METHODOLOGY OF 3D HYDRAULIC DESIGN OF A IMPELLER OF AXIAL TURBO MACHINE

Michal Varchola*, Tomaš Bielik*, Peter Hlbočan*

The paper deals with a hydraulic design of an axial propeller in function of pump and in function of turbine as well. A meridional cut of a turbo machine is proposed by classical method following guiding parameters. Experimental findings about an interaction between parameters of the turbo machine in pump and turbine mode are implemented in this procedure. Blade cuts are proposed following NACA airfoils with using of their aerodynamic characteristics, which are processed numerically. Also Voznesensky diagram, which is used to predict an influence of an airfoil in a blade grid was processed numerically as well. The result is a complete design with text-file output, which is directly capable to be used as an input for 3D environment (e.g. CATIA).

Keywords: *axial machine, turbine impeller, pump impeller, hydraulic solution*

1. Introduction

Hydraulic design of axial machine is characterized by a relatively complex procedure from design of meridional section to application of aerodynamic profiles into the blade cascade of axial impeller. Therefore numerical processing and graphical output to a 3D environment has a great importance because it leads to the operative hydraulic design of blade systems. The main subject of this paper is numerical processing and mechanism of the total 3D output process. Each turbomachine is fundamentally reversible. This means that it can work in the function of generator – pump as well as in the function of motor – turbine. The question of what are the parameters of the machine in the pump mode and in the turbine mode is also the subject of hydraulic design. In this paper, the same methodology is used for hydraulic design of the impeller of the pump and the turbine as well. Experimental results of pump mode operation are available for the comparison in Fig. 2.

Each hydraulic design consists of two almost independent procedures. The first one is the design of the pumpťs meridional section including the impeller and the second one is the calculation of the blades' shape on a cylindrical surface of the meridional section.

2. Hydraulic design of the meridional section of the pump and the turbine

The first principle is the constant meridional velocity from entering the impeller to exit from it. We utilize guiding parameters such as K_{m}, which implicitly contains optimizing elements obtained from the theoretical and experimental research. Basic dimensions of the meridional section are shown in Fig. 1.

* prof. Ing. M. Varchola, CSc., Ing. T. Bielik, Ing. P. Hlbočan, Institute of Chemical and Hydraulic Machines and Equipment, Faculty of Mechanical Engineering, Slovak University of Technology in Bratislava

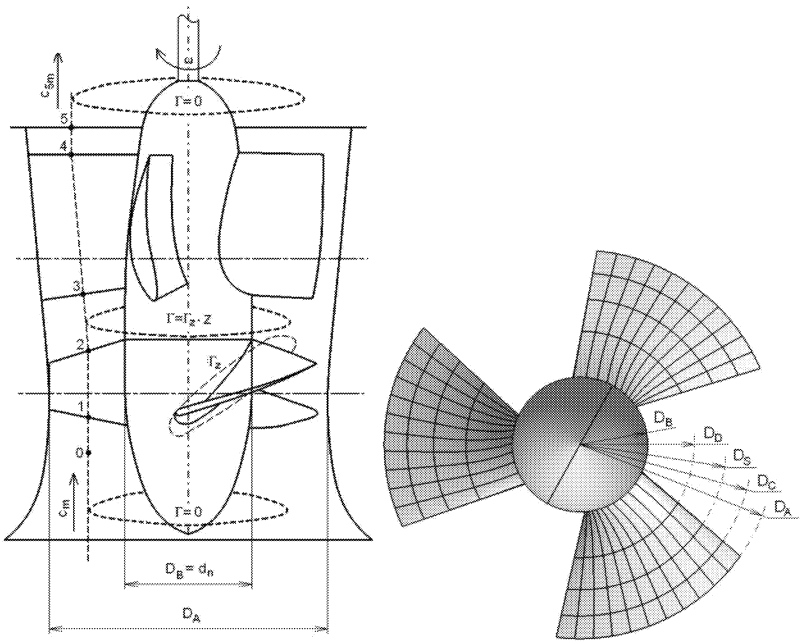


Fig.1: The main dimensions of the axial turbomachine

Hydraulic solution is based on Q, Y, n (we assume temperature of 20 °C) :

1. We calculate the specific speed

$$n_\mathrm{b} = n\,\frac{\sqrt{Q}}{Y^{0.75}}\ , \tag{1}$$

2. Guiding parameter :
   for the pump :

$$K_\mathrm{m} = 0.0688 + 0.733\,n_\mathrm{b}^{1.1}\ , \qquad 0.33 < n_\mathrm{b} < 1\ , \tag{2}$$

for the turbine :

$$K_\mathrm{mT} = 0.76\,n_\mathrm{bT} + 0.0206\ . \tag{3}$$

Then

$$c_\mathrm{mT} = K_\mathrm{mT}\,\sqrt{2\,g\,H_\mathrm{T}}\ . \tag{4}$$

3. Diameter of the pump's impeller (Fig. 1)

$$D_2 = D_\mathrm{A} = \sqrt{\frac{4}{\pi}\,\frac{1.04\,Q}{K_\mathrm{m}\,\sqrt{2\,Y_{(1)}}}\,\frac{1}{1-\left(\dfrac{D_\mathrm{B}}{D_\mathrm{A}}\right)^2}}\ . \tag{5}$$

Diameter of the turbine's impeller

$$D_\mathrm{2T} = D_\mathrm{A} = K_\mathrm{DT}\,\sqrt[3]{\frac{Q_\mathrm{T}}{n_\mathrm{T}}}\ . \tag{6}$$

Guiding parameter of the outer diameter :

$$K_\mathrm{DT} = 0.9781 - 0.3336\,\ln(n_\mathrm{bT})\ . \tag{7}$$

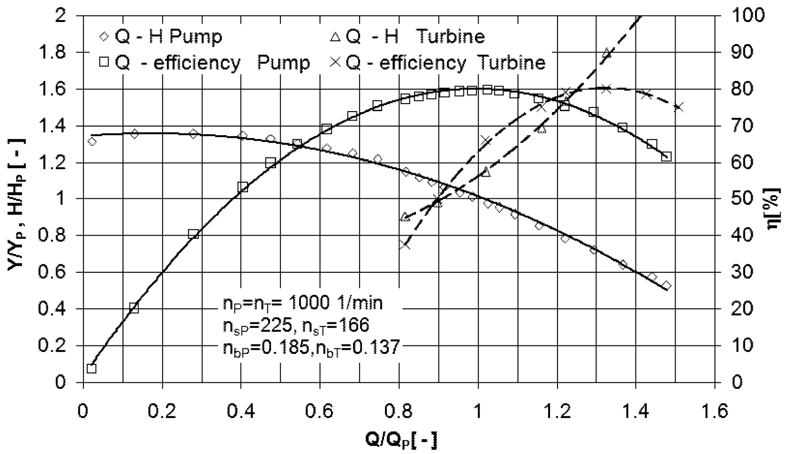


Fig.2: Characteristic of the pump and the turbine

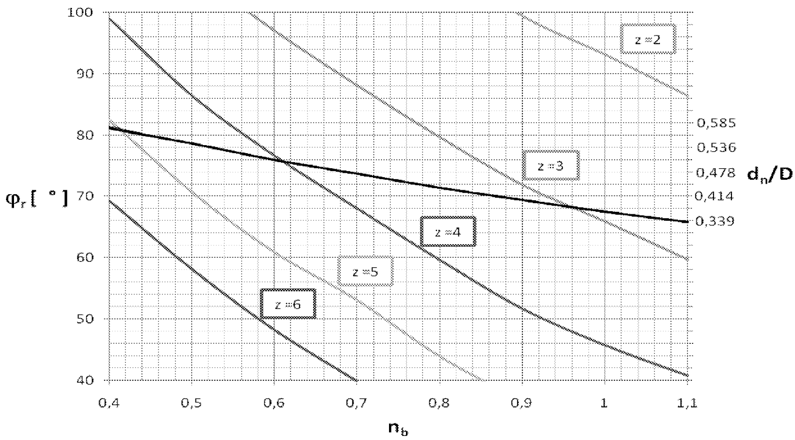


Fig.3: Dependence of the number of blades and n_b
(the meaning of the symbol φ_r is clear from the Fig. 5)

We obtain the diameter of the pump's hub as well as the turbine's hub. (We substitute n_bP using n_bT.) While

$$\frac{d_\mathrm{n}}{D} = \frac{D_\mathrm{B}}{D_\mathrm{A}} \doteq 0.63 - 0.346\,(n_\mathrm{bP} - 0.25)\ . \tag{8}$$

The blade's number z is dependent on the coefficient of specific speed and d_n/D rate according to Fig. 3 [3]. The curves on Fig. 3 were processed numerically.

3. Hydraulic design of blade section of the pump and the turbine

Hydraulic design of blade sections of cylindrical surfaces is based on the results of flow around the airfoils in the blade cascades. Cylindrical surfaces are divided according to the principle of constant flow as shown in Fig. 1.

The principle is to design the cascade's parameters in order to create circulation securing specific energy of the pump resp. use of its gradient. Circulation per one blade: $\Gamma = \Gamma_\mathrm{z}/z$, where z is the chosen number of impeller blades (see Fig. 3). Peripheral component of the mean relative velocity using the particular cylindrical section can be determined from the relation (Fig. 4).

$$w_{\mathrm{u}\infty} = u - \frac{c_{\mathrm{u2}}}{2} = u - \frac{Y}{2\pi\, D\, n\, \eta_{\mathrm{h}}} \ . \tag{9}$$

Then we can define angle β_∞ :

$$\beta_\infty = \arctan \frac{c_{\mathrm{m}}}{w_{\mathrm{u}\infty}} \ . \tag{10}$$

The angle of the cascade's inclination:

$$\beta_{\mathrm{e}} = \beta_\infty + \delta \ .$$

In the first iteration we choose the angle $\beta_{\mathrm{e}} = \beta_\infty$, then we choose $\beta_{\mathrm{e}} = \beta_\infty + \delta$, where δ is the chosen angle of the attack (Fig. 4).

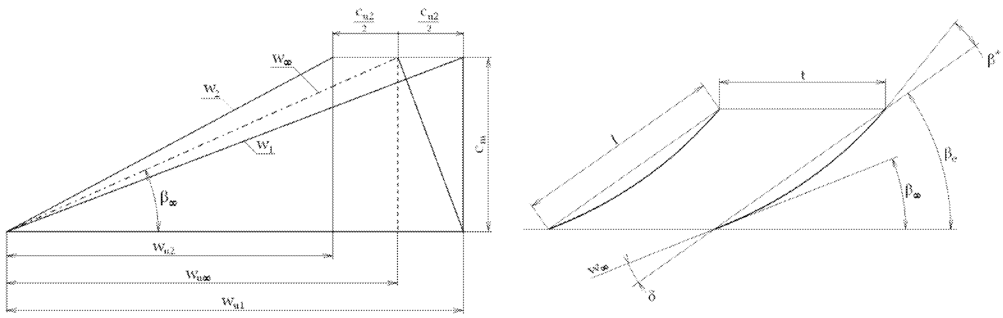


Fig.4: Velocity triangles and the cascade of axial pump

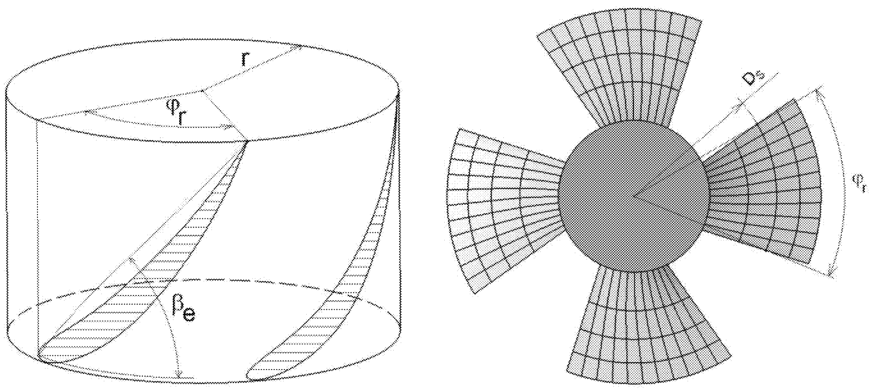


Fig.5: View on the cylindrical blade sections

The central angle φ_{r} (Fig. 5) depends on specific speed, $D_{\mathrm{B}}/D_{\mathrm{A}}$ ratio and blades' number z (Fig. 2). It can be calculated using numerically processed diagram (Fig. 3) with restrictive condition:

$$\varphi_{\mathrm{r}} = 9.4818\, n_{\mathrm{b}}^2 - 30.426\, n_{\mathrm{b}} + 94.502 \ . \tag{11}$$

After the calculation of the central angle φ_{r} we can estimate the length of the profile's chord:

$$l = \frac{\varphi_{\mathrm{r}} \dfrac{D}{2}}{\cos \beta_{\mathrm{e}}} \tag{12}$$

and relative pitch:

$$\frac{t}{l} = \frac{\pi\, D}{z\, l} \; . \tag{13}$$

Coefficient of cascade's impact ξ can be defined using the equations describing the diagram (Fig. 7) according to the relative pitch t/l and the angle of the cascade's inclination β_{e}. In order to process the calculation fully automatically with minimum user's input, it is necessary to transform this diagram into the digital form (Fig. 7). It is the most important change which determines the ratio of lift on a single profile in the tunnel to lift on the same profile located in the cascade [1]. Then the mean geometric velocity is:

$$w_\infty = \sqrt{c_{\mathrm{m}}^2 + w_{\mathrm{u}\infty}^2} \; . \tag{14}$$

The angle of profile's deflection:

$$\beta^* = \frac{\Gamma}{\xi\, w_\infty\, l} \; . \tag{15}$$

Change of the angle of attack $\Delta\delta$ will be defined using the diagram (Fig. 8) with dependence on the relative pitch t/l and the angle of profile's deflection β^*. The diagram was numerically processed as well. As a rule, the calculation can be more precise by changing the angle δ by $\Delta\delta$. The angle of the cascade's inclination:

$$\beta_{\mathrm{e}} = \beta_\infty + \delta + \Delta\delta \; . \tag{16}$$

Coefficient of cascade's impact: ξ – will be defined according to Fig. 7 with dependence on the relative pitch t/l and the angle of the cascade's inclination β_{e}. Single profile concludes lift factor $(c_{\mathrm{z}})_1$ and profile located in the cascade concludes lift factor (c_{z}).

$$\xi = \frac{(c_{\mathrm{z}})_1}{(c_{\mathrm{z}})} \; . \tag{17}$$

Lift factor for single profile:

$$(c_{\mathrm{z}})_1 = \frac{2\,\Gamma}{l\, w_\infty}\, \frac{1.6}{\xi} \; . \tag{18}$$

Then we control c_{z} using NACA profile. The induced angle of attack:

$$\delta_{\mathrm{i}} = 57.3\, \frac{(c_{\mathrm{z}})_1}{\pi\, \lambda} \; . \tag{19}$$

The angle of attack for the final span:

$$\delta_\lambda = \delta_{\mathrm{i}} + \Delta\delta \; .$$

Then we calculate the relative deflection $(m/l)_{40\%}$ in the distance $L^* = 0.4\, l$ (Fig. 6) [1]:

$$\frac{m}{l} = \frac{\sin^2\left(\dfrac{\beta^*}{2}\right)}{\sin\beta^*} - \frac{1}{20}\, \tan\frac{\beta^*}{5} \; . \tag{20}$$

Furthermore, we have to choose:

– the relative thickness of the profile,

– the relative distance of the maximum deflection.

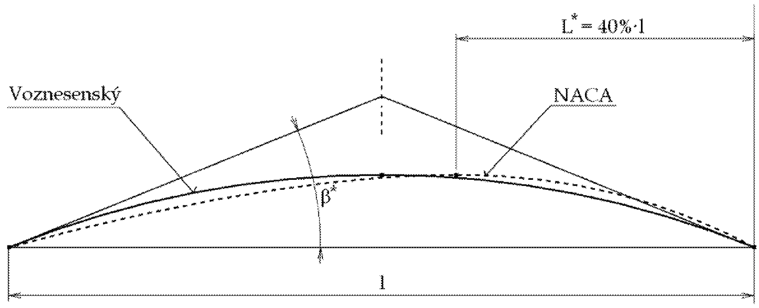


Fig.6: Centerline of the NACA profile compared to an equivalent circular arc of Voznesensky

Using calculated value m/l and chosen values t^*/l, L^*/l (which are chosen according to the stress and material) we can estimate the required NACA profile.

If the value (c_z) corresponds in tolerance 0–3 % with the value $(c_z)_1$ calculated using input parameters, then we can finish the calculation. Usually, the agreement is not reached for the first time and it is necessary to repeat the calculation with different angle of attack δ.

By the calculation we can obtain geometric characteristics m/l, t^*/l, L^*/l. Based on these characteristics and relations for the NACA profile [1], we define the complete blade's profile, which corresponds to the hydraulic design. Calculation is repeated for all five blade sections.

For the design of the entire blade's surface it is necessary to include the position of each blade section to match to the smallest torque (axis position normally resides in 40 % of the length of the profile).

Besides the correction of lift coefficients it is necessary to process a number of other corrections as well. Particularly the following corrections:

a) A correction to a difference of an airfoil span in a wind tunnel and in an impeller. While the profile wing, which was tested in a wind tunnel, has the finite span , blades in an impeller are restricted by a casing and by a hub of a pump, so they can be considered as profile wings with an infinite span. It can be expressed also that a wing span aspect ratio, which is given by a ratio , has a finite value in a case when the airfoil was tested in a wind tunnel but it has an infinite value in a case of profiled blades in an impeller.

b) A correction to different turbulence intensity in a wind tunnel and in an impeller. This equation is usually neglected because dimensions which are typical for turbomachines guarantee generally highly turbulent flow.

Voznesensky goes out from induced velocities with an infinite count of vortex filaments located around airfoils in a blade cascade (they are replaced by arcs), which are flown around by velocity w_∞. This velocity can be estimated according to a velocity triangle (Fig. 4). It follows the requirement that profiles in a blade cascade would be flown around optimally, it means they should be flown around with minimal losses and circulation caused by a blade cascade should correspondent to a given specific energy. It is necessary to replace a blade cascade which is represented by arcs by a blade cascade which has the same hydrodynamic properties. In this case arcs of a blade cascade are replaced by a NACA airfoil.

We choose value of L^* equal to $0.4\,l$ for designed airfoils because a camber line of an airfoil NACA is sufficiently coextend with an arc of a theoretical blade cascade of Voznesensky

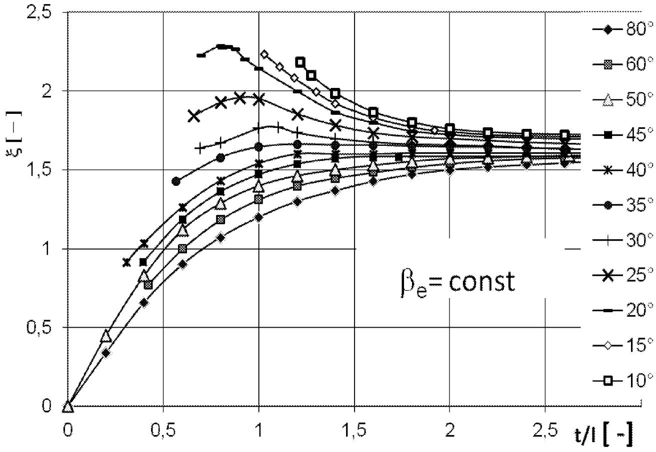


Fig.7: Dependency of a coefficient of cascade's impact ξ on relative pitch t/l and angle of a blade cascade inclination β_{e}

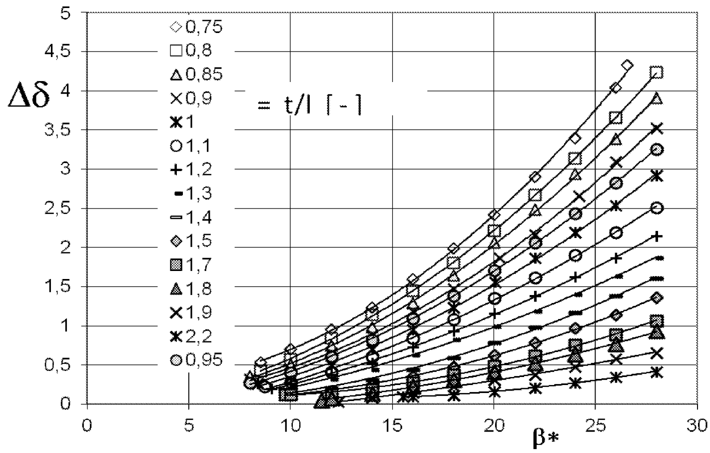


Fig.8: Dependency of a difference of an angle of attack $\Delta\delta$ on relative pitch t/l and angle of an airfoil deflecton β^* of a blade cascade β_{e}

(Fig. 6) for this value. Besides that the length $L^* = 0.4\,l$ is assumed as an optimal place for a pin of an impeller blade because of a favorable course of a torque due to hydrodynamic forces which force on a blade. A requirement on rigidity is not omitted because a maximal thickness of an airfoil t^* is usually located in an area of a maximal arching of an airfoil.

This algorithm follows the issue with more complexity because it comprises into calculation also a change of an angle of attack δ according to parameters of a blade cascade (according to a ratio t^*/l and an angle of arching of an airfoil β^* (Fig.8)).

Within the design of axial turbomachines is a procedure which governs a hydraulic design of an impeller based on theory of ala nasi. The complexity of a solution is a reason why only planar blade cascades can be investigated; it means only blade cascades with infinity thin camber profile. It is important to insist also on the requirement of blade rigidity, while impellers with swiveling blades are usually thicker than impellers with rigid blades. By this approach a utilization of theoretical exploration of planar blade cascades with experimental

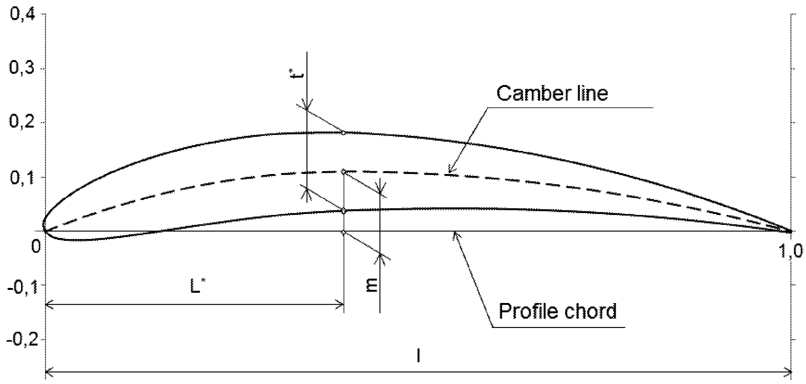


Fig.9: Main dimensions of NACA airfoil

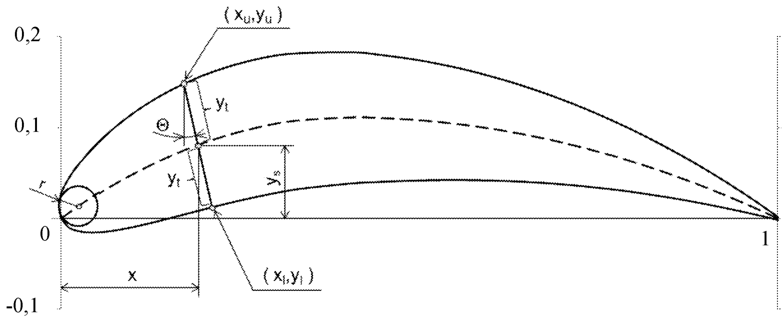


Fig.10: NACA airfoil – determining of vertices

results is monitored. Experimental results were obtained by measurements in wind tunnels (hydro tunnels) on NACA airfoils.

Design of NACA profile consists of a specification of an airfoil camber line and a calculation of a body of an airfoil follows. A camber line of an airfoil consists of two parabolic curves which have a common tangent line which is parallel with a profile chord. A distance between a tangent line and a leading edge is equal to L^*. We have to know geometric characteristics of a profile which was calculated during the design of an impeller to designate a shape of camber line. Then we can step up to calculation of NACA profile camber line of this algorithm.

a) It is necessary to choose coordinates from a leading edge of a profile where $x = 0$ to an end of the profile where $x = 1$ (Fig. 10).

b) After determining of necessary points with coordinates x we can begin with assessing of coordinates y_s of a camber line. These equations describe a camber line [4]:

$$y_\mathrm{s} = \frac{\dfrac{m}{l}}{\left(\dfrac{L^*}{l}\right)^2} \left[2\,\frac{L^*}{l}\,x - x^2\right] \quad \text{for } 0 \le x \le L* \,, \tag{21}$$

$$y_\mathrm{s} = \frac{\dfrac{m}{l}}{\left(1 - \dfrac{L^*}{l}\right)^2} \left[1 - 2\,\frac{L^*}{l} + 2\,\frac{L^*}{l}\,x - x^2\right] \quad \text{for } L^* < x \le 1 \,. \tag{22}$$

c) A half thickness of a profile y_{t} is for particular point of camber line $(x_{\mathrm{s}}, y_{\mathrm{s}})$ calculated according to the equation :

$$y_{\mathrm{t}} = \frac{\frac{t^*}{l}}{0.2} \left(0.2969\,\sqrt{x} - 0.126\,x + 0.3516\,x^2 + 0.2843\,x^3 - 0.1015\,x^4\right) \ . \tag{23}$$

d) We calculate the final coordinates of a upper profile curve $(x_{\mathrm{u}}, y_{\mathrm{u}})$ and lower profile curve $(x_{\mathrm{l}}, y_{\mathrm{l}})$ according to these equations :

$$x_{\mathrm{u}} = x - y_t\ \sin\Theta\ , \tag{24}$$

$$y_{\mathrm{u}} = y_{\mathrm{s}} + y_{\mathrm{t}}\ \cos\Theta\ , \tag{25}$$

$$x_{\mathrm{l}} = x + y_t\ \sin\Theta\ ,$$

$$y_{\mathrm{l}} = y_{\mathrm{s}} - y_{\mathrm{t}}\ \cos\Theta\ , \tag{26}$$

where

$$\Theta = \arctan\left(\frac{\mathrm{d}y_{\mathrm{s}}}{\mathrm{d}x}\right)\ . \tag{27}$$

We obtain coordinates of the whole profile in this way. Coordinates are expressed by non-dimensional numbers. Real coordinates are obtained if calculated coordinates are multiplied by a length of a profile chord l, which was calculated during a design of an impeller. Then it is necessary to place NACA airfoil into a blade so that an angle between an airfoil chord and x axis is equal to angle of blade cascade lean β_{e}. This algorithm is applied to all five blade sections.

y_{s} – a distance between a camber mean line and a chord in a general distance x.

y_{t} – a half thickness of an airfoil in a general distance x

r – a radius of a curvature of a leading edge can be evaluated according to this equation :

$$r = 1.1\,l\left(\frac{t^*}{l}\right)^2\ . \tag{28}$$

Aerodynamic characteristics give reciprocal dependency between geometrical and aerodynamic characteristics of an airfoil. Results of tests of stated series NACA can be summarized into diagrams which define a dependency of the most important aerodynamic characteristics on geometrical characteristics of an airfoil. For more accurate calculation of NACA airfoil a coefficient of resistance and a coefficient of torque are implemented. A coefficient of lift of a given airfoil is calculated according to the equation (29).

$$(c_{\mathrm{z}})_1 = \frac{\partial c_{\mathrm{z}}}{\partial \delta}\,(\delta_\lambda - \delta_0)\ . \tag{29}$$

A relation between δ_0 in degrees and L^*/l and m/l is given by interpolation equation (30) [2].

$$\delta_0{}^\circ = -83.3\,\frac{m}{l}\left(0.74 + \frac{L^*}{l}\right)\ . \tag{30}$$

A ratio decrease with a rising thickness almost linearly so a dependency can be expressed with a sufficient accuracy by the interpolation equation [2] :

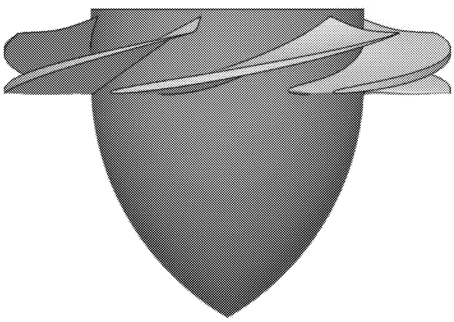
$$\frac{\partial c_{\mathrm{z}}}{\partial \delta} = 0.079 - 0.037\,\frac{t*}{l}\ . \tag{31}$$

There is an approximate geometrical similarity between the arc and the NACA airfoil if the camber mean line is coincident with the arc (Fig. 6). Then we can say that they are equal from the point of view of streaming. If values of a coefficient of lift for the airfoil and for the arc are roughly the same (according to equations 18 and 29) we say about dynamical similarity. This accord is possible to achieve by a suitable choice of an angle of attack δ.

For next applications it is necessary to realize that diagrams are made on a basis of tests on rectangular wings with a span aspect ratio (it means a ratio between a span and mean depth or ratio between a square of a span to a surface of a wing) $\Lambda = 6$ in gauge pressure tunnel NACA (an intensity of turbulence is about 2.5 %, a critical Reynolds number for a sphere is 120000) at Reynolds number of 3.5×10^6.

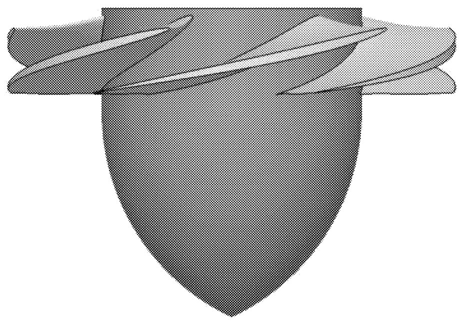
The realized algorithm of hydraulic design of the impeller of the pump and the turbine was tested on many control designs in a range of specific speeds between 0.3 and $1.2\,n_\mathrm{b}$, resp. $n_\mathrm{s} = 360-1460$ for a pump and $n_\mathrm{b} = 0.23-0.9$ for a turbine (n_s is 280–1100).

The resultant values also with 3D impeller are depictured in Fig. 11, and 12 and they are based on the algorithm stated above. The given parameters are the same for a calculation of the axial pump and the turbine as well.



n_{bP}	0.3	[-]	D_A	627	[mm]
Q_P	1	[m^3/s]	P_P	229	[kW]
Y_P	211.5	[J/kg]	z	6	[-]
n	16.66	[1/s]			

Fig.11: The impeller of an axial pump



n_{bT}	0.3	[-]	D_A	540	[mm]
Q_T	1	[m^3/s]	P_T	199	[kW]
H_T	21.6	[J/kg]	z	6	[-]
n	16.66	[1/s]			

Fig.12: The impeller of an axial turbine

A computational algorithm of the meridional section and blade sections is processed by the table editor Excel. Macros which comprise the whole computational algorithm were created in the program Visual Basic. As it was mentioned before all the necessary diagrams had to be numerically processed to provide the fully automatic calculation.

There is an ability of an interface between the table editor Excel and a graphical program CATIA. This ability was utilized by the design of the impeller of the axial pump and the turbine as well. Even before the creating of the interface we have to create an etalon 3D model of the impeller (special model for the pump and special for the turbine). All the constraints of the 3D model have to be parameterized including properly chosen links and technique. An output is a hydraulic solution of the impeller within a 3D setting.

After changing of input parameters (a design of the new impeller) we start a calculation in the table editor Excel which must be saved after recalculation. Then we obtain new calculated values of the impeller's parameters. After opening of the created document in the graphical program CATIA the dialog box occurs which asks whether the program should make changes which were noticed in the loaded Excel document. After accepting the changes of the impellert's geometry, it is going to be changed and new 3D model of the impeller is going to be obtained.

4. Conclusion

The presented approach of the hydraulic design of the axial turbomachine's impeller is important due to the fully automatic realization of a calculation. We use the conventional algorithm which utilizes geometrical and aerodynamic characteristics of the airfoil in the hydraulic design. Design of the axial turbine is based on the algorithm which was given by the design of the axial pump but the input parameters are corrected by special coefficients. An advantage of this approach is versatility with the respect to all details of the hydraulic design of the axial turbomachine. Another advantage is a processing which provides an output (blade cascade and the whole impeller of the pump or the turbine) realized in CATIA's environment. The output of the computational algorithm without any complementary conditions is the 3D model of the impeller of the axial pump or the turbine. This output can be utilized as a direct input into a 3D printer or as an input file for CFD simulation, eventually for a manufacturing of a model.

References

[1] Strýček O.: Hydrodynamické čerpadlá, STU Bratislava 1994
[2] Brůha O., Felber V., Smolař V.: Letecký Průvodce Díl 2, Matice česká 1939
[3] Nechleba M.: Vodní Turbíny jejich konstrukce a príslušenství, SNTL, Praha 1962
[4] http://people.clarkson.edu/˜pmarzocc/AE429/The%20NACA%20airfoil%20series.pdf
[5] Lewis R.I.: Turbomachinery performance analysis, ISBN 0340631910, Elsevier Science and Technology books, 1996
[6] Bláha J., Brada K.: Hydraulické stroje, SNTL, Praha 1992
[7] Lobanof V.S., Ross R.R.: Centrifugal Pumps – Design and Application
[8] Varchola M., Gančo M., Strýček O., Sikhart R.: Výskum diagonálneho čerpadla 150 BQZ v turbínovej prevádzke HZ95/95 SjF STU
[9] Varchola M., Sikhart R.: Diagonálne čerpadlo v turbínovej prevádzke, HYDROTURBO 2010
[10] Bielik T.: Hydraulický návrh axiálneho stroja v 3D prostredí, Diplomová práca SjF STU 2010

List of symbols

Q	[m^3/s]	Flow rate
Y	[J/kg]	Specific energy
P	[W]	Power input
ΔY_{kr}	[J/kg]	Net positive suction specific energy
n_{b}	[–]	Specific speed
β	[rad]	Blade angle
c_{m}	[m/s]	Meridional velocity
D	[m]	Diameter
n	[1/s]	Rotating
z	[–]	Blade number
c	[m/s]	Absolute velocity
w	[m/s]	Relative velocity
u	[m/s]	Peripheral velocity
t	[m]	Pitch (span)
L	[m]	Span of a blade
φ	[rad]	Mid angle
Λ	[rad]	Angle of a streamline lean
ϱ	[kg/m^3]	Density
l	[m]	Chord length
c_{z}	[–]	Lift coefficient
Γ	[m^2/s]	Circulation

Subscripts

n	Nominal, normal
m	Meridional
u	Peripheral
z	Axial, loss
∞	Infinite number of infinitesimally thin blades
1	Inflow
2	Outflow

Table of the resultant hydraulic solution

Input parameters :		PUMP			TURBINE			
Flow rate	Q =	1	[m^3/s]		1,33		λ_Q=	1,33
Specific energy	Y =	49	[J/kg]		80		λ_H=	1,622
Rotating	n =	16,66	[1/s]		16.66			
Density	ρ =	1000	[kg/m^3]		1000			

Calculation of main dimensions of meridional section:							
Specific speeds	n_b =	0,900	[-]	Diameter of the impeller	D =	0,472	[m]
	n_s =	1092,0	[-]	Hub diameter	d_n =	0,191	[m]
Efficiency	η =	0,847	[-]	Diameter at section B	D_B =	0,191	[m]
Hydraulic Efficiency	η_h =	0,890	[-]	Diameter at section D	D_D =	0,288	[m]
Power input	P =	55	[kW]	Diameter at main streamline	D_S =	0,360	[m]
Guiding parameter	K_m =	0,719	[-]	Diameter at section C	D_C =	0,420	[m]
Meridional velocity	c_m =	7,120	[m/s]	Diameter at section A	D_A =	0,472	[m]
Ratio of diameters	d_n/D =	0,405	[-]	Diameter at section F	D_F =	0,135	[m]

Hydraulic design of blade sections

	Quantities	Sec B	Sec D	Sec S	Sec C	Sec A	Sec F	Units
Blade number	z =	4						[-]
Circulation	Γ_z =	3,304						[m^2/s]
Circulation per one blade	Γ =	0,826						[m^2/s]
Peripheral component of velocity	c_{u2} =	5,503	3,651	2,923	2,507	2,230	7,789	[m/s]
Peripheral component of velocity of mean geometrical relative velocity	$w_{u\infty}$ =	7,252	13,253	17,371	20,700	23,568	5,952	[m/s]
Angle	β_∞ =	44,498	28,260	22,299	18,991	16,818	50,13	[°]
angle of blade cascade's inclination	β_e =	44,498	28,260	22,299	18,991	16,818	50,13	[°]
Mid angle	φ_r =	52,084						[°]
Blade chord length	l =	0,122	0,149	0,177	0,202	0,224	0,096	[m]
Relative pitch	t/l =	1,233	1,522	1,599	1,634	1,654	1,108	[-]
Coefficient of blade cascade's impact	x =	1,592	1,730	1,757	1,807	1,781	1,354	[-]
Mean geometrical velocity	w_∞ =	10,163	15,045	18,774	21,890	24,620	9,280	[m/s]
Angle of an airfoil inclination	β^{**} =	24,040	12,237	8,123	5,936	4,823	39,39	[°]
Difference of angle of attack	$\Delta\delta$ =	1,465	0,162	0,088	0,067	0,062	4,123	[°]
Selected angle of attack	δ =	3,310	1,830	1,180	0,830	0,640	-0,330	[°]
Calculation with higher precision:								
Blade cascade lean	β_e =	45,964	28,423	22,387	19,058	16,881	54,255	[°]
Length of an airfoil chord	l =	0,125	0,149	0,177	0,202	0,224	0,105	[m]
Relative pitch	t/l =	1,202	1,520	1,598	1,633	1,654	1,010	[-]
blade cascade's impact	x =	1,483	1,733	1,758	1,808	1,782	1,343	[-]
blade cascade's influence for $t/l = \infty$	$(x)_1$ =	1,600						[-]
Lift coefficient	$(c_z)_1$ =	1,404	0,681	0,453	0,331	0,269	2,020	[-]
Control of $(c_z)_1$ on an airfoil NACA								
Induced angle of attack	δ_i =	4,271	2,071	1,377	1,007	0,818	6,143	[°]
Angle of attack for finite blade span	δ_l =	9,047	4,064	2,645	1,904	1,521	9,937	[°]
Relative deflection	m/l =	0,102	0,051	0,034	0,025	0,020	0,172	[-]
Relative distance of a maximal deflection	L^*/l =	0,400						[-]
Maximal thickness of an airfoil	t^* =	14,000	12,000	10,000	8,000	6,000	6,000	[mm]
Relative thickness of an airfoil	t^*/l =	0,112	0,081	0,057	0,040	0,027	0,057	[-]
Difference of c_z as a function of angle of attack		0,075	0,076	0,077	0,078	0,078	0,077	[-]
Radius of leading edge	r =	1,726	1,064	0,622	0,349	0,177	0,377	[mm]
Angle of attack	δ_{01} =	-9,705	-4,884	-3,235	-2,362	-1,919	-16,33	[°]
Lift coefficient	(c_z) =	1,404	0,680	0,452	0,331	0,268	2,020	[-]

Received in editor's office: November 6, 2012
Approved for publishing: February 14, 2013