THE 3D BLADE SURFACE GENERATION FOR KAPLAN TURBINES USING ANALYTICAL METHODS AND CAD TECHNIQUES

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Abstract: *In the recent past, when the CAD techniques were not disposables, the operations in discussion were made through graphical constructions or in graphic-analytical mode, direct on the board or graph paper, using a lot of time and obtaining low precision. When the results were unsatisfactory all was taken again from the beginning. In actual conditions, having at command program mediums and graphical representation with high performance, their employment became a necessity in the graphical construction of the blade surfaces and the adjustment of the airfoils from different calculus sections.*

In this paper, simultaneously with CAD techniques are presented the results obtained for a hydraulic turbine blade computed through well established methods. As a result of hydrodynamic calculus, the geometrical characteristics of the airfoil cascades in each calculus section were obtained. From hydrodynamic conditions results also the stagger angle of the profiles and the adjustment in blade assembly is made ulterior from geometrical conditions. The development of those phases must use the CAD techniques. Plotting the used airfoils at a reasonable resolution, necessitate for the pressure side at least 100 points and the same figure for the suction side. Because the great number of computing cross sections (minimum 10), the manually plot became counterproductive. The CAD possibilities consist in the use of the TurboPASCAL and AutoLISP programs for 3D plotting in AutoCAD. The data files are introduced in the AutoLISP program which realizes the 3D plotting. The obtained graphical image is analyzed using the facilities of the AutoCAD. If adjustments are needed, the numerical program must be again operated to modify the necessary parameters. Finally the 3D blade image is introduced in the work drawing together with all needed details.

Keywords*: Kaplan turbine, blade surface, CAD techniques*

1. Introduction

The hydrodynamic calculus represents only a small part of the Kaplan turbine design, [1], [2]. An important next step is the graphical construction of the blade and assembling of them into the runner. In the past, when CAD techniques were not available, these operations were made by graphical constructions or graphic-analytically, directly on the drawing board or on the scale paper, which take a lot of time and has reduced precision, [5], [6]. In the case of unsatisfactory result all must be taken from the beginning. In the present, having access to computer programs provided

also with very performing graphical representation, it is a necessity to use them for graphical definition of the Kaplan turbine runner blade.

From hydrodynamic calculus, are obtained the geometrical characteristics of the airfoil cascades in each calculus section, [1], [2]. The ordering and numbering of the calculus sections is from 0 to n, beginning with the hub section (section 0) and finishing with tip section (section n). The chosen number of sections is 11. Those initial dates for the graphical construction of the blade are presented in Table 1.

Table 1. Runner geometric characteristics obtained with a classical method, using NACA airfoils

Number of section	Profile Type	Radius of calculus section r [mm]	Length of the profile l [mm]	Stagger angle $\beta_s[°]$	Relative thickness [d/l]
0	NACA 4412	600	694.2	36.0	0.12
1	NACA 4411	665	712.6	29.5	0.11
2	NACA 4410	730	748.3	25.0	0.10
3	NACA 4409	795	793.4	22.0	0.09
4	NACA 4408	860	841.9	19.7	0.08
5	NACA 4407	925	890.5	17.9	0.07
6	NACA 4407	990	939.8	16.4	0.06
7	NACA 4406	1055	988.4	15.2	0.05
8	NACA 4406	1120	1036.0	14.2	0.04
9	NACA 4406	1185	1083.0	13.3	0.03
10	NACA 4406	1250	1128.0	12.5	0.02

2. Airfoil design in the own system of representation

Initially, the geometry of the airfoils is taken in agreement to the catalogue data or the relations given for the NACA airfoil numerical code (with four, five or six digits), [7].

In dimensionless terms all dimensions are reported to length "l" of the profile chord. The NACA airfoils are given by the camber line function, $\dfrac{y_f}{l}\left(\dfrac{x}{l}\right)$, and the thickness function, $\dfrac{y_d}{l}\left(\dfrac{x}{l}\right)$. The thickness function defines semi-thickness of the profile measured to the normal of the camber line, Figure 1. Relative abscissa of the maximum thickness is at $\dfrac{x_{d\,max}}{l} = 0,3$
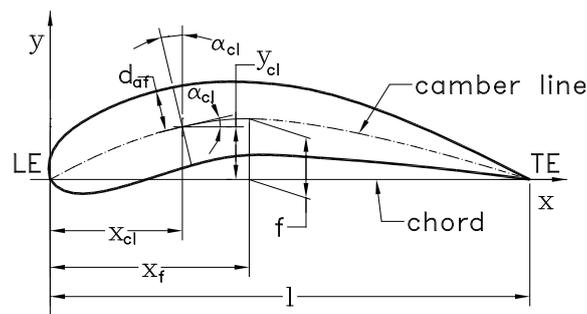
Figure 1. NACA airfoil geometric construction

It can be seen that the camber function is defined by two parabola arcs perfectly jointed so that airfoil camber line to be continues on the interval [0, 1]. Profile construction and implicit the blade is made through N points computed and distributed on the pressure side and respectively on the suction side. The simplest distribution (digitization) of the points is a uniform one and is realized using equal intervals for x between 0 and 1. This digitization has the disadvantage that in the zones where the curvature of the profile is more pronounced (especially at the leading edge) the smoothness of the curve is not very good. Therefore the correct option is the use of non-uniform distribution for different domains, amplifying the number of points at the leading edge. Working on the interval [0, 1], the best non-uniform distribution is offered by trigonometric functions. If N is the maximum number of intervals and *i* is the index of a current point, $i=0...N$, let it be t_i the argument of the trigonometric function defined of being, [3]:

$$t_i = \frac{\pi}{2}\frac{1}{N}i \qquad (i = 0,1,...N) \tag{1}$$

The abscissa of the digitization x_i, is computed with the relation:

$$x_i = 1 - \cos(t_i) \tag{2}$$

It can be observed immediately that for the extremities, just the extremes values, 0 respectively 1 are obtained and the maximum density area is in the proximity of 0, i.e. at the leading edge of the profile. This option will be reflected in all ulterior calculus and will affect favorably the accuracy and smoothness of the blade surfaces.

Forwards, to simplify the relations, the dimensionless expression will be abandoned and the employed values are:

- (x_{ex}, y_{ex}), the coordinate of the current point for the suction side of the airfoil
- (x_{in}, y_{in}), the coordinate of the current point for the pressure side of the airfoil
- (x_{cl}, y_{cl}), the coordinate of the current point for the camber line of the airfoil
- $d_{af}(x_{cl})$, thickness function

The abscissa x_{cl} is identical with x_i, abscissa of non-uniform distribution.

According to Figure 1, and using the calculated values for the camber line function and the thickness function, the points for the pressure side and the suction side can be obtained with the relations, [3], [4]:

$$\begin{cases} x_{in} = x_{cl} + d_{af}\sin(\alpha_{cl}) \\ y_{in} = y_{cl} - d_{af}\cos(\alpha_{cl}) \end{cases} \tag{3}$$

$$\begin{cases} x_{ex} = x_{cl} - d_{af}\sin(\alpha_{cl}) \\ y_{ex} = y_{cl} + d_{af}\cos(\alpha_{cl}) \end{cases} \tag{4}$$

The value α_{sc} represents the angle of the tangent at the camber line in the chosen point. It results from the derivative of the camber line function in the respective point. For NACA profile with four digits the derivatives of the two parabola arcs are:

$$\begin{cases} y'_{f1} = \dfrac{f_{max}}{x^2_{f\,max}} \left(2 \cdot x_{f\,max} - 2x\right) \\[4mm] y'_{f2} = \dfrac{f_{max}}{\left(1 - x_{f\,max}\right)^2} \left(2 \cdot x_{f\,max} - 2x\right) \end{cases} \tag{5}$$

3. The transposition of the airfoils to the stagger angle β_s, into the developed plane.

Starting from the representation of the figure 1, the profile will be transposed in the specific working position, in the cascade airfoil, of the corresponding section of the runner. This operation is made in the developed plane of the calculus section. The operation is realized in two stages:
- stage I: the translation of the coordinate system origin in the blade spindle axis,
- stage II: the rotation around the blade spindle axis until the stagger angle β_s is reached.

The two stages are illustrated in Figure 2 respectively Figure 3.
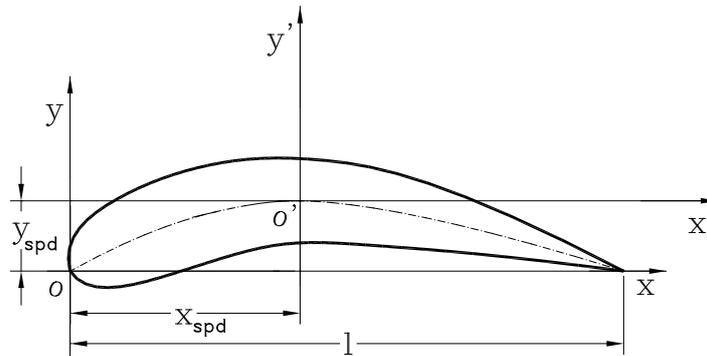
Figure 2. Stage I, translation of the axis system origin till the blade the spindle axis

The relations used for this translation are:

$$\begin{cases} x' = x - x_{spd} \\ y' = y - y_{spd} \end{cases} \tag{6}$$
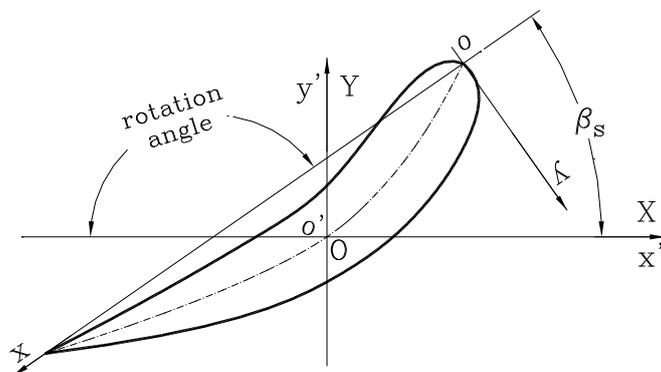
Figure 3. Stage II: the rotation around the blade spindle axis until the stagger angle, β_s is reached

The relations for the rotation around the blade spindle axis are:

$$\begin{cases} X = -x'\cos(\beta_s) + y'\sin(\beta_s) \\ Y = -x'\sin(\beta_s) - y'\cos(\beta_s) \end{cases} \tag{7}$$

4. The transposition of the airfoils from plane on the computing cylindrical surfaces

This stage is used for the 3D representation of one or all runner blades. This representation is helpful, in design phase, to see how the airfoils are assembled and correlated in the blade.

Working with the cylindrical surfaces, the most adequate coordinate system is a cylindrical one. The initial data for this transposition are the coordinates (X, Y) of the transposed profile at the stagger angle β_s in the developed plane. Let the current coordinates of the cylindrical coordinate system to be (r, θ, z). The coordinate r is the radius of the calculus section, R_{sec}. The θ angle, in radians, results from the condition:

$$R_{sec} \cdot \theta = X \quad \Rightarrow \quad \theta = \frac{X}{R_{sec}} \tag{8}$$

The plane coordinate Y became z.

$$z = Y \tag{9}$$

This mode of representation facilitates the rapid definition of all blades roundabout the rotor hub, because every homologue point for a certain radius differ only with an angle $\theta_{i,j}$ for every blade. Having the number of blades z_b, the angular step θ_b it is immediately obtained:

$$\theta_b = \frac{2\pi}{z_b} \tag{10}$$

The current angle $\theta_{i,j}$ can be computed with the relation:

$$\theta_{i,j} = \theta_{i,j} + j \cdot \theta_b \quad \text{where j=0,1,...(z_b-1)} \tag{11}$$

In AutoCAD, [8], [10], the representation of the 3D mesh request Cartesian coordinates (x, y, z) which resulted from the cylindrical coordinates according to the relations:

$$\begin{cases} x = r \cdot \cos\theta \\ y = r \cdot \sin\theta \\ z = z \end{cases} \tag{12}$$

In figures 4, 5 and 6 it is represented the 3D images of the runner. This representation has a great importance in the design phase because it gives the visualization of every surface detail of the blade regardless of the chosen angle, [4].
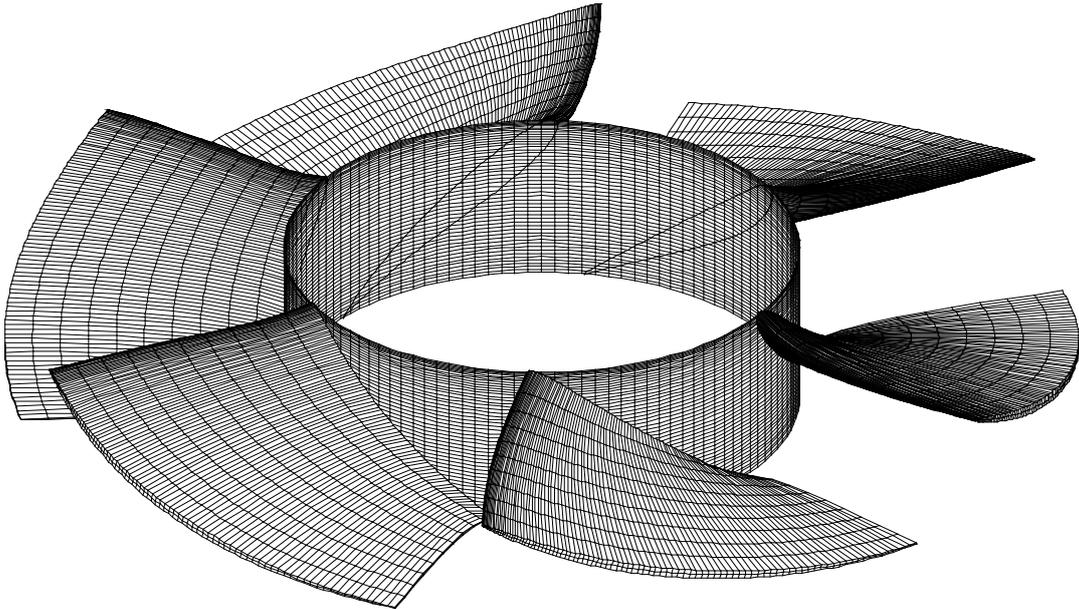
Figure 4. 3D image (hide type) of the runner (blades built with NACA airfoils)

Figure 5. 3D image (render type) of the runner

Figure 6. 3D image, frontal view of the runner

5. Sequences from the AutoLISP program

```
;AutoLISP program for 3D, [8], representation of the blades for a Kaplan turbine runner, using
NACA profiles
 (defun c:ROT()
(setq Cod (getstring "\n the data file code must be introduced: "))
 (setq Z_1 (getint "\n the number of blades must be introduced: "))
 (setq Z_2 Z_1)
 (setq FISIN (strcat "D:\\KAPLAN_3D\\DATE\\INSP_" Cod ".DAT"))
 (setq FISEX (strcat "D:\\KAPLAN_3D\\DATE\\EXSP_" Cod ".DAT"))
…………………………………………………………………………………………
(setq fis (open FISIN "r"))
     (setq poz0 (read-line fis))
     (setq Imax (atoi (substr poz0 1 3)) Jmax (atoi (substr poz0 5 3)))
     (setq poz1 (read-line fis)) (setq Xsup (atof (substr poz1 1 6)) Ysup (atof (substr poz1 8 6)))
     (setq poz2 (read-line fis)) (setq Xinf (atof (substr poz2 1 6)) Yinf (atof (substr poz2 8 6)))
     (setq poz3 (read-line fis)) (setq Deltx (atof (substr poz3 1 6)) Delty (atof (substr poz3 8 6)))
     (setq poz4 (read-line fis)) (setq Scx (atof (substr poz4 1 6)) Scy (atof (substr poz4 8 6)))
(CLOSE fis)
(command "limits" (list Xinf Yinf) (list Lx Ly))
(command "zoom" "all")
…………………………………………………………………………………………………
;------------- Plot the pressure side of the runner blades ----------------------------------
  (setq Imesh (1+ Imax))
  (setq Jmesh (1+ Jmax))
  (setq Fi0 (/ (* 2 pi) Z_2))
(setq dFi 0.0)
(setq k1 1)
(While (<= k1 Z_1)
  (command "3DMESH" Jmesh Imesh)
(setq fis (open FISIN "r"))
    (setq poz1 (read-line fis))
    (setq poz2 (read-line fis))
    (setq poz3 (read-line fis))
    (setq poz4 (read-line fis))
    (setq poz5 (read-line fis))
(setq j 0)
(While (<= j Jmax)
  (setq i 0)
  (while (<= i Imax)
      (setq poz7 (read-line fis))
      (setq Fi (atof (substr poz7 1 23)) Ri (atof (substr poz7 25 23)) Zi (atof (substr poz7 49 23)))
```

```
          (setq x (COS (+ (* k1 Fi0) Fi dFi)))
          (setq y (SIN (+ (* k1 Fi0) Fi dFi)))
          (setq x1 (* Ri x))
          (setq y1 (* Ri y))
          (setq x2 (* x1 Scx))
          (setq y2 (* y1 Scy))
          (setq z2 (* Zi Scy))
            (command (list x2 y2 z2))
     (setq i (1+ i)))
     (setq j (1+ j)))
     (CLOSE fis)
     (setq k1 (+ k1 1)))


;-------------Plot the surface of the hub -------------------------------------
     (setq Fi0 (/ pi 60))
     (setq Imesh (/ (+ Imax 2) 2))
(command "3DMESH" Imesh 121)
 (setq fis (open FISEX "r"))
     (setq poz1 (read-line fis))
     (setq poz2 (read-line fis))
     (setq poz3 (read-line fis))
     (setq poz4 (read-line fis))
     (setq poz5 (read-line fis))
     (setq i 0)
     (while (<= i (+ Imax 2))
        (setq poz7 (read-line fis))
        (IF (> i 0) (setq poz7 (read-line fis)))
        (setq Fi (atof (substr poz7 1 23)) Ri (atof (substr poz7 25 23)) Zi (atof (substr poz7 49 23)))
        (setq j 0)
       (While (<= j 120)
          (setq x (COS (* j Fi0)))
          (setq y (SIN (* j Fi0)))
          (setq x1 (* Ri x))
          (setq y1 (* Ri y))
          (setq x2 (* x1 Scx))
          (setq y2 (* y1 Scy))
          (setq z2 (* Zi Scy))
          (command (list x2 y2 z2))
       (setq j (1+ j)))
     (setq i (1+ i)))
     (CLOSE fis)
;------------- Plot the suction side of the runner blades----------------------------
 (setq fis (open FISEX "r"))
     (setq poz0 (read-line fis))
     (setq Imax (atoi (substr poz0 1 3)) Jmax (atoi (substr poz0 5 3)))
     (setq poz1 (read-line fis))
     (setq Xsup (atof (substr poz1 1 6)) Ysup (atof (substr poz1 8 6)))
     (setq poz2 (read-line fis))
     (setq Xinf (atof (substr poz2 1 6)) Yinf (atof (substr poz2 8 6)))
     (setq poz3 (read-line fis))
     (setq Deltx (atof (substr poz3 1 6)) Delty (atof (substr poz3 8 6)))
     (setq poz4 (read-line fis))
     (setq Scx (atof (substr poz4 1 6)) Scy (atof (substr poz4 8 6)))
(CLOSE fis)
     (setq Imesh (1+ Imax))
```

```
   (setq Jmesh (1+ Jmax))
   (setq Fi0 (/ (* 2 pi) Z_2))
(setq dFi 0.0)
(setq k1 1)
(While (<= k1 Z_1)
 (command "3DMESH" Jmesh Imesh)
(setq fis (open FISEX "r"))
    (setq poz1 (read-line fis))
    (setq poz2 (read-line fis))
    (setq poz3 (read-line fis))
    (setq poz4 (read-line fis))
    (setq poz5 (read-line fis))
(setq j 0)
(While (<= j Jmax)
  (setq i 0)
  (while (<= i Imax)
     (setq poz7 (read-line fis))
     (setq Fi (atof (substr poz7 1 23)) Ri (atof (substr poz7 25 23)) Zi (atof (substr poz7 49 23)))
     (setq x (COS (+ (* k1 Fi0) Fi dFi)))
     (setq y (SIN (+ (* k1 Fi0) Fi dFi)))
     (setq x1 (* Ri x))
     (setq y1 (* Ri y))
     (setq x2 (* x1 Scx))
     (setq y2 (* y1 Scy))
     (setq z2 (* Zi Scy))
        (command (list x2 y2 z2))
  (setq i (1+ i)))
  (setq j (1+ j)))
  (CLOSE fis)
  (setq k1 (+ k1 1)))
 (command "VPOINT" "1,1,0.8" "")
)
```

It can be seen that the starting data are those included in Table 1. The subsequent processing contains a very great volume of calculus. All the six stages of this computation were programmed in TurboPascal language, [9], with a source code having more than 1300 lines. The obtained data were transferred in files, graphical processed in AutoCAD by means of AutoLISP program.

6. Conclusions

The presented procedure is completely computerized, without appealing to the classical method, without using graph paper or board graphical constructions. The advantages of the method are:
- the increase of precision,
- the increase of the working speed,
- immediately verifications of blade geometrical shape and indications if some small corrections of airfoils length and thickness are necessary,
- realizing the files with the 3D geometry of the whole runner which can be used for ulterior modeling of flow in FLUENT, TASK FLOW or other specialized programs,
- a great part of graphical representations and tables can be used directly in the execution project or even in the manufacture of the blade,
- the data being in electronic format are transposable immediately to another scale and used to realize the model runner.

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