Effect of Inlet Distortion on the Performance of an Axial Cascade

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Abstract-- A cascade is defined as an infinite row of equidistant similarly aerofoil bodies. The cascade is used to divert a flow stream with a minimal loss. The flow over an axial cascade presents a complicated intra blade fluid dynamic interaction that causes the flow to behave differently than the flow over a single aerofoil blade. A cascade tunnel in which different shapes of cascades could be tested for performance evaluation has been built.

An axial flat plate cascade of 70 mm chord, 215 mm span and 0.55 pitch chord ratio has been tested in this tunnel for evaluating its aerodynamic performance. The distortion in the flow ahead of the cascade row was artificially created by using distorters of the outer size same as the cross section of the cascade tunnel and were fixed with the help of air tight flanged connections at a location which was four chords ahead of the cascade.

The present study aims to investigate the effect of inlet flow distortion on the performance of an axial two dimensional cascade. The results depict that the Reynolds number, incidence and blade angle of the cascade control the aerodynamic performance of the axial cascade. Further the experimental values of lift coefficient are less than that obtained using theory and the drag coefficients are more than the theoretical values. The aerodynamic parameters of the cascade, deflection, deviation, loss coefficients etc, have been found to depend on both the Reynolds number and the type of distortion.

Index Term-- Distortion, performance, cascade, deflection, deviation, drag, lift, coefficients

NOMENCLATURE

AR Aspect Ratio
b Length or Height of Cascade
c Chord of the cascade blades
Cd Drag coefficient $Cd = \frac{(p_1-p_2)c\cos\alpha_m}{\frac{1}{2}p_Vw^2c}$
Cl Lift Coefficient
$Cl = 2c\cos\alpha_m(tan\alpha_1-tan\alpha_2)-Cd\tan\alpha_m$
Cp Static pressure rise coefficient $Cp = \frac{p_1-p_2}{p_1-p_f}$
i Incidence angle $i=\alpha_i-\beta_i$
l Blade span
P Total pressure
p Static pressure
R Reynolds number $R = \frac{\rho V_f w}{\mu}$
s Pitch

1 INTRODUCTION

A cascade is a row of equidistant similar aerofoil bodies that is used to divert a flow stream with a minimal loss. It forms the basic block for the design and development of axial turbomachinery. Turbine usually shows tolerance to the blade design and alignment errors because blades of a turbine stage perform under a favorable pressure gradient whereas compressor blades are prone to aerodynamic losses as this work under adverse pressure gradients due to diffusing nature of the flow field. The blading of an axial compressor and axial turbine have high solidity which makes the flow structure in these machines highly complicated as the flow around any blade in these machines is affected by the presence of the adjacent blades. A cascade is a row of geometrically similar blades arranged at equal distance from each other and aligned to the flow at the same angle. The pressure ratio developed by a cascade depends on its aerodynamic characteristics. There are various types of shapes used in compressor blading. These range from C series, NACA series or DCA series profiles. In wind turbines also the aerofoil shapes for its rotors range from NACA44xx series for lower wind speeds to the composite shaped aerofoils for higher speeds. The aerodynamic parameters that are of paramount importance for compressor blades are stagger, solidity, camber, camber line shapes, thickness chord ratio and thickness distribution. The peculiar geometry of their blades cause the flow to be three dimensional. The passage flow in these machines is grossly effected by passage pressure gradient, secondary flows, boundary layer effects, cross flows, tip clearances, complications of stator rotor aerodynamic interaction, shock boundary layer interaction and
inlet flow conditions. Therefore understanding of cascade flow would result in systematic improvement of the aerodynamic art for design of such passages.

There have been many attempts to find solution of these problems. Roundbash (1) Scholz (2) and Gostalow (3) have discussed the summary of these works. Compusty (4) has reported the work of Felix and Emery (5) in which it has been suggested that the shape of a compressor blade has an insignificant effect on its performance at low mach numbers. Their tests on C4 and NACA65 series cascades revealed same results. Bacur(6) studied the flow development in S shaped profiles in a cascade tunnel. Andrews (7) has found out that the camber line shape, leading edge radius, and thickness chord ratio have small effect on the performance of a cascade. Serovy, et al. (8) have carried out detailed investigation of inter-passage flow in a baseline and modified versions of a two stage axial compressor and have observed similarities in their aerodynamic performance. Pullen and Harvrey (9) have arrived at a loading parameter for an axial flow turbine cascade by taking sweep of the blade into account. They have validated their results with the experimental results of linear cascade tests of low pressure ratio axial turbine. Kalpatrick and Barrows (10) have tested cascades of varying aspect ratio from 1.5 to 3. Mustaphe, et al. (11) have presented the results of an off design performance of a turbine cascade at its midspan with varying Mach numbers, Reynolds numbers and incidences. Nagasaki and Yamsaki (12) have developed a CFD code to compute unsteady aerodynamic forces on a vibrating annular cascade and have compared it with the linearized theory and have found the two to be almost similar. Sun, Q. and Boyd, I.D, [13] investigated gas flow over a flat plate airfoil at very low Reynolds number and found that minimum drag at an angle of 10° and the drag increased with the decreasing Reynolds number. There have been many theoretical and experimental studies on flow over a single aerofoil and wing. Rodoslav and Roger (14) have studied flow over NACA 0012 aerofoil using DES procedure. Hazarika, et al. (15) have carried out CFD analysis of flow over an aerofoil with variations in the inlet flow. Vareans, et al. (16) have used inverse method in the analysis of internal flow and flow in cascades.

The design of an axial turbomachine and axial compressor in particular usually presupposes a uniform flow at its inlet however this assumption is never realized. The installation of a turbomachine normally involves some form of ducting to direct the flow which may involve bends, boundary layer buildups and even some obstacles on the flow path that lead to the nonuniform flow at the inlet of such machines. Inlet distortion could also be due to wakes of stays in a compressor, guide vanes or adjacent rows. The placement of such turbomachines itself like that in aircrafts may lead to excessively distorted flow at their inlet distortion. The shape of inlet particularly in case of twin duct side wing or under wing air intakes is also a major cause of the flow non-uniformity. This flow non uniformity in the flow of such machines is called inlet distortion. This could be either in radial in nature or circumferential. The inlet distortion has been reported by Seo, et al. (17) to cause noise and vibration in the engines. Conrad and Sobolewsky (18) have determined the performance of a complete turbojet engine under various shapes of radial distortion. Seo, et al. (17) have carried out flow measurements on inlet flow distortion and its attenuation in an axial compressor with radial and circumferential distortions. The development and effect of distorted flow in straight channels has been of wide interest. Owen and Zienkiewics (19) have proposed a simple method of obtaining a two dimensional flow distortion in a duct by placing a section of parallel rods, perpendicular to the direction of the flow, in which the distance between the adjacent rods varies in the y direction. Another method to develop the strong constant shear flow was developed by Woo and Cermak (20). They have put a pair of closely spaced shaped gauzes at the upstream of the flow. First gauze had non-uniform porosity whereas the second had uniform porosity. Maull and Young (21) have used curved sheet of wire gauze in the flow channel to produce the non-uniform flow distribution. Ahmed and Lee (22) have used a shaped honeycomb technique to produce the linear shear flow. Liu, et al. (23) have used perforated plates to generate the distortion. They used nine plates having a combination of three solidity values and three hole values for this study. Their results showed a development of a shear flow with very low level of turbulence. In the present investigation the method of Ahmed and Lee (22) has been modified to incorporate the actual situations as encountered in a turbomachine.

Inlet distortion has been contemplated to be taking place in total pressure distribution and total velocity distribution. There have been many ways to demonstrate the formation and analysis of total pressure distortion coefficient. Ariga, et al (24) have used distortion index as the criteria for measuring the inlet flow distortion. O’ Neil et al (25) has used concept of shock loss for the same. Kim, et al. (26) have quantified in terms of mass rate averaged value of normal velocity, pressure, flow angle and their respective value of standard deviation. Another form of distortion index has been proposed by Wright, et al. (27) in terms of total pressure loss coefficient. Similar method has been adopted by Salim (28) for both total velocity and total pressure distortions. The present study aims to investigate the effect of inlet flow distortion on the performance of an axial two dimensional cascade. The performance characteristics of the cascade with different distortions at the inlet will be investigated experimentally. The distortion has been created by using different shapes of honey comb cut outs with the aim to partially block the flow of air so as to create the inlet flow distortion.

2 Experimental Setup
The experimental setup for testing the cascade is a blow down, close jet, low speed cascade tunnel shown in figure (1). The tunnel facility is build around a radial blower of 3.6 kW power, pressure rise of 3.5 kPa and a flow rate of 0.83 cubic meters per second. The blower speed is 3450 rpm .The blower is fitted with an inlet duct of 200mm internal diameter and 300 mm length. The inlet duct has a cup and cone valve at the free
end to control the flow rate through the cascade tunnel. The cup can be moved into the cone by an axial movement system. The cup can fully close the valve. A circular duct of diameter 270 mm is fitted at the exit of the blower. The duct is connected to a settling chamber. The settling chamber has three parts. The inlet part is of diffusing section with inlet of diameter 270 mm where as its exit is rectangular of size 680mm x 600 mm. This diffusing section is connected to the middle part which is further divided into three portions of size 680mm x 600 mm and length 190 mm. These parts are connected tightly and wire gauze is fitted at each connection. These gauzes reduce the turbulence of the flow emerging out of the blower. The exit of the settling chamber is a rectangular converging duct of inlet size 680mm x 600mm and exit of size 220mm x 210mm. The converging section is connected to a small rectangular duct of size 220mm x 210mm and length 200 mm. This duct is in turn connected to the rectangular test section of size 220mm x 210 mm and length 300 mm. The test section is fabricated from Perspex sheet of 12mm thickness. All the ducts etc are made from sheet metal. The test section discharges the air to the atmosphere. The cascade row is fitted at the end of the test section. The cascade row was made to rotate from -10° to +10° by a moving mechanism which kept the pitch of the blades same all through. The blades of the cascade were made from stainless steel sheet of 1 mm thickness. The blades had 70 mm chord, 215 mm span and a pitch chord ratio of 0.55.

The distortion in the flow ahead of the cascade row was artificially created by using distorters of the outer size same as the cross section of the cascade tunnel and were fixed with the help of air tight flanged connections at a location which was four chords ahead of the cascade. The distorters were made from honey comb sheets. The configuration c1 did not have any distorter ahead of cascade row whereas configuration c2 had a full honey comb sheet covering the full test section of the tunnel. The configuration c3 had a central cut out of the size of half the area of test section whereas configuration c4 had outer cut out of half the size of the test section. Two of these were able to partially block 50% of the cascade passage where as the third one partially blocked the full passage. The 50% distortors distorted the inlet velocity profile where as the full distorters acted like a filter. The fourth configuration was without any distorter. The shape of the distorters and the nomenclature of the configurations is given in table (1).

3 RESULTS AND DISCUSSION
The present investigations were carried out to establish the dependence of the performance of a linear cascade on the inlet flow distortion that was created artificially by placing distorters in front of the row of linear cascade. Karanja and Sayers (29) and Wolf and Jhonston (30) have documented that presence a diffuser downstream of a straight duct reconfigures the flow upstream of it in that duct. This becomes more urgent in case where the straight duct is blocked by the cascade row. Hence it becomes necessary to determine a position which can represent free stream location. Therefore traverses of velocity probe were carried out upstream of the diffuser and a location was found where the velocity profile would match the normal velocity profile in a rectangular duct. The free stream condition of symmetrical flow behavior was found at a distance of 1.75 times the width of the diffuser. This was taken as a free stream location for all the configurations tested. The measurement of velocity profile at this location yielded almost a uniform velocity profile although the passage of the diffuser except very near the wall. This was taken as a free stream location for all the test conditions. The inlet velocity profile in the free stream region of the cascade for the four configurations is shown in figures (2). These profiles were measured by traversing a standard NPL. These investigations were carried out at two flow rates corresponding to the free stream Reynolds numbers for 2.26x10^5 and 2.52x10^5. These Reynolds numbers are based on the dimensions of the inlet duct. All the results are reported at these two Reynolds numbers. The inlet velocity profile for different configurations was measured at a distance of six chords upstream of the leading edge of the cascade. The output of the probe was read on an inclined manometer. Figure (3) show the inlet velocity profiles for these configurations at the two Reynolds numbers. These figures show almost uniform velocity for the configurations c1 and c2 with a little non uniformity at the walls which can be attributed to the wall effect of the tunnel. The c3 configuration which had an outer side opening and blockage on inner side showed lesser velocities at the central part of the traverse where as the configuration c4 showed the reverse trend, higher velocities on the inner side and lower values of velocities at the outer part. These velocity profiles clearly showed the velocity distortion of the inlet flow particularly for configuration c3 and c4. The distortion produced by these combinations can be grouped into three categories. Full distortion causes, a filtered flow through the honeycomb of which it is made of, and no distortion configuration is a situation without any artificial distortion. These two types can be said to be distortion free cases. These two types of inlet flow generate almost symmetrical and uniform velocity profile at the inlet of the cascade. The other two cases of distortion, inner (c3) and outer distortion (c4), creates an asymmetrical flow at the inlet of the cascade. The asymmetrical flow at the inlet of the cascade generates more distortion of the flow.

Variation of Flow and Performance Parameters:- The flow over an axial cascade presents a complicated intra blade fluid dynamic interaction that causes the flow to behave differently than the flow over a single aerofoil blade. But if the aspect ratio of the cascade blade row is high then two dimensionality of the flow prevails. The most important aerodynamic flow parameters that govern the two dimensional flow behavior in a cascade are angle of incidence, angle of deflection, angle of deviation, static pressure rise coefficient, total pressure loss coefficient, drag coefficient and lift coefficient. These flow parameters were measured by a pre-calibrated three hole probe near the centre of the span of the cascade at half chord distance upstream and downstream of the central blade of the
cascade. The probe output was measured with the help of an inclined water manometer. The different flow and performance variables for the cascade were calculated using two dimensional cascade aerodynamics (3). The full performance of axial cascade without any distortion, c1 configuration, has been presented in (31). This paper reveals the effect of inlet distortion on the performance of axial cascade.

Figure (4) reveals the variation of the angle of incidence with the blade angle at two Reynolds numbers. The angle of incidence is defined as the difference between the flow angle and blade angle at the inlet of the cascade. These depict that the angle of incidence decreases with the blade angle at both Reynolds numbers for all configurations except configuration c3 for which it decreases up to zero blade angle and then it increase again with the blade angle. At lower Reynolds number the variation of the incidence values at different blade angles is more than the higher Reynolds number. This variation in values is expected because of the gross difference in the flow distortion at the inlet of the cascade which is more at lower Reynolds number than at higher number. Configuration c4 having tip distortion has higher values of incidence than other configurations. Figure (5) shows the variation of deviation angle with the blade angle at two Reynolds numbers. The deviation angle is the difference between the flow angle and the blade angle at the exit of cascade row. At lower Reynolds number the deviation angle for configuration c1 decrease up to zero blade angle and there after it increases again. At higher Reynolds number it progressively decreases with the blade angle. For other configurations a continuous decrease of deviation angle with blade angle is evident. The difference in values of deviation angle for various configurations is more observed at lower Reynolds number which can be due to higher effect of distortion at lower flow rate. A maximum incidence of 35° is observed, for c1 configuration, at lower Reynolds number. At higher Reynolds number the deviation decreases with incidence and achieves a maximum value of 20° for a deviation angle of -8°. The deviation of the flow is observed to decrease with the increase in Reynolds number and the blade angle. Figure (6) shows the variation of deflection angle with the blade angle at two Reynolds numbers.

The deflection angle is the difference between the flow angles at the inlet and the exit of cascade row. The deflection angle for configurations c1 and c4 is seen to decrease with the increase the blade angle. For configuration c2 the deflection angle at lower Reynolds number is observed to increase up to zero blade angle and then decrease where as for c3 it shows the reverse trend. At higher Reynolds number both the configurations behave in the similar manner as other two configurations. The deflection seems to be governed by the distortion shapes and velocity profiles. For the configurations with almost uniform velocity along the cascade length, c1 the deflection angle uniformly decreases with blade angle.

Variation of static pressure rise coefficient through the cascade at the two Reynolds numbers is presented in figure (7). It shows that in configuration c1 the variation at lower Reynolds number is of a wavy form showing lowest and highest values at blade angles of ±5°. The variation for other configurations is seen to be small and of rising nature. At higher Reynolds number all the configurations depict a slight decrease in the values of Cp with the increase in the blade angle. This behavior indicates that both the change of blade angle and the shape of distorter effect the variation and the magnitudes of static pressure rise in the cascade passage.

The variation of total pressure loss coefficient at two Reynolds numbers along the passage through the cascade is presented in figures (8). At lower Reynolds number the total pressure loss coefficient for configurations c1 and c3 is minimum at zero blade angle where as it increases both for the positive and negative values of the blade angle. For c2 configurations it increases with the blade angle and for c4 configuration it decreases with the blade angle. At higher Reynolds number the total pressure loss coefficient is almost invariant with the blade angle. The least changes in the values total pressure loss coefficient is an indicator of stable behavior within the passage creates such fluid dynamic conditions that give rise to losses. The fact that the variations in case of c1 configurations are small in comparison to the other configurations shows that the distortion at the inlet of the cascade changes the flow behavior with its passage that results in increases total pressure loss coefficient.

Figure (9) presents variation of lift coefficient at two Reynolds numbers for these configurations. The lift coefficient is observed to decrease with the blade angle for the configurations c1 and c4. Configuration c3 shows an increase of lift coefficient with blade angle at lower Reynolds numbers and parabolic variation at higher Reynolds number with minimum at zero blade angle. Configuration c2 depicts a parabolic variation at lower Reynolds number with minimum at zero blade angles and consistent decrease of lift coefficient with the blade angle at higher Reynolds number. When compared with the variations of incidence with blade angle it is observed that the lift coefficient will increase with the incidence for configurations c1 where the inlet flow is not distorted. This variation is typical of a linear cascade. Other two configurations c2 and c3, show a different behavior with the incidence due to perturbed nature of inlet flow as indicated by inlet velocity profiles for these configurations. Thus the inlet flow distortion is seen to cause the changes in the lift producing capabilities of the cascades.

The drag coefficient variations of the cascade, shown in figure (10), indicates that at lower Reynolds number the drag is minimum at zero blade angle for configurations c1,c2 and c3 and increase at the lower and higher values of the blade angle in a shape of cup. For configuration c4 it decreases with the blade angle and hence should increase with incidence which is the normal case. But at higher value of Reynolds number the drag coefficient is almost invariant with blade angle for all the configurations.

A comparison of the main performance parameters like lift coefficient and drag coefficient was carried out with different published empirical results for a flat plate with no distortion.
case. Lanzafame, et al. [32] have obtained the following empirical formula for the lift coefficient and the drag coefficient.

\[ C_d = C_{d\text{max}} \sin^2 \alpha \]

\[ C_l = \frac{C_{l\text{max}} \sin \alpha \cos \alpha}{\pi AR} \]

Where AR is aspect ratio of the cascade = b/c

The comparison of these results also shows that the experimental values of lift coefficient are higher than the experimental values whereas theoretical drag coefficients are lower than the experimental values. This is because the cascade performance of an aerofoil section or flat plate is different, rather degraded, than when the same is placed in infinite surroundings.

4 Conclusions:

From the investigations it has been found that under the conditions of the test the angle of incidence for all the configurations decreases with the blade angle. The variation in angle of incidence is more at lower Reynolds number than the other one. The deviation of the flow is observed to decrease with the increase in Reynolds number and the blade angle for all configurations. The deflection seems to be governed by the distortion shapes and velocity profiles. The flow is found to deflect less at higher blade angles and flow rate. Both the change of blade angle and the shape of distorter effect the variation and the magnitudes of static pressure rise in the cascade passage. At higher Reynolds number a small change is observed in the values of Cp with the change in the blade angle whereas almost no changes are observed with the angle of incidence. The distortion at the inlet of the cascade changes the flow behavior with its passage that results in increases total pressure loss coefficient. At higher Reynolds number the total pressure loss coefficient is almost invariant with the blade angle. The inlet flow distortion is seen to cause the changes in the lift and the drag of the cascades. The lift coefficient is observed to decrease with the blade angle. The drag coefficient, blade angle and the incidence are interrelated to each other.

ACKNOWLEDGEMENT

This project was supported by King Saud University, Deanship of Scientific Research and Research Center College of Engineering.

REFERENCES


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Fig. 3. Inlet Velocity Profiles for different Configurations

Fig. 4. Variation of incidence angle with blade angle for different configuration

Fig. 5. Variation of Deviation angle with blade angle for different configuration
Fig. 6. Variation of deflection angle with blade angle for different configuration

\[ R_1 = 2.26 \times 10^5 \quad R_2 = 2.52 \times 10^5 \]

Fig. 7. Variation of Static Pressure Rise Coefficient with blade angle for different configuration

\[ R_1 = 2.26 \times 10^5 \quad R_2 = 2.52 \times 10^5 \]

Fig. 8. Variation of Total Pressure Loss Coefficient with blade angle for different configuration

\[ R_1 = 2.26 \times 10^5 \quad R_2 = 2.52 \times 10^5 \]
Fig. 9. Variation of Lift Coefficient with blade angle for different configuration

Fig. 10. Variation of Drag Coefficient with blade angle for different configuration

Fig. 11. Comparison experimental and theoretical values with blade angle for Lift and Drag Coefficient for different configuration Reynolds Numbers $R_1=2.26 \times 10^5$ and $R_2=2.52 \times 10^5$
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<thead>
<tr>
<th>Shape of distorter</th>
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<tr>
<td></td>
<td>c1 Configuration</td>
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