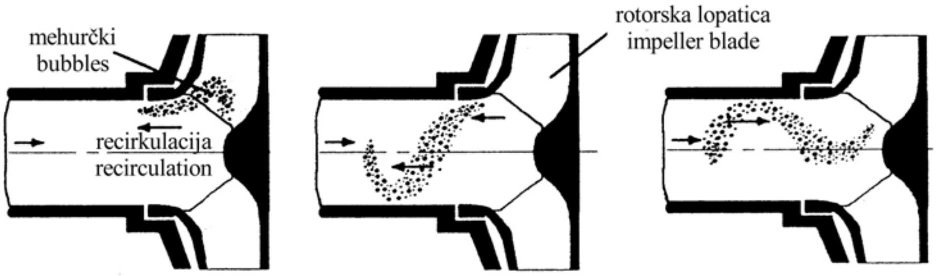
Unstable cavitation operating regimes or hydro-dynamically induced flow fluctuations usually appear as a consequence of too small a pump operating



Sl. 2. *Stabilni kavitacijski obratovalni režim*
Fig. 2. *Stable cavitation operating regime*

tudi skupaj z nezadostno čisto pozitivno sesalno višino (ČPSV - NPSH). V tem režimu se pojavi močno povratno gibanje znotraj rotorja, ki inducira spiralno gibanje mehurčkov v vstopnem cevovodu, kot je prikazano na sliki 3. Tlak na ustju črpalke lahko zelo utripa (slika 1 b), kar še bolj razširi kavitacijsko prerotacijski vrtinec v vstopni cevovod. Amplituda tlačnih utripov je močno odvisna od rasti oz. implozije mehurčkov v rotorju (odvisnost od NPSH) in od prerotacije toka (odvisnost od vstopne geometrije rotorja in sesalnega cevovoda).

capacity, possibly by interacting with the small pump net positive suction head (NPSH). In this regime a strong flow recirculation appears inside the impeller. This flow recirculation induces a spiral movement of bubbles in the entrance pipe, as shown in Figure 3. At the impeller eye the flow pressure could strongly pulsate (Fig. 1.b), increasing the cavitation prerotation swirl into the entrance pipe of the pump. The amplitude of the flow pressure pulsation strongly depends on the bubbles' growth or implosion in the impeller (dependency on NPSH), and on the prerotation flow, which depends on the impeller and entrance-pipe geometry.



začetek kroga
cycle iniciated

rast vrtinca
swirl growth

implozija vrtinca
swirl implosion

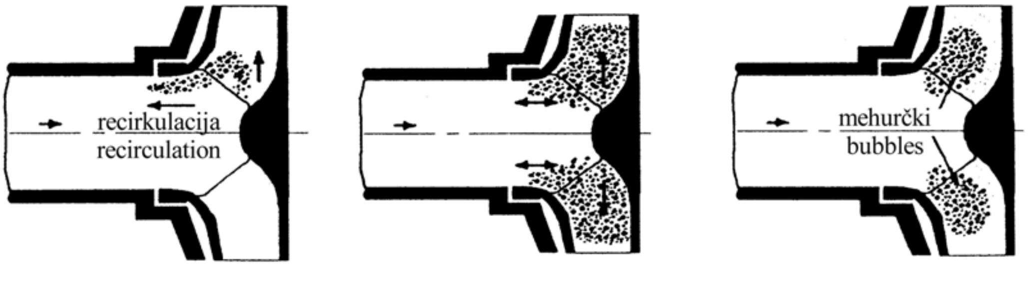
Sl. 3. *Nestabilni kavitacijski obratovalni režim*
Fig. 3. *Unstable cavitation operating regime*

0.3 Prehodni kavitacijski obratovalni režim

Prehodni obratovalni režim (slika 4) nastopi, ko je pretok skozi črpalko minimalen oziroma enak nič in govorimo o termodinamičnih spremembah toka. Režim je spremenljiv, kavitacijsko prerotacijski vrtinec pa se zaradi prehodnih razmer ne more razširiti v vstopni cevovod, saj porast tlaka, povzročen z mešanjem tople tekočine iz rotorja s hladnejšo v vstopnem cevovodu, povzroči izmenično implozijo in rast mehurčkov. Tlak na vstopu v črpalko lahko v skrajnem primeru preseže trdnost črpalke in vstopnega cevovoda. Njegov časovni potek kaže slika 1 b.

0.3 Transient cavitation regime

The transient cavitation operating regime appears (Fig. 4) when the pump operating capacity is almost at zero. Under these conditions we could define regions of thermodynamically induced flow fluctuations. The regime is changeable; the cavitation-prerotation swirl cannot propagate to the entrance pipe while the flow pressure is increasing. The pressure increase is caused by liquid circulation between warmer standing water at the impeller with colder water at the entrance pipe. Under the worst conditions the flow pressure could increase above the pump-casing or entrance-pipe strength. The pressure course for this regime is in the time domain given in Figure 1 b.



začetek kroga
cycle initiated

nagla rast
explosive growth

delna implozija
partial implosion

Sl. 4. *Prehodni kavitacijski obratovalni režim*
Fig. 4. *Transient cavitation operating regime*

1 POJAV RECIRKULACIJE NA SESALNI STRANI ROTORSKE LOPATICE

Pri vsakem relativnem gibanju med tekočino in steno se oblikuje mejna plast, torej območje velikih hitrostnih gradientov v smeri normale na površino in s tem viskoznih sil, saj hitrosti tekočinskih delcev preidejo iz vrednosti v zunanjem toku na vrednost hitrosti gibanja stene, v našem primeru rotorske lopatice. Opazujmo trikotnika hitrosti na vstopnem robu rotorske lopatice prikazana na sliki 5. Pri zmanjšanju pretoka, iz optimalnega prikazanega s trikotnikom hitrosti na sliki 5a, pri nespremenjeni obodni hitrosti u_1, se zmanjša velikost absolutne hitrosti in s tem natočni kot β_1. Zaradi zmanjšanja kota (slika 5b) se odebeli mejna plast na sesalni strani lopatice, kar lahko privede do pojava zastojne cone, torej do odlepljanja toka od površine in pojava povratnega toka v smeri proti vstopnemu robu in v sesalni vod sistema. V omenjenem primeru se pozitivni tok premakne proti tlačni strani rotorske lopatice, kjer se kreira vrtinčno, oziroma cirkulacijsko gibanje. Nastalo cirkulacijsko gibanje izpira mejno plast na tlačni strani lopatic in zaradi prisotnosti tlačnega padca predstavlja mesto pojava parnih mehurčkov, v primeru, da tlak pade pod uparjalni tlak kapljevine pri dani temperaturi.

Od tod izhaja tudi temeljna razlika med kavitacijskimi poškodbami zaradi recirkulacijskih tokov in poškodbami zaradi nezadostne ČPSV, saj slednje nastopajo na sesalni strani lopatic.

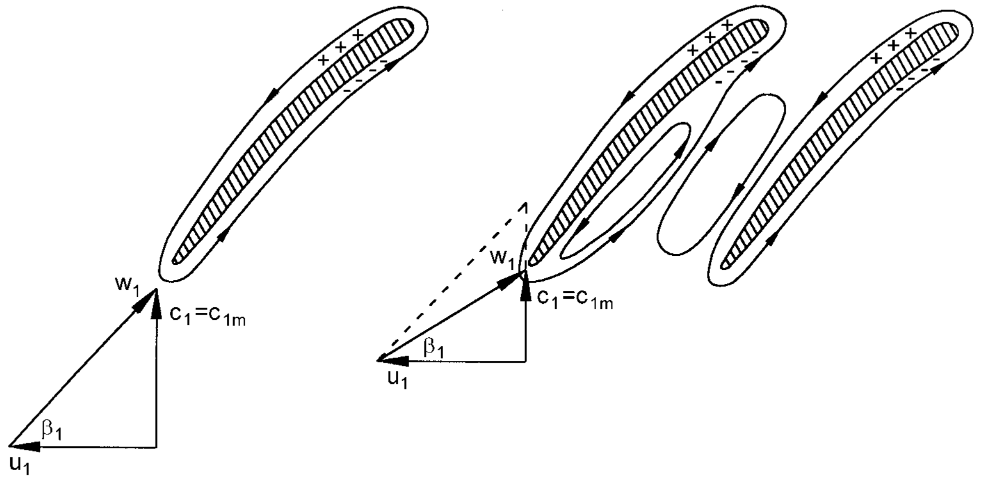
Breugelmans [2] je predstavil mehanizem, po katerem se zgoraj omenjeno recirkulacijsko gibanje razširi v vstopni vod.

1 RECIRCULATION FLOW APPEARANCE AT THE SUCTION SIDE OF THE IMPELLER BLADE

Any relative movement between a solid and a fluid causes a boundary layer to form at the solid surface. In this area, large velocity gradients in the direction normal to the solid surface appear and, therefore, viscous flow forces are present. In our case a very significant velocity change appears on different sides of the impeller blade surface (suction on the upper and pressure on the lower). Let us consider the flow velocity triangles (Euler triangles) at the impeller trailing (entrance) edge (Fig. 5). When decreasing the pump operating capacity from the optimum (Fig. 5a) a velocity-triangle change is evident. At a constant circumferential velocity u_2 the absolute flow velocity c_1 and, consequently, its angle β_1 decrease. Because the absolute flow velocity and its attack angle decrease (Fig. 5b) the boundary-layer thickness on the suction side of the impeller blade increases, this leads to the appearance of the fluid-flow stall zones and, consequently, for flow separation from the blade surface. The reversible flow in the upstream direction (up to the entrance edge of the blade on the suction side) appears in this place. In this case the active flow moves up to the pressure side of the blade surface, where the swirl or circulating flow is created. The flow that appears thins the boundary layer on the pressure side of the blade surface, and if it is present the pressure drop decreases the pressure to below the evaporation pressure and at a certain temperature, gas (vapour) bubbles appear in the liquid (water).

This fact is the reason for the difference between cavitation damage resulting from recirculating flows and cavitation damage caused as a consequence of insufficient NPSH values when damage appears on the suction side of the blade surface.

Breugelmans [2] presented a mechanism where the mentioned recirculation flows propagate in the upstream direction in the entrance pipe.



a) b)

Sl. 5. *Vstopni trikotnik hitrosti pri zmanjšanju pretoka skozi črpalko in nespremenljivi vrtilni frekvenci*
Fig. 5. *Entrance angle at the decreased pump operating capacity for a constant impeller speed*

2 PREROTACIJA TOKA IN KAVITACIJSKI VRTINEC V VSTOPNEM VODU

Dejansko pride pri zmanjšanju pretoka skozi črpalko poleg zmanjšanja natočnega kota tudi do pojava obodne komponente absolutne hitrosti in sicer v smeri vrtenja rotorja, kot je to prikazano na sliki 6.

Zaradi prisotnosti obodne komponente hitrosti, ko jo lahko razložimo tudi s cirkulacijo v rotorskem kanalu [3], se v vstopni cevi oblikuje specifični recirkulacijsko prerotacijski tokovni režim [4], pri katerem je na obodu rotirajoč oblak povratnega toka, v osi pa jedro v katerem velja kontinuitetna enačba.

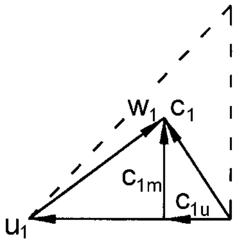
Neumann [5] je predpostavil, da je hitrostni profil v vstopnem vodu paraboličen in izpeljal, da je meridianska hitrost enaka nič na polmeru $r_0 = 0{,}75 \cdot R$, kjer je R polmer vstopne cevi (slika 7).

2 PREROTATION FLOW AND CAVITATION SWIRL IN THE ENTRANCE PIPE

In practice the appearance of the absolute flow velocity component in the circumferential direction is connected with the relative velocity angle decrease when we reduce the capacity below the optimum (Fig. 6).

The apparent flow velocity component has the same direction as the impeller rotation. Because of the presence of this flow velocity component we can explain the circulation flows in the impeller channels [3], and the specific recirculation - prerotation flow regime [4] being created. Under this situation the bubbles cloud at the outside swirl diameter and the flow swirl core where the continuity equation is valid.

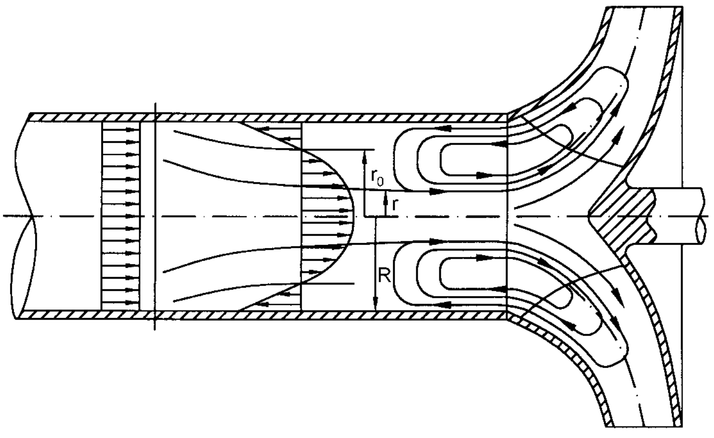
Neumann [5] predicted that the velocity profile in the entrance pipe has a parabolic shape and is derived from the fact that zero-meridian-velocity is present at $r_0 = 0.75 \cdot R$ where R is the entrance pipe radius (Fig. 7).



Sl. 6. *Dejanski vstopni hitrostni trikotnik*
Fig. 6. *Actual entrance flow velocity triangle*

Omenjen padec koristnega prereza vstopne cevi povzroči v skladu s kontinuitetno enačbo povečanje pretočnih hitrosti v jedru toka. Če opazujemo posamezne tokovnice, sledi iz Bernoullijeve enačbe zmanjšanje tlaka v toku. Če je padec tlaka dovolj velik, pride do uparjanja kapljevine. Tako se ustvarijo razmere potrebne za združitev območja parne faze na tlačni strani lopatic, ki nastane zaradi zmanjšanja natočnega kota in parne faze, ki nastane v osi vstopnega voda. Iz smeri rotorskega

A decrease of the active flow area, caused by recirculation flow propagation in the entrance pipe, causes, according to the continuity equation, larger flow velocities in the core of the pipe. If we observe the individual streamlines we can (from Bernoulli's equation) conclude that the pressure decreases. If this pressure drop is sufficient, the water starts to evaporate. In this way conditions are created which are suitable for connecting the vapour phase in the entrance pipe with the vapour phase on the pressure side of the blades, which is a



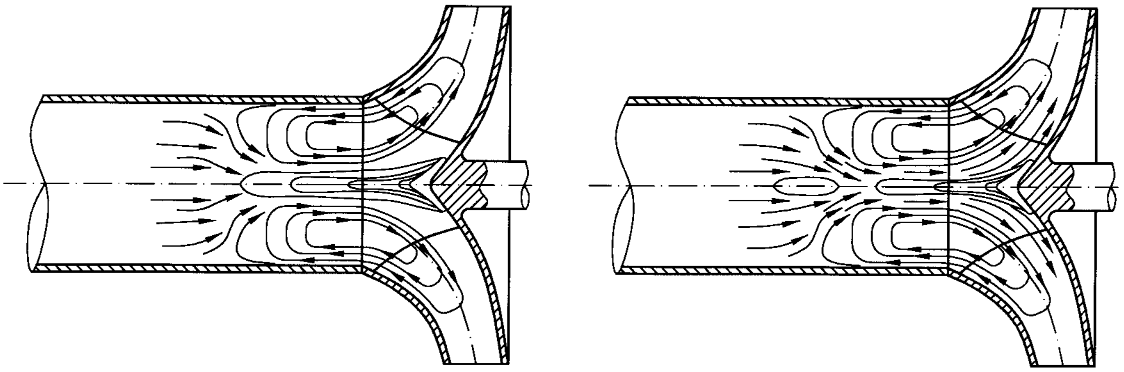
Sl. 7. *Paraboličen vstopni hitrostni profil*
Fig. 7. *Velocity profile with parabolic shape*

ustja se v vstopni (sesalni) vod razširi parni vrtinec, ki se vrti s prerotacijsko obodno hitrostjo in lahko sega relativno daleč v sesalni vod. Z razširitvijo plinaste faze iz rotorskih kanalov v ustje in sesalni vod smo prestopili prag globalnih nestabilnosti tokovnega režima v vstopnem vodu [2].

Kavitacijski vrtinec še dodatno manjša dejanski prerez vstopne cevi, lahko prostornina plinaste faze naraste do te mere, da pride do “zamašitve” vstopne cevi in s tem do ustavitve pretoka skozi sistem. Posledica ustavljanja tekočinskega toka je tlačni udar (slika 8a), ki ima za posledico porast tlaka in s tem implozijo nastalega kavitacijskega vrtinca ter sprostitev toka. V primeru zelo majhnih pretokov, torej na meji med nestabilnim in prehodnim kavitacijskim režimom, lahko pride na mestu, kjer se je zgodil tlačni udar, do trganja vrtinca, prerez cevi pa se ne sprosti v celoti, temveč samo delno, kar je razvidno iz zmanjšanja premera kavitacijskega vrtinca (slika 8b).

consequence of a low flow attack angle. The vapour swirl propagates from the impeller eye upstream into the entrance pipe by the same distance and rotates with the prerotation circumferential velocity. The instabilities of the flow regime in the entrance pipe become global at the moment when both vapour-phase areas connect [2].

The cavitation swirl additionally decreases the active flow area at the entrance pipe. In the worst case, the gas phase increases over the whole active part of the entrance pipe and the active flow is stopped. In this way the pump operating capacity is zero (cut off condition). The consequence of this is that the water hammer effect (Fig. 8a) reflects the sudden pressure rise in the entrance pipe. This pressure rise is the reason for the bubbles’ implosion at the cavitation swirl and with that the operating capacity release through the impeller eye and consequently through the whole impeller. In the cases of very small operating capacities (close to zero), this is in the area between the unstable and transient cavitation regimes the swirl cut off appears where the water hammer effect applied. The active flow area at the entrance pipe is not released at the whole entrance pipe but only at part of it. This is evident from the decreased cavitation swirl diameter (Fig. 8b).


a) b)

Sl. 8. *Nastanek udarnega vala (a) in trganje ter zožitev kavitacijskega vrtinca (b)*
Fig. 8. *The water hammer pressure wave (a) and the swirl cut-off of the thinner swirl (b)*

Pojav in jakost kavitacijskega vrtinca je določena z obliko rotorskih lopatic na vstopu v rotor, dolžina vrtinca je funkcija geometrije vstopnega cevovoda, njegov premer pa je odvisen od tlačnih razmer v sesalnem vodu.

V črpalkah, pri katerih je vstopni cevovod osno simetričen z rotorskim ustjem, se recirkulacijsko gibanje lahko razširi tudi do osem vstopnih premerov daleč v sesalni cevovod.

Pojav kavitacijsko prerotacijskega vrtinca je tesno povezan z nagnjenjem rotorja h kreiranju zastojnih con in racirkulacijskega toka.

3 KAVITACIJSKI VRTINEC V PREHODNEM KAVITACIJSKEM REŽIMU

Pri popolnoma zaprtem pretoku skozi črpalko se v vstopnem vodu pojavi krožno gibanje

The impeller blades, shape at the impeller entrance determines the phenomenon and the swirl strength. The swirl length is a function of the entrance-pipe geometry. Swirl diameter depends on the flow conditions in the entrance pipe.

In pumps with a straight entrance pipe the cavitation swirl could develop up to eight entrance pipe diameters in the upstream direction from the impeller eye.

The appearance of the cavitation-prerotation swirl is closely related by the impeller trend to the stall zone and recirculation flow’s creation.

3 CAVITATION SWIRL AT THE TRANSIENT CAVITATION REGIME

The circular movement of fluid in the entrance pipe occurs when the operating capacity is completely kapljevine (tokovnice so sosrednji krogi), vsa energija pa se porablja za njeno mešanje in segrevanje. Če zanemarimo gravitacijsko polje, lahko zapišemo enačbo za spremembo totalne energije s polmerom v naslednji obliki [6]:

closed. This means that streamlines form a set of concentric circles and, therefore, all the energy is consumed by the flow mixing and heating. If we ignore gravitation we can write the change in total energy with a radius in the following form [6]:

$$\frac{dH}{dr} = \frac{v}{g}\left(\frac{v}{r} + \frac{dv}{dr}\right) \tag{2}$$

Iz te enačbe izhajajo naslednji tipi vrtincev:

From this equation the following swirls can be defined:

Vsiljen vrtinec

Tekočina se v primeru vsiljenega vrtinca vrti s konstanto kotno hitrostjo ω, tako da na vsakem polmeru r velja enačba:

Forced swirl

In the case of the forced swirl the fluid rotates as a solid body with constant angular velocity ω, so at any radius r:

$$v = \omega r \tag{3}$$

in zato:

and therefore:

$$\frac{dv}{dr} = \omega \qquad \frac{v}{r} = \omega \qquad (4).$$

Iz enačbe (2) izhaja:

From equation (2) it follows that:

$$\frac{dH}{dr} = \frac{\omega r}{g}(\omega + \omega) = \frac{2\omega^2 r}{g} \qquad (5).$$

Z integracijo dobimo:

Integrating, we have:

$$H = \omega^2 r^2 / g + C \qquad (6),$$

kjer je C konstanta. Ker velja za vsako točko v tekočini:

where C is a constant. But, for any point in the fluid

$$H = p/\rho g + v^2/2g + z = p/\rho g + \omega^2 r^2/2g + z \qquad (7),$$

dobimo z združitvijo zgornjih enačb:

the joint equation is obtained:

$$p/\rho g + z = \omega^2 r^2/2g + C \qquad (8).$$

Ta enačba podaja porazdelitev tlaka za vsiljen vrtinec, kjer je za primer prisotnosti proste površine tlak enak atmosferskemu (relativni tlak je nič).

Above equation gives the pressure distribution at forced flow swirl, where, for as an example of flow with free surface, the pressure above the water free surface is equal to atmospheric pressure (relative pressure is zero!).

Prosti ali potencialni vrtinec

V primeru potencialnega vrtinca je porazdelitev hitrosti takšna, da s polmerom ni spremembe totalne energije na enoto mase. Tako velja dH/dr = 0 in lahko zapišemo:

Free or potential swirl

In this case, the streamlines are concentric circles, but the variation of velocity with radius is such that there is no change of total energy per unit weight with the radius, so that dH/dr = 0. Substituting equation:

$$\begin{gathered} 0 = \frac{v}{g}\left(\frac{v}{r} + \frac{dv}{dr}\right) \\ \frac{dv}{v} + \frac{dr}{r} = 0 \end{gathered} \qquad (9).$$

Z integracijo dobimo:

Integrating, we have:

$$\begin{gathered} \ln v + \ln r = \text{konst} \\ vr = C \end{gathered} \qquad (10).$$

Zdaj lahko zapišemo, da je potencialni vrtinec krožno gibanje tekočine, pri čemer je radialna komponenta hitrosti popolnoma enaka nič, obodna komponenta hitrosti pa se zvečuje z manjšanjem polmera, s singularnostjo pri $r = 0$. Ker v vsaki točki tekočine velja:

Now we can conclude that the potential swirl is a circular motion of fluid where the radial flow velocity component is equal to zero, and the circumferential component increases with decreasing radius, with a singularity at $r = 0$. Since at any point in the fluid:

$$H = p/\rho g + v^2/2g + z = \text{konst} \tag{11),}$$

lahko zapišemo:

we can write:

$$H = p/\rho g + C^2/2gr^2 + z \tag{12).}$$

Za horizontalno ravnino je z stalen, tlačna porazdelitev pa je podana s:

For any horizontal plane, z is constant and the pressure variation is given by:

$$p/\rho g = (H - z) - C^2/2gr^2 \tag{13).}$$

Iz enačbe je razvidno, da se pri potencialnem vrtincu tlak manjša, obodna hitrost pa veča s približevanjem osi vrtenja.

Thus, in the free vortex, pressure decreases and circumferential velocity increases as we move towards the center of rotation.

Sestavljen vrtinec

V potencialnem vrtincu velja $v = C/r$ in zato bi morala biti teoretična hitrost v središču neskončna. Hitrosti pri osi so sicer zelo velike, ker pa se torne izgube zvečujejo s kvadratom hitrosti, jih ne moremo zanemariti (tok ni potencialen) in zato totalna energija ni več nespremenljiva. Sestavljen vrtinec v središču rotira kot togo telo (vsiljen vrtinec) na nekem polmeru R pa preide v potencialni vrtinec. Na stičišču obeh vrtincev, torej na polmeru R, morata biti hitrosti enaki. Tako velja:

Composed swirl

In the free swirl, $v = C/r$ and thus, theoretically, the velocity becomes infinitive at the centre. The velocities near the axis would be very high and, since friction losses vary as the square of the velocity, they will cease to be negligible (flow is not potential) and the assumption that the total remains constant will cease to be true. The compound swirl in the center rotates as a solid body (forced swirl) but at a certain radius R it becomes a potential swirl. At the contact of swirls, at the radius R, both velocities must be equal:

$$\omega R = C/R \tag{14}$$

oziroma:

or:

$$R = \sqrt{C/\omega} \tag{15).}$$

Izračunajmo cirkulacijo vzdolž poljubne tokovnice okoli osi vrtinčnega toka. Cirkulacija je krivuljni integral vektorske veličine po sklenjeni krivulji, zato lahko zapišemo:

Let us calculate the circulation at any concentric streamline around the axis of the swirl on Fig. 4.2. Circulation is defined as the integral of the vector quantity along a closed curve and can be written as:

$$\Gamma = \oint \vec{v} \cdot d\vec{s} = v\,2\pi r \tag{16).}$$

Ker je $r{\cdot}v = C$, lahko zapišemo, da je:

Because $r{\cdot}v = C$, we can write:

$$C = \frac{\Gamma}{2\pi} \tag{17}$$

in zato za polmer na stičišču obeh vrtincev:

so, that the radii R at the contact of both swirls is:

$$R = \sqrt{\frac{\Gamma}{2\pi\omega}} \tag{18}$$

V primeru, da je polmer R dovolj majhen, je hitrost tako velika, da pride do nastanka plinaste faze tudi v tem kavitacijskem obratovalnem režimu. Ker pa na fazni meji zaradi zaprtega pretoka ne moremo

If the radius R is small enough and if the velocity is big enough, the vapour phase can appear even at this cavitation operating regime. Because of the closed capacity through the pump, the isotherm pričakovati izotermnega uparjanja, se dvofazno območje pri običajnih sistemih, izvedenih z nepovratnimi ventili v sesalnem in tlačnem vodu zaradi zvišanja tlaka ne razširi daleč v vstopni vod. Tlačno zvišanje lahko v skrajnem primeru privede tudi do uničenja vstopnega ali izstopnega cevnega sistema, pa tudi okrova črpalke [1].

4 MERJENJE TLAČNIH UTRIPOV KAVITACIJSKEGA VRTINCA

Tlačne utripe v vstopnem vodu smo izmerili ne merilni progi prikazani na sliki 9. Merilna proga je izdelana v skladu s priporočili za izvajanje kavitacijskih testov s spreminjanjem ČPSV po ISO 2548. Sistem je zaprtega tipa, v katerem radialna črpalka (slika 9 poz. 1) črpa vodo iz rezervoarja (poz. 2) po sesalnem cevovodu (poz. 3) in ga vrača v rezervoar po tlačnem cevovodu (poz. 4). V sistemu je z vakuumsko črpalko (poz. 5) možno spreminjanje tlaka nad spodnjo vodno gladino in s tem posredno tudi spreminjanje sesalne višine. Ker je merilna proga namenjena snemanju kavitacijskih karakteristik črpalk namenjenih obratovanju v različnih pogojih, je v rezervoarju še uporovni električni grelec (poz. 6). Za boljši vpogled in razumevanje dogajanja v kavitacijskih obratovalnih režimih je na vstop v črpalko nameščena prozorna cev (poz. 7). Pretok lahko dušimo v sesalnem in tlačnem cevovodu in sicer s pomočjo ventilov (poz. 8), prostorninski pretok pa merimo z zaslonko (poz. 9), izdelano po standardu DIN 1952 [7].

Nazivna vrtilna frekvenca črpalke Litostroj CN 50-250 je $n = 2900$ min^{-1}, največja črpalna višina je $H = 85$ m in največji pretok enak $Q = 0{,}03$ m^3/s. Vstopni premer cevi je 65 mm, dolžina 1500 mm, na izstopu pa je premer cevi 50 mm na dolžini 2000 mm.

Vibracije, ki so posledica izsrednosti in neuravnoteženosti pogonskega sistema dušimo z amortizerjem (poz. 10) in jih s tem ne prenašamo na črpani medij. Za odplinjevanje toka skrbi poseben

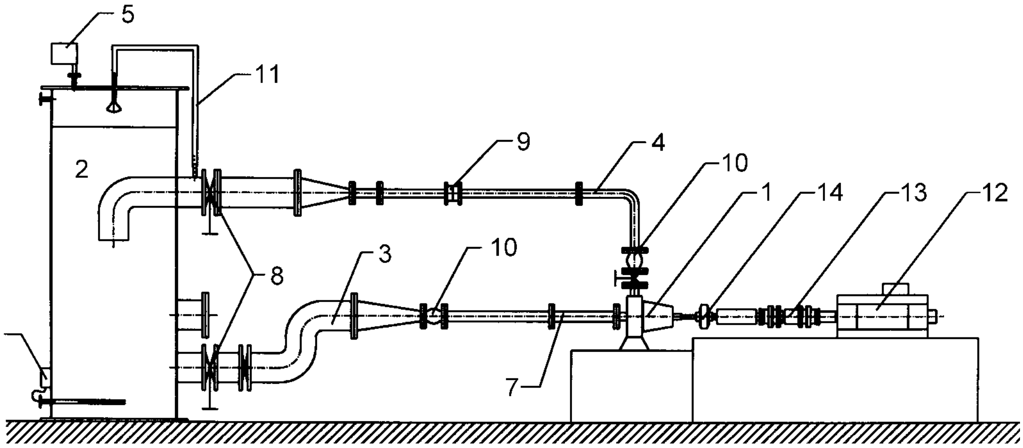
evaporation cannot be expected when both phases contact. The reason for this is that this gas phase area could not be propagated far into the entrance pipe for conventional pump systems that have a non-return valve in the suction (entrance) and exit pipes. The present pressure rise can, in the worst case, cause the pump casing to break [1].

4 CAVITATION SWIRL PRESSURE PULSATIONS MEASUREMENTS

The pressure pulsations are measured at the entrance pipe of the radial pump as is shown in Figure 9. The measurement testing system is manufactured to conform to ISO 2548 recommendations for cavitation tests performed using pump NPSH variation. The system is developed as a closed loop in which the radial pump (Fig. 9, position 1) is positioned. The suction pipe system (Fig 9, pos. 3) goes from the reservoir (pos. 2) to the pump the pressurized water flow to the pressure pipe system (pos. 4), which returns the water to the reservoir. The gas pressure above the water level in the reservoir can be changed using the vacuum pump (pos. 5) and so the pump suction head can be varied. Since the measuring system is geared for pump characteristic measurements under different operating regimes, an electric heater was put into the reservoir (pos. 6). The transparent suction pipe, which allows cavitation swirl observation, was placed at the pump entrance. The operating capacity can be changed by the valve (pos. 8) and measured by the orifice plate (pos. 9) manufactured according standard DIN 1952 [7].

Pump, Litostroj CN 50-250, design speed is 2900 rpm, maximum pump head is $H = 85$ m, maximum capacity is $Q = 0.03$ m^3/s. The pump intake diameter is 0.065 m, the length is 1.5 m, and exit pipe diameter is 0.050 and its length is 2 m.

A rubber compensator (pos. 10) dampens vibrations, which are caused as a consequence of the un-centric and un-balanced driving system. The compensator is put into the pressure pipe system



Sl. 9. *Skica merilne proge*
Fig. 9. *Measuring system drawing*

vod (poz. 11), ki se konča z razpršilom v rezervoarju. Elektromotor (poz. 12), je povezan s črpalko preko gredi za merjenje momentov (poz.13) in elastične sklopke (poz. 14).

S kombinacijo različnih podtlakov nad spodnjo vodno gladino in dušenjem pretoka, lahko tako določamo točko začetka kavitacije in razvoj kavitacijskega vrtinca pri različnih obratovalnih pogojih.

Tlačne utripe merimo v treh legah različno oddaljenih od ustja s tremi absolutnimi tlačnimi zaznavali HBM P19 in zaznavalom KRISTAL tip 4285A5, katerih tehnični podatki so podani v preglednici 1. Pretok nastavljamo z zasunom nameščenim za izstopom iz črpalke (slika 9), za zajemanje podatkov uporabljamo kartico Inteligent Instrumentation PCI 20428 W-1, za obdelavo podatkov pa programski paket Visual Designer.

Tlačne utripe zaradi prisotnosti kavitacijskega vrtinca merimo pri 1450, 1550 in 1650 min^{-1} in treh različnih relativnih tlakih nad spodnjo vodno gladino (v rezervoarju) ($p_{rez,1}$ = - 0,4 bar , $p_{rez,2}$ = - 0,5 bar , $p_{rez,3}$ = - 0,6 bar). Da bi zmanjšali napako meritve izvedemo v vsakem režimu 50 meritev, frekvenčno analizo pa zaradi frekvenčnega območja uporabljenih zaznaval izvedemo do 2000 Hz.

directly after the pump. The special pipe system (pos. 11) for water degazization is created. The driving motor (pos. 12) drives the pump over the elastic gear (pos. 14). The operating torque is measured using the measuring torque shaft (pos. 13).

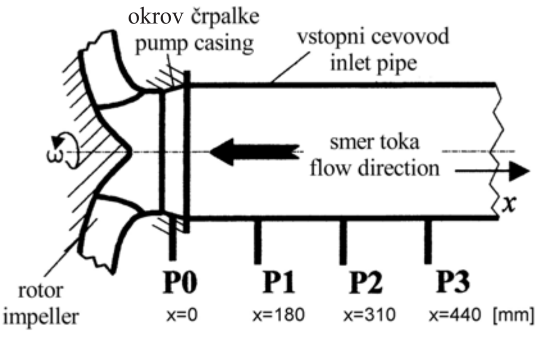
The moment (point) of cavitation appearance can be determined by a combination of different pressures over the water level at the reservoir, and by operating capacity change.

The flow pressure pulsations are measured at three different measuring points placed in the upstream direction from the impeller eye (Fig. 10). Absolute pressure transducers HBM P19 and KRISTAL type 4285A5 (technical data are given in Table 1) were used. PC A/D board – Intelligent Instrumentation PCI 20428 W-1, was used to take measuring data, which is evaluated using Visual Designer software. Operating capacities are controlled by valve at the pump exit (Fig. 9).

Pressure pulsations are measured during pump operation at impeller speeds: 1450, 1550 and 1650 rpm at three different pressures over the water level at the reservoir ($p_{rez,1}$ = - 0.4 bar , $p_{rez,2}$ = - 0.5 bar , $p_{rez,3}$ = - 0.6 bar). To decrease the measuring error, at each measuring regime 50 measuring repetitions are performed. The frequency analyses are performed in a range up to 2000 Hz, considering transducers operating regime.

Preglednica 1. *Seznam uporabljenih tlačnih zaznaval*
Tabel 1. *List of used pressure transducers*

Vrsta naprave Type	Proizvajalec in tip Producer and Type	Merilno območje Measuring area	Napaka Error	Frekvenčno območje Frequency area
Abs. tlačno zaznavalo Abs. pressure transducer	HBM P 19	0 do/to 10 bar	0,5%	2 kHz
Abs. tlačno zaznavalo Abs. pressure transducer	HBM P 19	0 do/to 10 bar	0,5%	2 kHz
Abs. tlačno zaznavalo Abs. pressure transducer	HBM P 19	0 do/to 4 bar	0,5%	2 kHz
Abs. tlačno zaznavalo Abs. pressure transducer	Kristal 4285A5	0 do/to 5 bar	0,5%	5 kHz



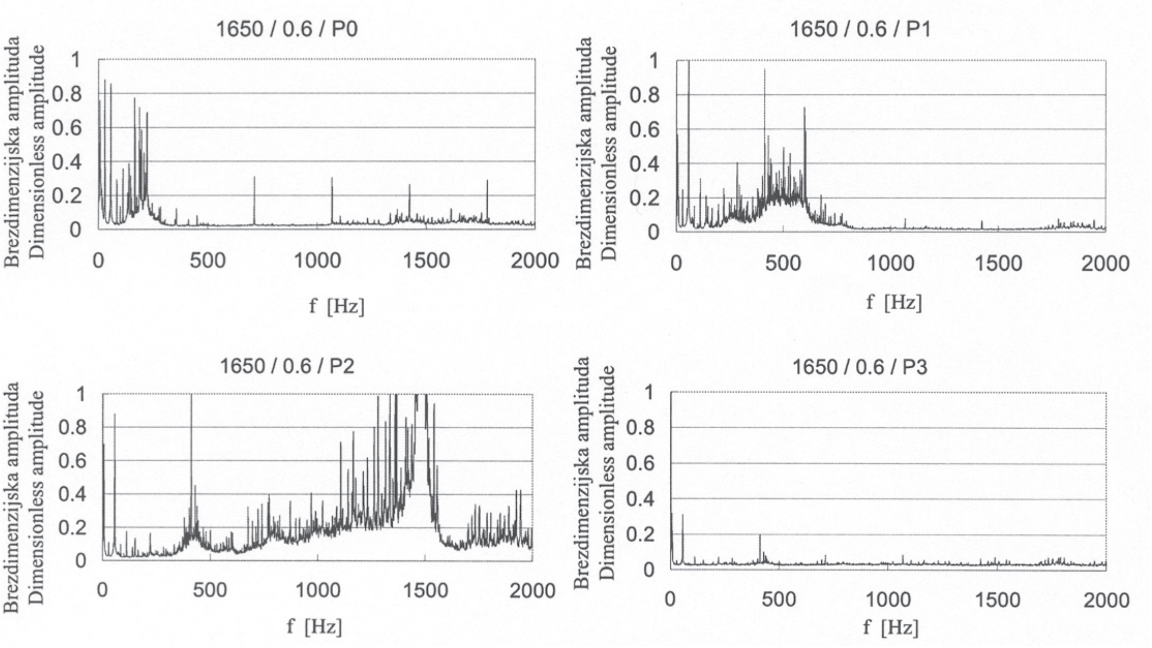
Sl. 10. *Skica merilnih mest za snemanje tlačnih utripov*
Fig. 10. *Measuring places for pressure pulsations*

5 REZULTATI MERITEV

Na sliki 11 so prikazani razultati hitre Fourierjeve transformacije za n=1650 min^{-1} in p_{rez}=-0,6 bar v obratovalnem režimu pri katerem je v vstopnem vodu razvit kavitacijski vrtinec (Q = 0,0011 m^3/s).

5 MEASURING RESULTS

The results of the frequency analyses after fast Fourier transform at a pump operating speed of n= 1650 rpm and at a pressure over the water level in the reservoir of p_{rez} = 0.6 bar, at operating capacity Q = 0.0011 m^3/s (at operating regime where in the entrance pipe the cavitation swirl is developed) are shown in Figure 11.



Sl. 11. *Rezultati HFT tlačnih utripov*

Fig. 11. *The results of the FFT analyses of the pressure pulsations*

Iz diagramov lahko sklepamo naslednje:

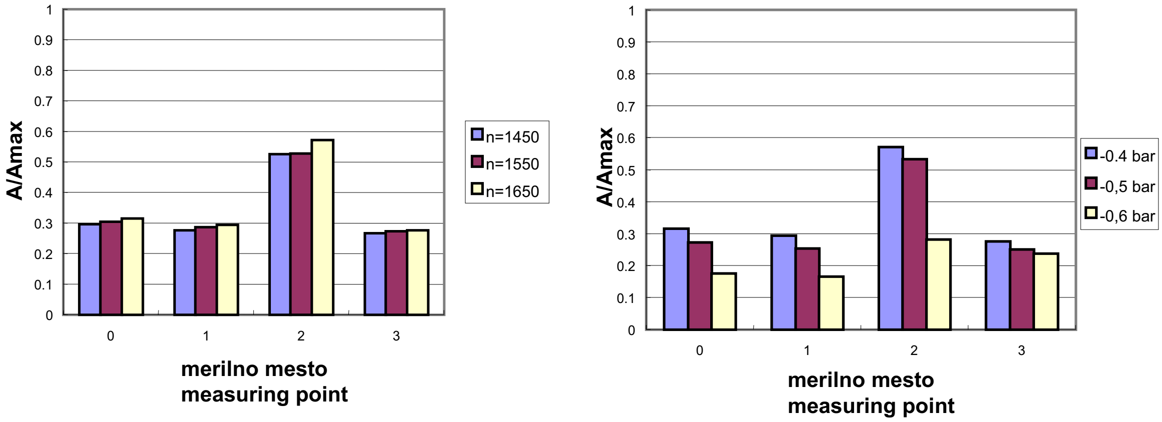
1. V legi P0 prevladujejo frekvenca vrtinca, frekvenca vrtilne hitrosti in njena prva harmonska ter druga harmonska frekvence prehoda lopatic. Opazna je tudi frekvenca vrtinca in sicer v skladu z ugotovitvami Grista med 2 in 10 Hz v odvisnosti od velikosti prerotacijske komponente hitrosti in glede na opletanje vrtinca. Pri velikem radialnem opletanju se namreč frekvenca vrtinca zniža z velikosti frekvence vrtenja rotorja na približno 1/3 le te.
2. V legah P1 in P2 prevladujejo prva višja harmonska vrtilne hitrosti, druga harmonska frekvence prehoda lopatic in višje frekvenčna nihanja povezana z lastno frekvenco merilnega sistema.
3. V legi P3 je prisoten prva višja harmonska vrtilne hitrosti in druga harmonska frekvence lopatic

Iz prikazanih diagramov je razvidno, da amplituda tlačnih utripanj raste z večanjem števila vrtljajev, kar je v skladu z večjimi pretoki, hitrostmi in vztrajnostjo; in pada z nižanjem tlaka nad spodnjo vodno gladino, kar je v neposredni zvezi z velikostjo tlakov v vstopnem vodu. Razvidno je tudi, da so največja tlačna utripanja

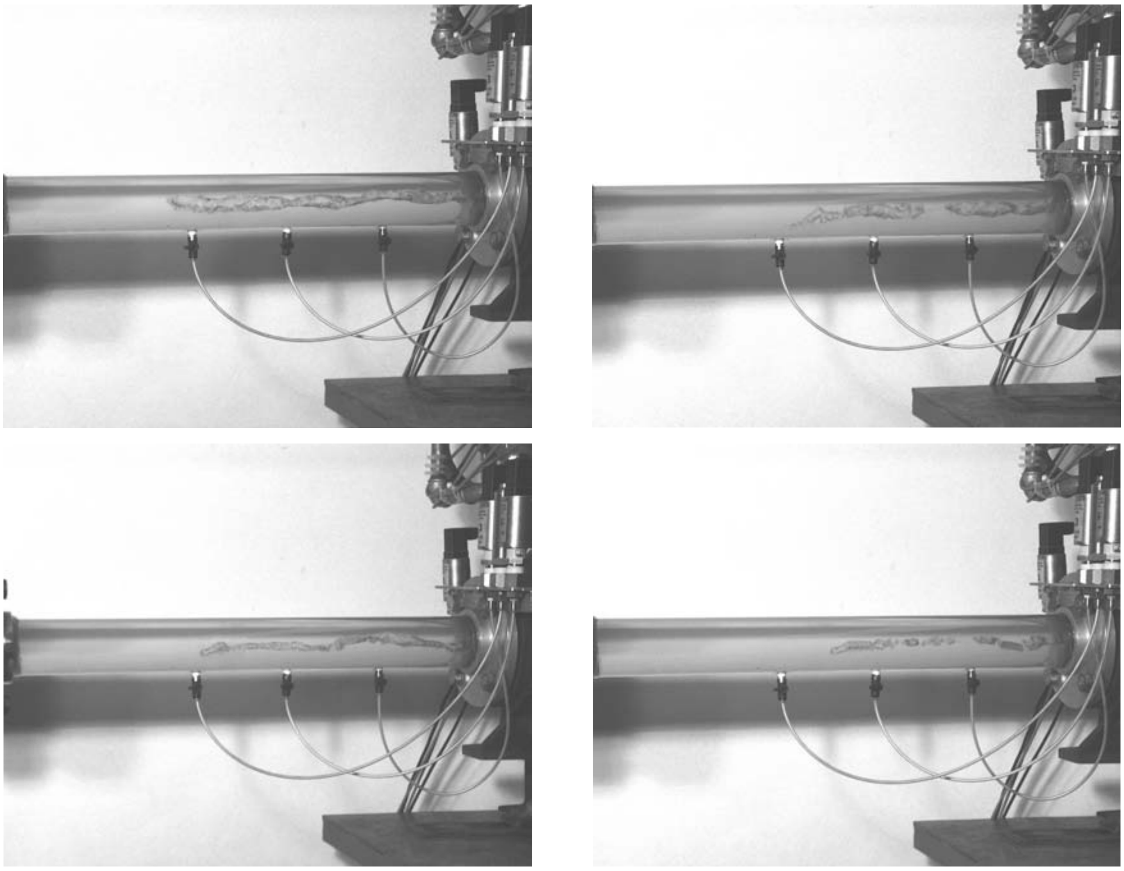
From the diagrams (Fig. 11) it can be concluded:

1. At the measuring position P0, the frequency of the cavitation swirl and its first higher harmonic, and the second higher harmonic of the blade passage frequency are dominant. The swirl frequency is between 2 and 10 Hz, which coincide with Grist's considerations. During big radial swirl swing the pulsation frequency is decreased to 1/3 of impeller speed frequency.
2. At the positions P1 and P2 the first higher harmonic of the impeller speed frequency and the second higher harmonic of the blade passage frequency are dominant. Present are also higher frequency peaks that belong to the measuring system eigen frequency.
3. At the position P3 the first higher harmonic of the impeller speed frequency and the second harmonic of the blade passage frequency are present.

From the pressure amplitudes recorded (Fig. 12), the pressure amplitude increase at increased impeller speed is evident. This is in good agreement with higher capacities where the velocities and flow inertia are increased. When the pressure over the water level in the reservoir decreased the pulsations amplitude decrease is evident. This is directly depending on flow pressure at entrance pipe. The larger measured pressure pulsations were taken at position P2,



Sl. 12. *Primerjava povprečnih tlačnih amplitud*
Fig. 12. *The average pressure amplitude comparison*



Sl. 13. *Trganje kavitacijskega vrtinca v vstopnem vodu črpalke in manjšanje njegovega premera*
Fig. 13. *Cavitation swirl tearing and reducing its diameter with pressure in the reservoir*

izmerjena v legi P2, kar je v skladu s trganjem vrtinca med legama P1 in P2 prikazanim na fotografijah 13 b in 13 d. Na fotografijah 13 c in d je razvidno tudi tanjšanje vrtinca z višanjem tlaka v rezervoarju.

6 SKLEP

Kavitacijski vrtinec je rezultat obratovanja črpalke s podoptimalnimi pretoki pri različnih tlakih nad spodnjo vodno gladino.

which is also in agreement with the photos in Figures 13 b and d, where the swirl tearing between positions P1 and P2 are evident. From 13 c and 13 d we can conclude that the swirl diameter is smaller when the pressure over the water in the reservoir is increased.

6 CONCLUSION

The cavitation swirl is a consequence of a pump operating with small, under-optimum capacities at different pressures above the water level of the reservoir.

Je rezultat zapletenih tokovnih razmer v rotorskih kanalih in v ustju rotorja.

Kavitacija se začne v rotorskih kanalih zaradi spremembe natočnega kota toka.

Razširitev kavitacijskega vrtinca iz območja rotorskih kanalov v vstopni vod je povezana z recirkulacijskim tokom in zmanjšanjem dejavnega dela vstopnega voda.

Kavitacijski vrtinec se pojavlja pri različnih vrtilnih hitrostih, tudi pri manjših od preračunske. Zaradi sekundarnih tokov v rotorskih kanalih, povzročenih s podoptimalnimi pretoki, ko črpalka obratuje v nestabilnem kavitacijskem obratovalnem režimu, lahko kavitacijski vrtinec povzroči kavitacijske poškodbe na tlačni strani rotorskih lopatic.

Dolžina kavitacijskega vrtinca se ne spreminja s spremembo števila vrtljajev in spremembo tlaka nad spodnjo vodno gladino, iz česar lahko sklepamo, da je dolžina kavitacijskega vrtinca odvisna od geometrije ustja.

Dolžina kavitacijskega vrtinca lahko znaša do 8 premerov vstopnega voda in je odvisna od njegove geometrije.

Tlak nad spodnjo vodno gladino vpliva na velikost prostorninskega toka plinaste faze in na premer kavitacijskega vrtinca.

Pri višjih tlakih nad spodnjo vodno gladino je premer kavitacijskega vrtinca manjši.

Frekvenca kavitacijskega vrtinca je med 4 in 10 Hz ter se spreminja s prerotacijsko vrtilno hitrostjo.

It is a result of complicated flow conditions in the impeller channels and in the impeller eye.

Cavitation starts in the impeller channels as a result of the entrance flow angle change.

The cavitation swirl transition from the area of the impeller channels up to the entrance pipe is connected with recirculation flow and with a decreased active flow area in the intake pipe.

The cavitations swirl appears at different impeller speeds (also at smaller speeds than its design speed). Because of secondary flows appearing at the impeller channels caused by small, under-optimum operating capacities, during pump operation in the unstable cavitation regime, the cavitation swirl can cause erosion damage to the impeller material at the pressure side of the impeller blades.

The cavitation swirl does not change its length during impeller speed change or pressure above the water level change. This means that the swirl length is a function of the pump impeller eye geometry.

The swirl length is based on the geometry of the pump entrance area and could propagate up to 8-entrance diameters length in the upstream direction.

Pressure above the water level in the reservoir defines the volume flow rate of the gas phase and the cavitation swirl diameter.

Higher pressures above the water surface in the reservoir cause a smaller swirl diameter and tearing at more places.

The frequency of the cavitation swirl is in a range between 4 and 10 Hz and is changed by the prerotation speed.

8 OZNAKE
8 SYMBOLS

absolutna hitrost na vstopnem polmeru	c_1	absolute velocity at entrance diameter
meridianska komponenta hitrosti na vstopnem polmeru	c_{1m}	meridional velocity component at entrance diameter
obodna komponenta absolutne hitrosti na vstopnem premeru	c_{1u}	circumferential component of absolute velocity at entrance diameter
konstanta	C	constant
gravitacijski pospešek	g	gravitational acceleration
totalna energija	H	total energy
čista pozitivna sesalna višina (ČPSV)	$NPSH$	netto positive suction head
tlak	p	pressure
tlak na vstopu v črpalko	p_1	pressure at pump inlet
polmer	r	radius
polmer stičišča vrtincev	R	radius of swirls connection
obodna hitrost na vstopnem polmeru	u_1	circumferential velocity at entrance diameter
hitrost	v	velocity
relativna hitrost na vstopnem polmeru	w	relative velocity at entrance diameter
koordinatna smer	x	coordinate direction
koordinatna smer	z	coordinate direction
cirkulacija	Γ	circulation
gostota	ρ	density
kotna hitrost	ω	angular velocity

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Naslov avtorjev: doc.dr. Andrej Predin
mag. Ignacijo Biluš
Fakulteta za strojništvo
Univerze v Mariboru
Smetanova 17
2000 Maribor

Authors' Address: Doc.Dr. Andrej Predin
Mag. Ignacijo Biluš
Faculty of Mecahnical Eng.
University of Maribor
Smetanova 17
2000 Maribor, Slovenia

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