Simplified Design Method and CFD Analysis of Blade Profile for Hydraulic Turbine

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ABSTRACT

Among the 4th industrial revolution, the structure of turbines has been wide spread and used in different professions. Turbo drill in the down-hole motors already has a developed designed procedure, especially the method of designing blade profile which is the most vital part for influencing mechanical properties. By learning from turbo drill's designing procedure, using quantic polynomial and empirical formula, a simple and rapid way was find to design a hydraulic turbine's blade profile. The result shows that blade's mechanical property could be improved 6-8% percent averagely by using this method. And this kind of method could also be applied in hydro axial turbine designing process no matter in what area.

KEYWORDS: blade profile, quantic polynomial, simple, rapid.

INTRODUCTION

As one of the three most valuable newly-developing instruments, down-hole drill motor occurred in the end of the 20th century. Through 20 years research and test, turbo drill, the major component of down-hole drill motor, already had a developed designing procedure. Turbo drill's mechanical properties depend on the hydraulic properties, and hydraulic properties depend on the turbine's properties. Turbine structure is a kind of rotary type motive power machinery, and widespread used in different areas, from industrial technology, transportation and communication to aerospace engineering. According to the working medium of classification, there are wind turbine, hydro turbine and gas turbine. In different flowing method, there are axial turbine, radial turbine and outward flow turbine. To find a simple and rapid way design hydro axial turbine's blade profile, the process of designing turbo drill used for reference and combining with some designing experience in other professions. To make it clear, we supposed a down-hole drilling rig which has a turbine structure, and used some of its real parameters in construction site [4, 10, 11].

Limited by the space and structure of drilling rig, usually turbine's blade profile is a crucial element of turbine's properties. General process of designing a blade profile is: Firstly, according to drilling rig's parameter and applying for reality, choose the liquid parameter like velocity and quantity of flow. Secondly, confirm the structure parameter of turbine. Thirdly, design blade profile[1,2]. There are many methods to design blade profile. From early times, combine circles and straight lines to create curve, use hyperbola or parabola. Recent times, utilize the method of polynomial and spline or successive circles. But blade profile should be smooth and curvature changed continuously. The early times method could not guarantee it and some of recent times means are much more complicated, usually contains complex equations and geometrical relationships. To show a simple way to design hydraulic turbine, and keep its mechanical property run well, which utilize the experience from designing turbo drills. Here is an example using polynomial way to design blade profile and CFD to simulate working conditions [3, 6].

CONFIRM LIQUID PARAMETERS

In this part, we need to combine utilizing purpose and conditions of reality to confirm liquid parameters. To show the universality, the data from an ultra-deep drilling program belongs to CCSD (Chinese Continental Scientific Drilling) will be used [5]. As shown in Table 1:

Table 1: Turbine's liquid parameter

Name and unit	quantity	Name and unit	quantity
Outer diameter/mm	127	Inner diameter/mm	90
Quantity flow/(L•s^{-1})	10~15	Pressure drop/MPa	<3
Rotate speed/(r•min^{-1})	200~500	Torque/(N•m)	1000~2000
Fluid density/(kg•m^{-3})	1000~2000		

CONFIRM GEOMETRIC PARAMETER

There is no certain formula for designing blade profile. But some experience and methods from designing turbo drill turbine could be consulted. In the same time, practical application and feasibility of machining should also be included [7]. The main parameters should be considered are shown in Fig. 1.

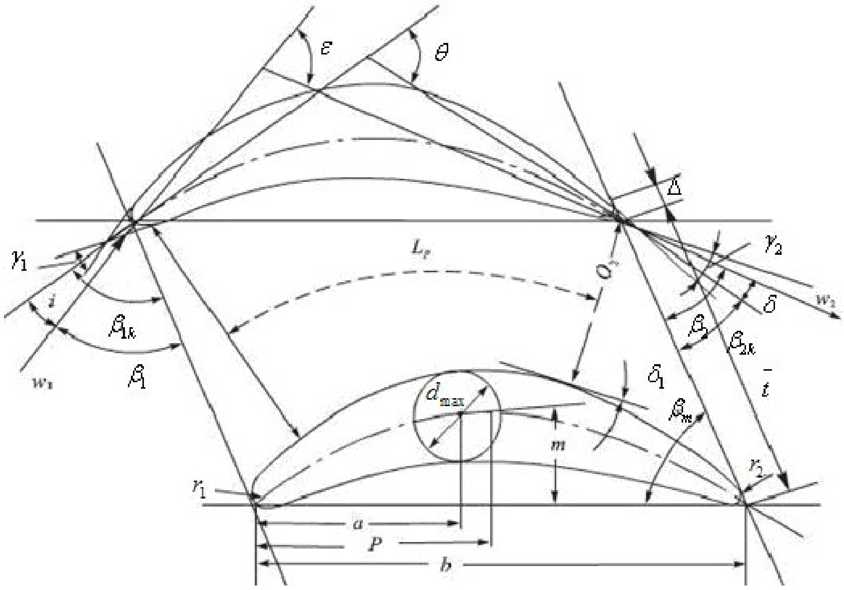

Figure 1: Geometric parameters of a single blade [8]

Radius of leading and trailing edge circle r1、r2

$$r_1 = 0.6\sim0.8 \text{ or } 0.8\sim1.0 \text{ or } r1 = (0.008\sim0.081)\, b \tag{1}$$

$$r_2 = 0.4\sim0.5 \text{ or } 0.3\sim1.0 \text{ or } r2 = (0.005\sim0.025)\, b \tag{2}$$

Height of blade in axial direction H

$$H = b\text{-}2\times0.5\text{-}0.5 \tag{3}$$

Established angle of blade βm

$$\beta_m = 38.82 - 0.2959\beta_1 + 0.914\beta_2 + 0.3718\delta + 25.48\frac{a}{B} \tag{4}$$

Chord length of blade B

$$B = H/\sin\beta_m \tag{5}$$

Location of maximum thickness on a blade, referred to experience of turbo drill design:

$$a/B = 0.3\sim0.45 \tag{6}$$

Maximum thickness of blade dmax

$$(\frac{d}{B})_{opt} = 0.09\sim0.19 \text{ or } (\frac{d}{B})_{opt} = 1\text{-}A\sin\beta_1\text{ ， } d_{max} = (0.09\sim0.19)\, B \tag{7}$$

Structure line of blade Ln

$$B = \frac{L_n - r_1 - r_2}{\sin\beta_m} + r_1 + r_2, \quad L_n = \sin\beta_m(B - r_1 - r_2) + r_1 + r_2 \tag{8}$$

Leading taper angle γ_1 and trailing taper angle γ_2

$$\gamma_1 = 3.51\arctan\frac{\frac{d_{max}}{2}-r_1}{\left(\frac{a}{B}\right)L_n - r_1}=14° \quad \gamma_2 = 2.16\arctan\frac{\frac{d_{max}}{2}-r_2}{\left(1-\frac{a}{B}\right)L_n - r_2}=12° \tag{9}$$

relative pitch of blade $\bar{t}$

Relative pitch of blade is used to represent density of all the blades on the turbine, in case of preventing broken stones or rubber debris block tunnel of flow, the coefficient could be greater than usual. $\bar{t}=0.9$.

Pitch of blade t, number of blades Z

$$t=\bar{t}\cdot B \tag{10}$$

$$Z=3.14D/t \tag{11}$$

Profile angle of turbine

To confirm the profile angle of turbine, we should use three non-dimensional coefficients-axial velocity coefficient ($\overline{C_z}$), impact coefficient (ma), circulating coefficient ($\overline{C_u}$). According to experience, entrance profile angle (β_{1k}) and exit profile angle (β_{2k}) are between 70° and 110° [8]. To simplify the process of solving, and depends on turbine's liquid parameters before, we make $\beta_{1k}=95°$ and $\beta_{2k}=75°$.

In the subsequent designs, we can adjust these parameters to make turbine's hydraulic performance suit for requirement. Because there are 14 different parameters, it makes blade profile design more accurate. And change one or two parameters would not change probable form, so there is no need to repeat the whole design progress from the beginning. In conclusion, geometric parameters would be used as follows in Table 2:

Table 2: Turbine's geometric parameters

Parameter	Quantity	Parameter	Quantity	Parameter	Quantity
r_1	0.8mm	d_{max}	5.17mm	B	28.72mm
r_2	0.4mm	L_n	22.28mm	T	13
H	22mm	γ_1	14°	β_{1k}	95°
β_m	50°	γ_2	12°	β_{2k}	75°
a	11.49mm	Z	20		

TURBINE'S BLADE PROFILE DESIGN

To use quantic polynomial and MATLAB generate blade profiles, a blade profile should be put in a rectangular coordinate system. After creating a geometrical relationship between blade's geometric parameter and profile, we use quantic polynomial to express its profile. Finally, by solving equations, we can get the blade profile expression equation in quantic polynomial [8]. The rectangular coordinate system is as follows in Fig. 2:

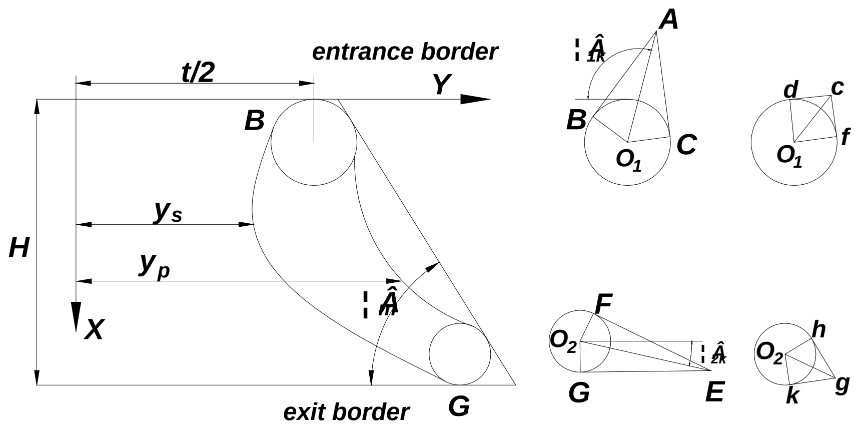

Figure 2: Rectangular coordinate system of blade profile [8]

There are two individual lines in a blade profile-pressure surface and suction surface, the quantic polynomial equations of them are as follows:

$$y_p = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5 \tag{12}$$

$$y_s = b_0 + b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4 + b_5 x^5 \tag{13}$$

First and second derivative equations indicated below:

$$y_p' = a_1 + 2a_2 x + 3a_3 x^2 + 4a_4 x^3 + 5a_5 x^4 \tag{14}$$

$$y_s' = b_1 + 2b_2 x + 3b_3 x^2 + 4b_4 x^3 + 5b_5 x^4 \tag{15}$$

$$y_p'' = 2a_2 + 6a_3 x + 12a_4 x^2 + 20a_5 x^3 \tag{16}$$

$$y_s'' = 2b_2 + 6b_3 x + 12b_4 x^2 + 20b_5 x^3 \tag{17}$$

By using turbine blade's geometric parameter express unique points in the rectangular coordinate system, which also on the pressure and suction surface lines, we can establish two linear systems of equations (as follows) and use MATLAB to solve equations.

$$\begin{bmatrix} 1 & x_{p1} & x_{p1}^2 & x_{p1}^3 & x_{p1}^4 & x_{p1}^5 \\ 1 & x_{pn} & x_{pn}^2 & x_{pn}^3 & x_{pn}^4 & x_{pn}^5 \\ 0 & 1 & 2x_{p1} & 3x_{p1}^2 & 4x_{p1}^3 & 5x_{p1}^3 \\ 0 & 1 & 2x_{pn} & 3x_{pn}^2 & 4x_{pn}^3 & 5x_{pn}^3 \\ 0 & 0 & 2 & 6x_{p1} & 12x_{p1}^2 & 20x_{p1}^3 \\ 0 & 0 & 2 & 6x_{pn} & 12x_{pn}^2 & 20x_{pn}^3 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{bmatrix} = \begin{bmatrix} y_{p1} \\ y_{pn} \\ y_{p1}' \\ y_{pn}' \\ y_{p1}'' \\ y_{pn}'' \end{bmatrix} \begin{bmatrix} 1 & x_{s1} & x_{s1}^2 & x_{s1}^3 & x_{s1}^4 & x_{s1}^5 \\ 1 & x_{sn} & x_{sn}^2 & x_{sn}^3 & x_{sn}^4 & x_{sn}^5 \\ 0 & 1 & 2x_{s1} & 3x_{s1}^2 & 4x_{s1}^3 & 5x_{s1}^4 \\ 0 & 1 & 2x_{sn} & 3x_{sn}^2 & 4x_{sn}^2 & 5x_{sn}^2 \\ 0 & 0 & 2 & 6x_{s1} & 12x_{s1}^2 & 20x_{s1}^3 \\ 0 & 0 & 2 & 6x_{sn} & 12x_{sn}^2 & 20x_{sn}^3 \end{bmatrix} \begin{bmatrix} b_0 \\ b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \end{bmatrix} = \begin{bmatrix} y_{s1} \\ y_{sn} \\ y_{s1}' \\ y_{sn}' \\ y_{s1}'' \\ y_{sn}'' \end{bmatrix} \tag{18}$$

Through writing a program in MATLAB these two equation systems can be solved easily, and by using function "plot" we can get one image of these two lines so that blade profiles can be observed directly. The result of it is shown below in Fig. 3:

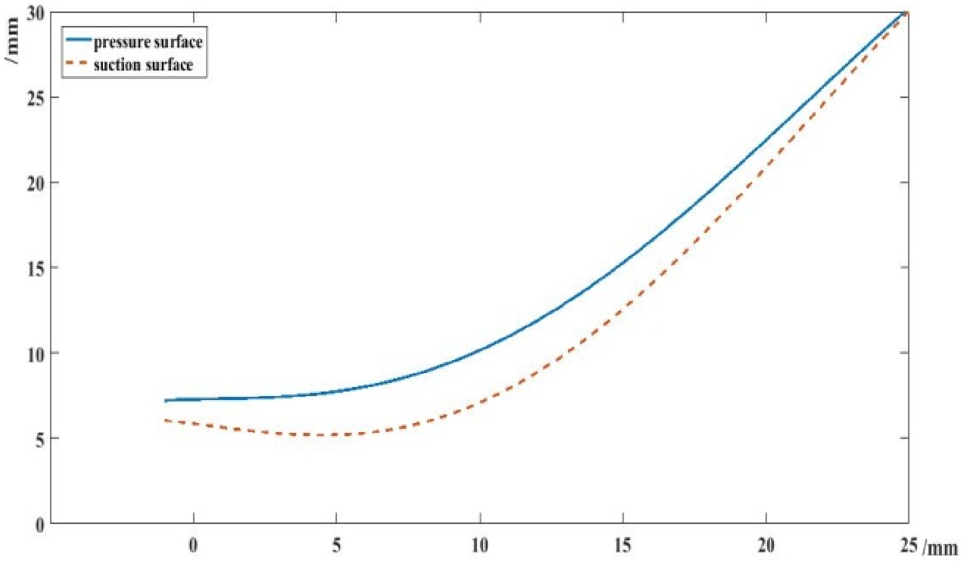

Figure 3: The result of a blade profile

CFD ANALYSIS OF HYDRAULIC EFFICIENCY

To emphasize this designing method's advantages and effectiveness, through comparing flow velocity and pressure in the simulation results among three kinds of blades-straight blade, helical blade and quantic polynomial blade. Simulation results indicated below in Fig. 4, Fig. 5, Fig 6:

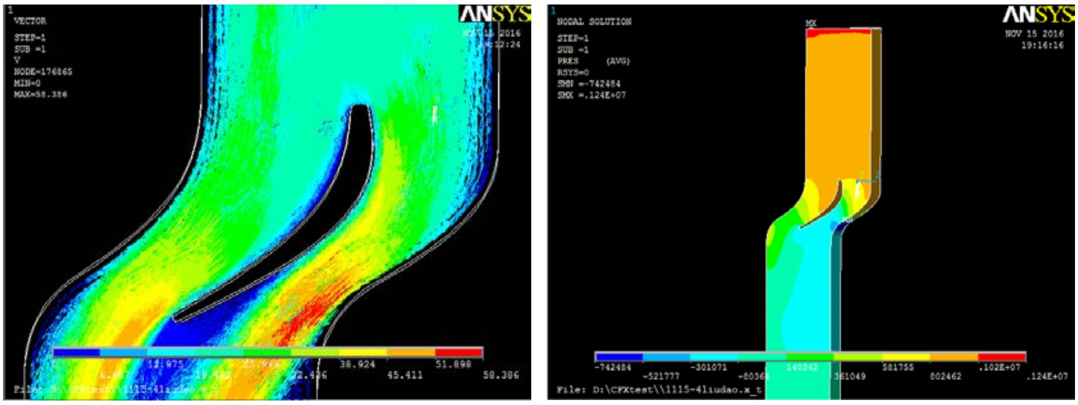

Figure 4: velocity lines and pressure contour of quantic polynomial blade

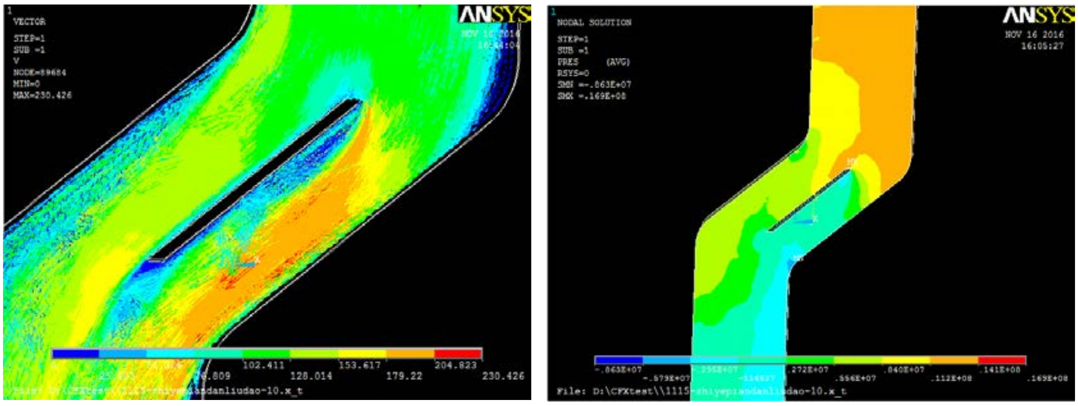

Figure 5: velocity lines and pressure contour of straight blade

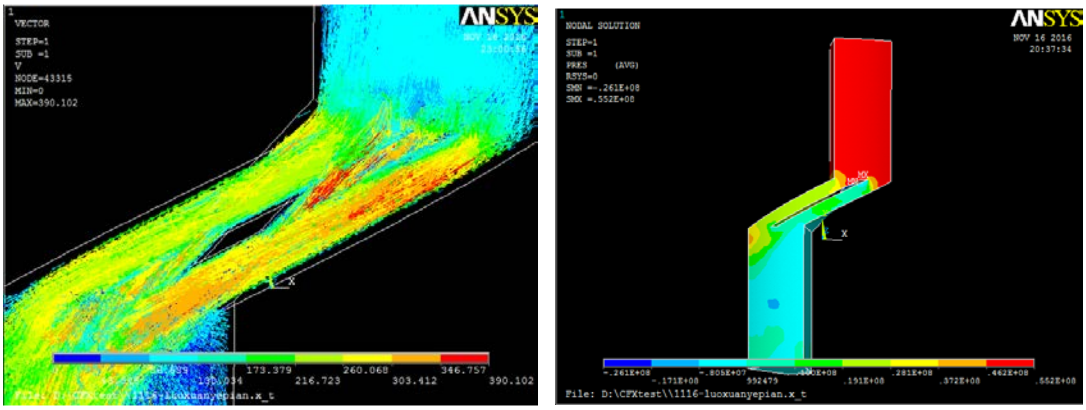

Figure 6: Velocity lines and pressure contour of helical blade

By comparing these three kinds of blade's velocity lines, a conclusion we can get: when working liquid flow into the blade channel and strike pressure surface, the velocity of flows speed up, kinetic energy and some of gravitational potential energy turned into blade's mechanical energy. In these three conditions, velocity of blade speeded up 200% averagely by passing the channel. But in first figure, the lines are smoother, and velocity changed more uniformly. That will give turbine a better mechanical property.

In the pressure contour pictures, the pressure changed 88.7%, 83.9% and 81.9% in each of blade channel. The quantic polynomial blade's pressure conversion percent was higher than rest of two. In the condition that velocity conversion percent was similar, that means turbines mechanical of quantic polynomial is 6% and 8% than those two kinds of blade. Pressure distribution is uniform also gives it a better conversion working condition.

SUMMARY

Through this turbine blade profile design process, after confirming liquid and geometric parameters and combining with practical application requirements, a kind of blade profile was designed simply and rapidly.

(1) The blade profile are controlled by 14 different parameters, change one or two of them would accurately alter the profile, and repeat all the design process is not necessary.

(2) By using MATLAB we can observe a profile image directly. And with pressure and suction lines' equations we can use 3D modeling software to make a 3D model which can be used in subsequent experiments.

(3) In the CFD simulation, the quantic polynomial blade has a better working condition and mechanical properties. The conversion percent of it can improve 6-8% averagely. It means that this method of designing turbine blade is simple, rapid and effective.

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