AERODYNAMIC DESIGN OF MULTI-STAGE AXIAL FLOW COMPRESSORS USING VISUAL BASIC

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Abstract. A software was developed in Visual Basic to estimate the aerodynamic design of multi-stage axial compressor. Given mass flow rate, compression ratio, gas properties, number of blades per stage, and other parameters, it determines the number of stages, fluid-dynamic properties and flow angles for each stage, and the three-dimensional geometry for each blade with the C4 airfoil family. The software interface allows for partial results and graphs to be analyzed. The blade geometry may be exported for CFD simulation. The procedure employed is in reasonable accord with accepted open literature.

Keywords: Turbomachinery, axial compressor, aerodynamic design

1. INTRODUCTION

Axial compressors are those where the fluid flows in the rotor axis direction, therefore increasing its pressure through the rotation of the rotor blades. It is an equipment frequently used in industrial gas turbines. In previous work, the overall geometry and velocity diagrams for the rotor were determined given mass flow rate, compressor ratio, gas properties, number of blades per stage and some design parameters, Moreira et al. (2009). In this work, that was expanded to also determine and export the three-dimensional geometry of the blades, allowing for CFD simulation, and give a preliminary analysis of the compressor behavior in an off-design situation. Also, a graphic interface was created using Visual Basic 6.0 to ease the use of the code.

2. TECHNIQUE APPROACH

2.1 Preliminary Geometry

The following method was based in the work of Aungier (2003). At first, it is necessary to know the mass flow and the compression ratio the compressor will work in, as well as the external ambient conditions and the fluid to be compressed. This project allows for air, helium and CO_2 as the fluid, and also permits that the user specifies other fluids properties. The fluid will be treated as an ideal gas, and the state equation for ideal gas will be used.

Before estimating the number of stages and each stage's properties, a reference radius must be chosen. It is defined as:

$$r_c = \sqrt{\frac{r_h^2 + r_s^2}{2}} \tag{1}$$

The velocity of the reference radius is:

$$U_c = U_s \sqrt{\frac{1 + (d_r)^2}{2}} \tag{2}$$

Through the velocity of the reference radius, the axial velocity was determined. An interactive method was then created to calculate temperature, velocity and pressure. Using the initially established mass flow rate, the initial area of the section was determined, and then the diameters of hub, reference radius and shroud were calculated for both the inlet and the outlet of the compressor. The diameter for the shroud is assumed as constant in this project. The blade length for those stages was estimated as well.

To project the number of stages, an average enthalpy per stage needs to be chosen. The total isentropic variation is:

$$h_{iso} = \frac{\gamma}{\gamma - 1} T_1 \Gamma((\frac{p_n}{p_1})^{\frac{\gamma}{\gamma-1}} - 1) \tag{3}$$

At this point parameters such as flow coefficient (4), reaction ratio (5) and stage loading factor (6) are defined.

$$\phi = \frac{c_x}{U} \tag{4}$$

$$R = \frac{h_2 - h_1}{h_3 - h_1} \tag{5}$$

$$\psi = \frac{h_{03} - h_{01}}{U^2} = \frac{c_{y2} - c_{y1}}{U} \tag{6}$$

The hub and reference radius for each stage are now calculated in an interactive method, with six equations:

$$T_c^i = T_c^{i-1} + \frac{\psi_c U_c^2}{\frac{\gamma}{\gamma-1}\Gamma\eta_s} \tag{7}$$

$$p_c^i = p_c^{i-1}\left(\frac{T_c^i}{T_c^{i-1}}\right)^{\frac{\gamma}{\gamma-1}\eta_s} \tag{8}$$

$$\rho_c = \frac{p_c}{T_c\Gamma} \tag{9}$$

$$d_h = \sqrt{(d_s)^2 - \frac{4\dot{m}}{\pi\rho_c\phi_c U_c}} \tag{10}$$

$$r_c = \frac{d_s}{2}\sqrt{\frac{1 + (d_r)^2}{2}} \tag{11}$$

$$U_c = \omega r_c \tag{12}$$

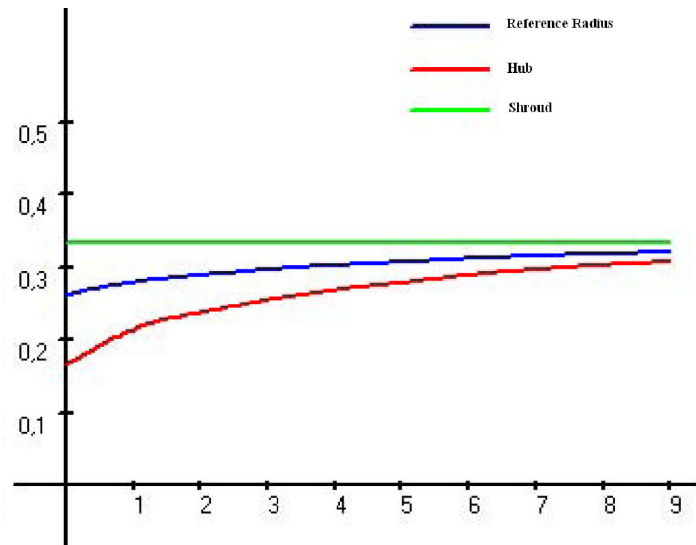Figure 1 shows a profile generated by the program.

Figure 1. Axial section of compressor

2.2 Velocity Diagrams

The velocity diagrams are of extreme importance, as the blade geometry cannot be determined without them. Five span sections were chosen in the radial direction in each stage where the velocity diagrams were resolved. Those sections were: hub, shroud, reference radius, and the averages between the reference radius and the other sections ($\{r_h, (r_h + r_c)/2, r_c, (r_c + r_s)/2, r_s\}$). Figure 2 represents the velocity diagram.

It is necessary to model the vortex type to obtain C_y distribution. Hence, the following equations were applied at inlet and outlet, respectively:

$$\frac{c_{y1}}{U_c} = (1 - R_c)(r_c/r)^n - \frac{\psi_c}{2}(r_c/r)^m \tag{13}$$

$$\frac{c_{y2}}{U_c} = \frac{c_{y1}}{U_c} + \psi_c(r_c/r) \tag{14}$$

In this project, a constant reaction vortex flow was used: $m = 1$ and $n = -1$.
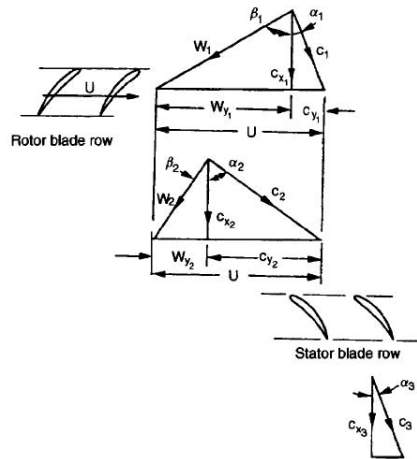
Figure 2. Velocity diagrams

3. 2D-Geometry

The two-dimension design is based on empirical cascade models. To begin the design, the user must choose the ratio between the blade maximum thickness and the chord and the number of blades for each stage. In this project, the C4 airfoil family was used.

The solidity of the chosen section was calculated through the approximation made by $Howell(1942)$ and frequently used in preliminary performance estimation, the tangent difference rule:

$$\tan\beta_1 - \tan\beta_2 = \frac{1.55}{1 + 1.5s/l} \tag{15}$$

It is then possible to determine the blade chord (c), and the angles that pertain to the cascade. From the cascade geometry, shown in Figure 3, four equations are constructed:

$$\alpha = \beta_1 - \gamma \tag{16}$$

$$i = \beta_1 - \kappa_1 \tag{17}$$

$$\delta = \beta_2 - \kappa_2 \tag{18}$$

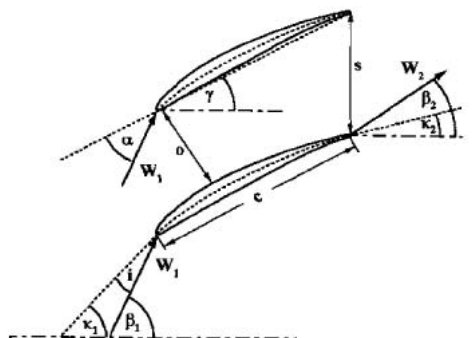$$\theta = \kappa_1 - \kappa_2 \tag{19}$$

Figure 3. Two-dimension cascade diagram

Through the equations 16 and 17 and the empirical models for deviation and incidence angles, an interactive method is built to find the inlet and outlet angles between the axial direction and the camberline. The stagger angle (ξ) is calculated after determining the angle of attack. The following formulation was used:

$$\alpha_p = [3.6K_{sh}K_{t,i} + 0.3532\theta(a/c)^{0.25}]\sigma^{(0.65-0.002\theta)} \tag{20}$$

In which

$$i = K_{sh} K_{t,i} (i_0)_{10} + n\theta \tag{21}$$

$$K_{t,i} = (10 t_b/c)^{0.28/[0.1 + (t_b/c)^{0.3}]} \tag{22}$$

The stagger angle is:

$$\xi = \beta_1 - \alpha_p \tag{23}$$

Figure 4 shows the radial variation of camber and stagger angles for the first stage of a project.
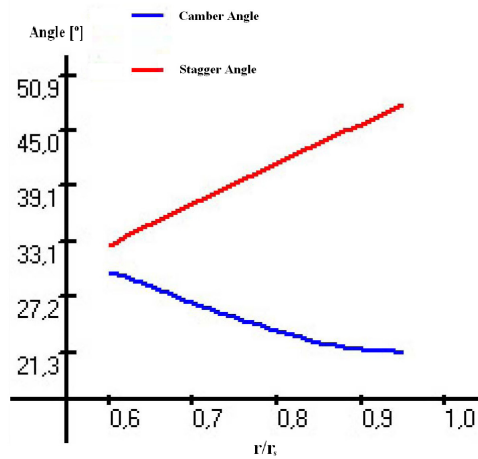

Figure 4. Radial distribuition of construction angles

3.1 3D-Geometry

The three dimension methodology was based on Dixon (2005). To design the three-dimensional geometry, first it is necessary to specify the width profile of the airfoils. The dimensionless width profile for the C4 airfoil, used for this project, is known in open literature, as well as the associated correction factors. The profile points were then interpolated and adjusted for the dimensions of each chord to form a function used in airfoil geometry ($Profile$).

The camberline is found through the 2D cascade angles and parameters of the 3-Dimension cascade. The cascade is solved iteratively by a two-equation system, equations 24 and 25.

$$(b_c - R_c)^2 + 50^2 = R_c{}^2 \tag{24}$$

$$\varphi_c = Tan^{-1}\left(\frac{50}{R_c - b_c}\right) \tag{25}$$

In which:

$$\varphi_c = \beta_1 - \xi \tag{26}$$

The camberline is then given through equation 27, for an airfoil of fixed chord, that is then adjusted for each section chord.

$$Y_c = b_c - R_c + \sqrt{R_c{}^2 - (x - 50)^2} \tag{27}$$

At this point, the rotation line (P_{rot}) of the blade must be given. Each section is then rotated and parameterized, according to equations 28 and 29.

$$X_{Par} = (x - P_{rot})\cos(\xi) - c\left(Profile\left(\frac{x}{c}\right)\right) + Y_c\left(\frac{x}{c}\right) - Y_c\left(P_{rot}\right)\sin(\xi) \tag{28}$$

$$Y_{Par} = (x - P_{rot})\sin(\xi) + c\left(Profile\left(\frac{x}{c}\right)\right) + Y_c\left(\frac{x}{c}\right) - Y_c\left(P_{rot}\right)\cos(\xi) \tag{29}$$

Figure 5 shows the projection of the sections of the first stage. The sections of the blade can then be exported to CAD tool for mesh generation and subsequently used in CFD simulation. Figure 6 shows the rotor of the first stage of a compressor designed by the program.
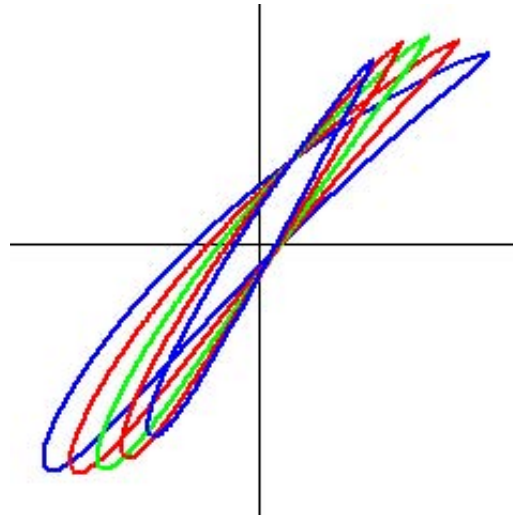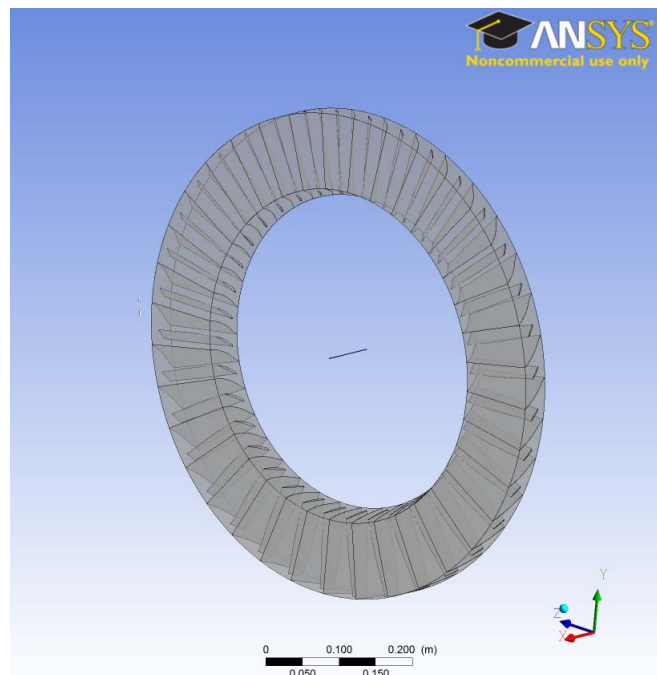
Figure 5. Projection of the blade's sections

Figure 6. First stage rotor in CFX

4. OFF-DESIGN ANALYSIS

This part of the code was implemented separately, and its parameters may be input by the user, or taken directly from the initial results.

This was based on an analytical one-dimensional estimate, proposed by Camp and Horlock (1994), and is valid for small perturbations in the operating conditions from the design point. The hypothesis for the method are that the flow and loading coefficients vary linearly, the polytropic efficiency is constant through the whole compressor, and that the variations from design point are of, at most, 5%.

The parameters requested for this calculation are:

- ψ^* - Loading coefficient in the design point

- U^* - Blade velocity in the reference radius and design point

- η_p - Polytropic efficiency

- T_1 - Inlet temperature of the fluid

- C_p and γ - Fluid properties. The code allows for air, helium and CO_2 as the fluid, and also permits that the user specify properties for other fluids

- N - Number of stages

- K_U - Variation in rotation

- ω^* - Rotation

The program calculates for perturbations in the mass flow, using the following points:

$k_{\dot{m}}$ = {0.04, 0.035, 0.03, 0.025, 0.02, 0.015, 0.01, 0.005, 0, -0.005, -0.01, -0.015, -0.02, -0.025, -0.03, -0.035, -0.04}

From these parameters, the variations are determined, through the equations:

$$Q = (1 - 1/\psi^*)(k_{\dot{m}} - k_U) + 2k_U$$
$$k_T(x) = \frac{Q}{P}\left[1 - \left(1 + \frac{x}{R}\right)^{-P}\right]$$
$$K_p = (n+1)k_T$$

In which:

- $n = \eta_p \frac{\gamma}{\gamma - 1} - 1$

- $P = 1 + n\left(1 - \frac{1}{\psi^*}\right)$

- $R = \frac{C_p T_1}{\psi^* U^{*2}}$

Finally, it is shown a graph of $R_p/R^*{}_p$ x m/m^*, where:

$$m = 1 + k_{\dot{m}}$$
$$R_p = 1 + k_p$$

The following properties were used to generate the graph shown in Figure 7.

Table 1. Input data

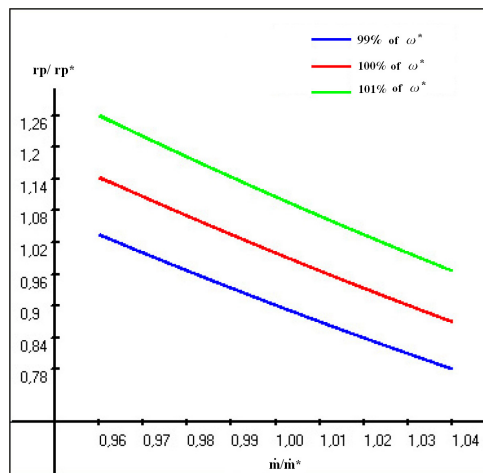| Variable	Value
ψ^*	0.5
η_p	0.9
T_1	300 K
U^*	250 m/s
γ	1.4
c_p	1005 J/(kg K)
N	9 stages
K_U	1%

Figure 7. Off Design Analysis

5. CONCLUSIONS

The program presented no error and is operating properly. The results obtained, as compared to initial data, are proportional to what was expected. A blade designed through it has been exported and meshed. It can now be simulated in CFD softwares.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Aungier, R. (2003). Axial-flow compressors. pages 217–302, New York.

Camp, T. and Horlock, J. (1994). An analytical model of axial compressor off-design performance. *Journal of Turbomachinery*, 116.

Dixon, S. (2005). Fluid mechanics and thermodynamics of turbomachinery. Oxford.

Moreira, F., Silva, A., and Su, J. (2009). Preliminary aerodynamic design of multi-stage axial flow compressors using mathematica. *COBEM International Congress of Mechanical Engineering*.