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Parametric study on axial compressor performance in design condition

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Abstract

In this paper, a parametric study of compressor performances is performed by the streamline curvature method. Effects of three input parameters in the design process, e.g., number of blades, distribution of blade thickness, and blade sweep angels, on the main objective parameters in the aerodynamic design, e.g., velocity distribution, efficiency, and pressure ratio, are investigated in the parametric study. Initially, a certain two-stage axial compressor is designed by the streamline curvature method. Validation of the results is confirmed by comparing the obtained results with the experimental ones. Regarding various values for the aforementioned input parameters, the first stage of the axial compressor is redesigned, and the output parameter is established. Therefore, the sensitivity of the design results to each of the aforementioned parameters is recognized. Results show that increasing the blades sweep angle causes the flow behavior, such as efficiency and pressure ratio in the axial fan, to improve while reducing it provides a completely contrary result. Also, reducing the rotors blades number leads to an increase in the pressure ratio and efficiency while its increase causes a contrary result. It is concluded that a reduction in the number of the blades has a stronger effect on the performance parameters than when it increases. The results also show that the effect of the thickness in the hub is greater than the thickness of the tip, and its increase leads to reduce both efficiency and pressure ratio.

1. Introduction

Recently, several attempts have been made to enhance the performance of turbomachinery by using parametric study and optimization methods with the help of the computational power and expensive experimental setup. Applying the parametric study leads to better design of turbomachines to enhance the performance in terms of increasing efficiency, pressure ratio, and reducing weight and flow loss, etc.

Several investigations have been studied on the performance of an axial compressor by using parametric study. Sweep, lean and skew angles which form the 3D shape of the blades are considered as the most important parameters for optimization. These parameter can lead to a significant effect on overall compressor performance, loss coefficient, and flow structure. In this regard, Gallimore, et al. [1]

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studied the effect of using sweep and dihedral angles on the performance of a multi-stage axial compressor. Benini, et al. [2] and Denton, et al. [3] focused on the effect of sweep and lean angles on the performance of a transonic fan. Cai, et al. [4] studied both the aeroacoustic and aerodynamic performance of a skewed rotor. Fischer, et al. [5] examined the performance of the bowed stator on a four-stage axial compressor. Samad et al. [6] conducted optimization of an axial compressor in which sweep, lean and skew angles are considered as the design variables, efficiency and total pressure ratio as the objective ones. Multi-objective optimization results in improving efficiency and total pressure ratio comparing with the reference case. Hao et al. [7] presented a comparative numerical study to investigate the effects of blade sweep on inlet flow in axial compressor cascades using (CFD) package. A series of swept and straight cascades was modeled. In another research, Batti et al. [8] optimized the number of the blade, as an important parameter in highly loaded compressor with the conceptual approach. By considering a high range number of the blade for stator and rotor and optimizing parameters, the effect of these parameters was investigated. An experimental investigation on the effect of blade profile and surface finish on the aerodynamic performance of a turbine was conducted by Roelke et al [9]. Zheng et al. [10] studied the effect of blade number on the performance of drag type vertical axis wind turbine (VAWT) by Ansys numerical simulation. They considered 3-blade, 5-blade and 6-blade VAWTs. The results showed a variation of maximum power efficiency and the stability of the wind turbine with the number of blade changes. Sarraf et. al [11] studied experimentally the effects of blade thickness on the performances of an axial-flow fan. In this research, two fans that differ only in the thickness of their blades were considered. The overall performances of the fans were measured in a test bench designed. The results showed that the curve of aerodynamics characteristics is slightly steeper for the fan with thick blades. The literature survey shows that most of the researches done on the effect of input parameters on axial compressor performance were performed experimentally or numerically (CFD method). In experimental tests, limitations of instrument and cost cause this method to be impractical for parametric study. Also, the application of CFD analysis in the parametric study which associated with solving complete flow and energy equations in a very complex geometry like compressor or fan takes too much time and is not reasonable especially in the design phase.

Due to difficulties in experimental and CFD analysis, different methods with some simplifications are presented for design purpose and flow analysis. In this respect, most of the researchers and designers prefer working on the meridional plane of turbomachine [12]. Governing equations on the hub to tip through flow surface (referred to as S2-surface) can be solved on a meridional plane using the streamline curvature (SLC) method. This method is mostly used because of its rapid convergence and accurate results. Final results based on this method are comparable with those obtained through CFD methods, which usually consume extreme time and expenses [13]. This method has been employed by Hearsy [14], Hu et al. [15] and Gong et al. [16] to design and analyze different kinds of turbomachinery. To achieve the ideal design, which is associated with optimum efficiency and pressure ratio as the main objective parameters in the aerodynamic design, a parametric study of axial compressor inputs is very valuable.

An overview of the literature reveals that few studies are carried out on the effect of the input parameters on the overall axial compressor performance in the design conditions. In the prior research, experimental and numerical methods (CFD) have been used to study the parametric parameters which are very difficult and costly, especially the parameters related to geometry. So, in the current research, with the development of a computerized program based on the streamline curvature method (SLC) as a rapid and accurate method, a parametric study of compressor performances is performed. Effects of three input parameters in the design process, e.g., number of blades, distribution of blade thickness, and blade sweep angels, on the performance parameters, e.g., velocity distribution, efficiency, and pressure ratio, are investigated in the parametric study. Therefore, the sensitivity of the design results to each of the aforementioned parameters is recognized and the most effective parameter in the design of the compressor is determined.

2. Streamline curvature method and verification

2.1. Streamline curvature method

The streamline curvature method (SCM) is widely used for the quasi-three-dimensional design of an axial compressor blade. SCM is utilized primarily for inviscid flow. In fact, it offers a flexible method of determining an Euler solution of axisymmetric flow through a turbomachine. Then, a discrete increase of entropy, which is determined from loss correlations, is imposed to represent the viscous effects. It is clear that the accuracy of results highly depends on the validity of loss correlations. Governing the main system of equations consists of linear momentum and continuity equations. Then, combined with the thermodynamic equation of state, the resultant equation is mapped into the meridional plane of the flow passage. Consequently, based on the assumptions made in this method and mapping into the meridional plane, the final form of the governing equation can be presented as Eq. (1) and Eq. (2). Fundamentals of this method, including its precise concept, details of the governing equations and necessary correlations can be addressed to Hearsey [13].

$$V_m \frac{dV_m}{dl} = sin(\varphi - \gamma)\left[V_m \frac{\partial V_m}{\partial m} - F_m\right] + cos(\varphi - \gamma)\left[\frac{V_m^2}{r_c} - F_n\right] + \frac{dh_0}{dl} - T\frac{ds}{dl} - \frac{V_\theta}{r}\frac{d(rV_\theta)}{dl} \tag{1}$$

$$\dot{m} = \int_{hub}^{case} V_m \cos(\varphi - \gamma)\, \rho\lambda(1 - K_B) 2\pi r d \tag{2}$$

In the above equations, V_m and V_θ are meridional and swirl velocity, respectively, F_m and F_n are blade forces (meridional and normal blade forces, respectively), l and m are respectively quasi-orthogonal and meridional direction, r and r_c are the radial direction and streamline curvature radius, respectively, h_o is stagnation enthalpy, s is entropy, T is static temperature, and φ and γ are deflection and sweep angles, respectively, λ is a surface coefficient determined by the chord length and blade thickness, and K_B is the blockage factor.

Eq. (1) is solved as an ordinary first-order differential equation. In this respect, a computerized program is developed which consists of two main parts. The frst part is mainly used for obtaining three-dimensional geometry of blades and the next part produced a performance curve of turbomachines. Computerized code utilizes empirical correlations for calculations of various kinds of loss accompanied by axial compressors. Obviously, the reliability of the final results highly depends on the degree of precision of these correlations.

2.2. Loss and angle correlations

In order to implement viscous effects in governing equations, empirical correlations must be used for loss coefficient, incidence and deviation angles. The loss coefficient is divided into four parts; profile loss, shock loss, secondary flow loss, and tip clearance loss. The profile loss coefficient is calculated from Koch and Smith's correlation [17], the shock loss coefficient from Swan's correlation [18], the secondary flow loss coefficient from Griepentrog's correlation [19], and tip clearance loss coefficient from Storer [20] and Cumpsty's correlation [20]. Other parameters that are computed via empirical correlations are incidence and deviation angles. In the software, popular correlations of Lieblein [21] are used for obtaining these parameters.

2.3. Experimental validation

To validate results in design conditions, Urasek's experimental data [22] are used. These data refer to a two-stage axial compressor with a pressure ratio of 2.4. The overall characteristics of this compressor are also shown in Table 1. The radial distribution of the pressure ratio in the rotor and stator of the first stage is shown in Fig. 1. It can be seen that the general tendency of the results is close to the experimental data. It is clear that experimental and numerical results are in good agreement.

3. Results and discussion

Input parameters of the aerodynamic design process by streamline curvature method are classified into four groups, including cyclic inputs, geometrical inputs, loading coefficient distribution, and blades characteristics. As mentioned above, the effect of changing some input parameters on the output results is investigated. The change rate for all parameters is considered about 5%. Output between the geometric parameters, the sweep angle, the number and thickness of the blades are the most effective parameters selected for parametric study. The effect of the aforementioned parameters on the design of the axial fan is explored below.

Table 1. Overall characteristics of Urasek's two-stage compressor [22].

Inlet total pressure (kPa)	101.325
Inlet total temperature (K)	288
Mass flow rate (kg/s)	33.2
Rotational velocity (r/min)	16042
Overall pressure ratio	2.4
Number of stages	2
First rotor aspect ratio	1.56
Aerodynamic efficiency (%)	84.9

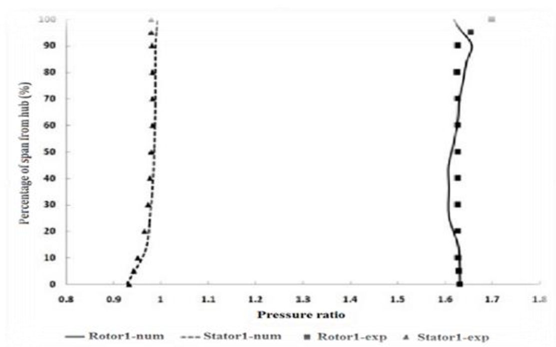

Fig. 1. Experimental validation of pressure ratio at design condition.

3.1. Blades sweep angle

According to the aforementioned definitions, the sweep angle is one of the parameters which exists in the momentum equation (Eq. (1)). Therefore, by varying the sweep angle, the meridional velocity is varied as well. To study the effect of the blades sweep angle on the performance outputs, besides the design case (case I), two other cases are also considered and the obtained results are compared. According to Table 2, the sweep angle in the leading edge and trailing edges for all the blades increase by 5% in case II whereas reverse manner is considered for case III. The effect of all cases for the blade sweep angle on the efficiency, pressure ratio, and meridional velocity is shown in Figs. 2-4, respectively. It is clear that increasing the blades sweep angle causes improving the flow behavior in axial fan and reducing it, having a completely contrary result.

Referring to Figs. 2 and 3, it is recognized that increasing the sweep angle leads to enhance efficiency and pressure ratio. Also referring to Fig. 4, one can realize that growing the sweep angle causes increasing velocity minimum and reduce its maximum. Velocity distribution is more sensitive to the blades sweep angle relative to efficiency and the pressure ratio.

Table 2. Different cases for sweep angle of blade.

	Sweep angle
Case1 (design)	0%
Case 2	5% increase
Case 3	5% decrease

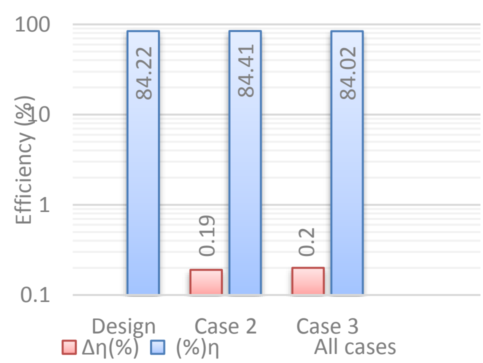

Fig. 2. Effect of blade sweep angle on efficiency.

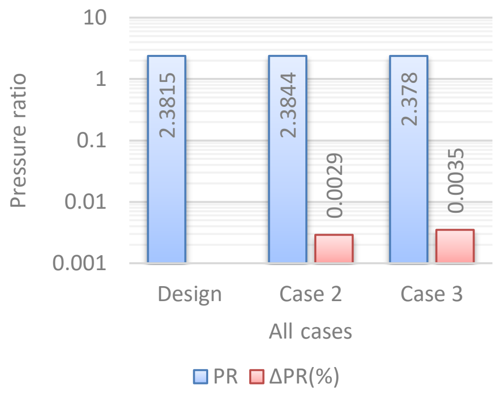

Fig. 3. Effect of blade sweep angle on pressure ratio.

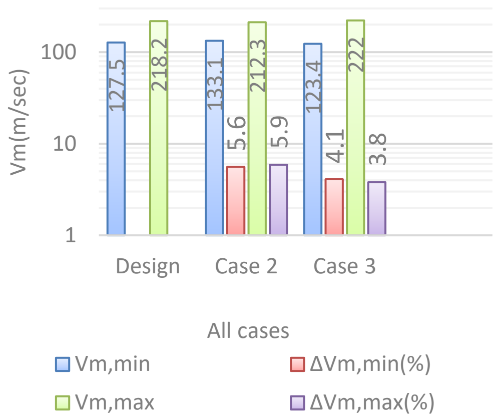

Fig. 4. Effect of blade sweep angle on meridional velocity.

3.2. Number of blade

The number of blades is one of the important parameters affecting the velocity field and loss generated in the design process of the fan. The number of blades also is one of the influential parameters in flow equations. It directly enters the solidity coefficient (Eq. (3)). According to Eq. (4), the diffusion factor is employed to determineet the compressor loss which is the function of the solidity coefficient. Additionally, the incidence and deviation angles are computed via empirical correlations in which solidity coefficient has been observed directly. The loss coefficient is used for calculation of entropy which is in the momentum equation (Eq. (1)).

$$\sigma = \frac{C}{S} = \frac{C}{2\pi R / N} = \frac{C \times N}{2\pi R} \tag{3}$$

$$D^* = 1 - \frac{V_2}{V_1} + \frac{\Delta V_\theta}{2V_1\sigma} \tag{4}$$

$$D^* = 1 - \frac{V_2}{V_1} + \frac{\Delta V_\theta}{2V_1\sigma} \tag{5}$$

In order to study the effect of the number of blades on the output parameters, besides the number of the considered blades in the design condition (case I), four different cases are regarded. The number of blades in the rotor and stator for all cases are presented in Table 3. In all cases, the rate of increase or decrease in the number of blades is two blades (which is equal to 5% of all the blades). In Fig. 5, different cases are shown to explore the effect of the number blades. For each blade's row (rotor or stator), the number of blades is marked above each graph. It can be inferred from Fig. 6 that the cases II and IV, which are associated with increasing the number of blades in rotors in both cases, reveal similar behavior. Likewise, in case III and V with similarity in reducing the number of rotor blade rows, a similar behavior appears. The only difference between cases II and IV is the minimum meridional velocity. Hence, it can be concluded that the role of the rotors blades number is greater than the stators' blades number.

The results reported in Figs. 6 and 7 clearly indicate that reducing the rotors blades number leads to an increase in the pressure ratio and efficiency, respectively, while its increase cause a contrary result. Also, it is concluded that a reduction in the number blades has a stronger effect on the performance parameters than its increment. It is worth mentioning that by increasing the number of the blades, the area of flow passing is reduced, and the profile loss is increased which can be attributed to the physical reason for reducing efficiency and pressure ratio. But it should be noted that the number of blades cannot be reduced too much because it reduces the correct conduction of the flow and increases the deviation and incidence angles. Referring to Fig. 8, it is clear that the velocity minimum occurs in cases II and IV which are different in stator blades number. Then, it can be concluded that the velocity minimum occurs in the stator, and with reducing the blades number the minimum velocity decreases. In addition, it is recognized that the role of the number of blades in the velocity minimum is greater than the velocity maximum.

Table 3. Description of all cases for the number of blades.

	Number of rotor blades	Number of stator blades
Case I	Design condition	Design condition
Case II	Increase	Decrease
Case III	Decrease	Increase
Case IV	Increase	Increase
Case V	Decrease	Decrease

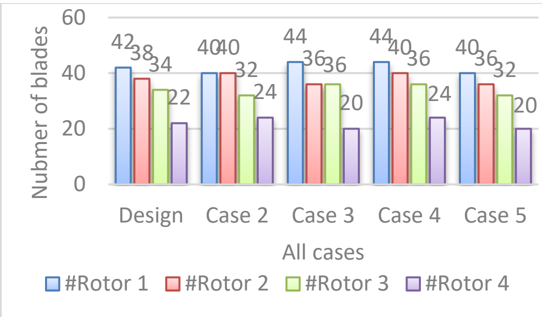

Fig. 5. Number of blades considered in different cases.

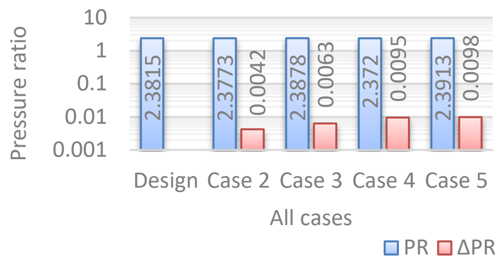

Fig. 6. Effect of number of blades on pressure ratio.

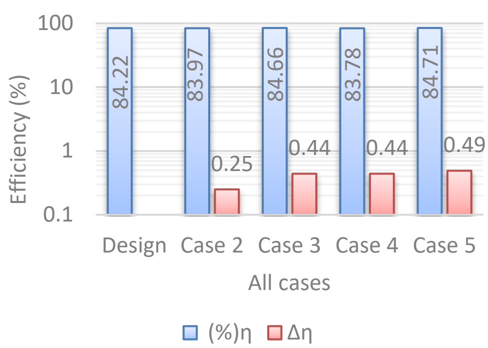

Fig. 7. Effect of number of blades on efficiency.

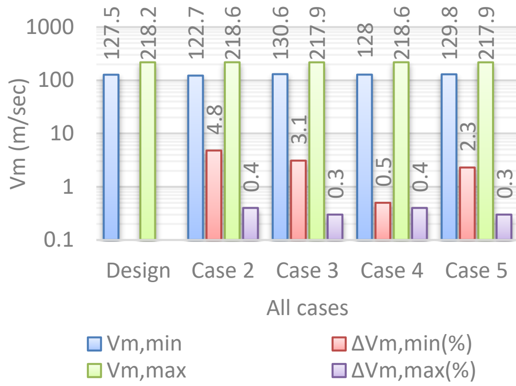

Fig. 8. Effect of number of blades on efficiency.

3.3. Thickness of blade profile

The geometric shape of blades in an axial compressor has a significant effect on the aerodynamic performance and 3D flow characteristics. One of the main parameters in the geometry of the blades is the blade thickness. Based on Eq. (2), the surface coefficient is related to the blade thickness. Accordingly, the meridional velocity and performance parameters such as pressure ratio and efficiency are changed. Also, in order to study the effect of the blade thickness on the compressor performance characteristics, besides the considered maximum thickness in the design case (case I), four other cases are also employed for the blades maximum thickness.

How to vary the blade maximum thickness in different cases is described in Table 4. It is worth noting that the change in the maximum thickness is 5% relative to the design case (case I). The effects of the different thicknesses of the blades on the efficiency, pressure ratio, and velocity field are illustrated in Figs. 9-11, respectively. According to Figs. 9 and 10, the cases II and V have the same behavior in the efficiency and pressure ratio.

Table 4. All considered case for maximum thickness.

Cases	**Hub**	**Tip**
Case I	Design	Design
Case II	Decrease	Increase
Case III	Increase	Increase
Case IV (reverse case II)	Increase	Decrease
Case V (reverse case III)	Decrease	Decrease

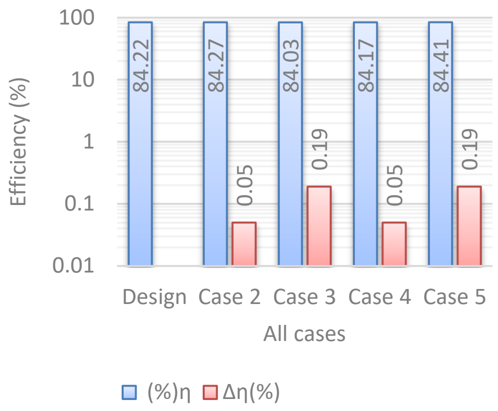

Fig. 9. Effect of blade thickness on efficiency.

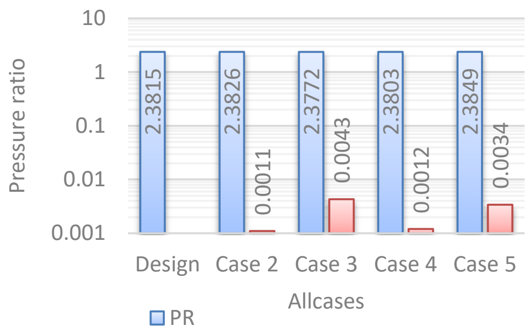

Fig. 10. Effect of blade thickness on pressure ratio.

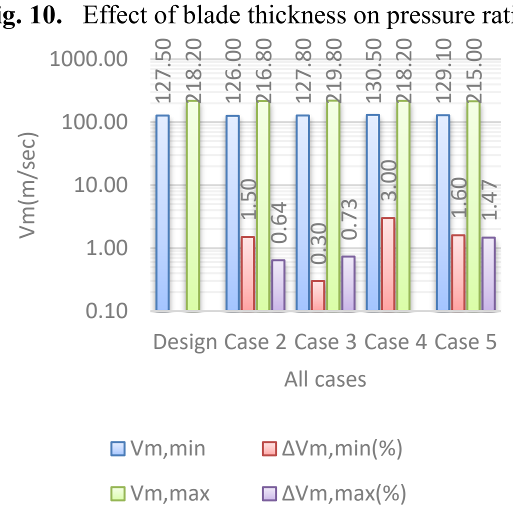

Fig. 11. Effect of blade thickness on meridional velocity.

In other words, both cases cause increasing efficiency and pressure ratio. In contrast to the design cases (case I), the cases III and IV have the same behavior in reducing efficiency and pressure ratio, respectively. The similarity of the cases II and V is the reduction of the maximum thickness in the hub, and that of the cases III and IV is the increase in the maximum thickness of the hub. Therefore, it can be concluded that the effect of the thickness on the hub is greater than the thickness of the tip, and its increase leads to reduce both efficiency and pressure ratio.

The effect of the thickness increase, like increasing the number of blades, is to reduce the passing flow passage. It is deduced from Fig. 11 that the only case which plays a positive role in the velocity field is case V which is accompanied by thickness reduction along the hub to the tip.

4. Conclusions

In this paper, the effect of the inlet parameters on the efficiency, pressure ratio, and velocity field, as the main objective parameters of the aerodynamic design, is studied by the streamline curvature method. First, a certain two-stage axial compressor is designed and the results are validated against the experimental ones. It is confirmed that the results are in good agreement with experimental results. Three input parameter, including the number, thickness, and sweep angle of the blades are employed for parametric study. The main conclusions derived from this research work can be stated as follows: Based on the results of the parametric study, it is shown that the number, thickness, and sweep angle of the blades have significant effect on the performance of the compressor. It is cleared that increasing the blades sweep angle improves the flow behavior in axial fan and reduces it having a completely inverse result. It is recognized that increasing the sweep angle enhances the efficiency and pressure ratio. Furthermore, the effect of thickness on the hub is greater than the thickness of the tip, and its increase leads to the reduction of the both efficiency and pressure ratio.

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