2-D COMPUTATIONAL STUDIES OF SUBSONIC AXIAL-FLOW COMPRESSOR ROTORS INCORPORATING DUAL AIRFOILS

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Abstract

The dual airfoil compressor rotor configuration is where two separate blades are mounted on a common rotating wheel. The premise of this study is that a dual airfoil rotor can do more work at the same loss level as a single airfoil, which would reduce the number of required stages in a compressor. While dual airfoils are commonly used in centrifugal impellers, they have yet to be applied to a commercial axial-flow rotor. This paper presents some results of a 2-D computational study of the axial dual configuration in a fully subsonic flow field. It was found that the dual airfoil begins to offer benefits over a conventional airfoil when highly loaded (i.e. Lieblein D-Factor greater than 0.55). Future work will include completion of the 2-D computations and a rigorous wind tunnel experimental program for validation.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AB</td>
<td>Aft Blade</td>
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<td>AO</td>
<td>Axial Overlap of dual blades</td>
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<tr>
<td>C</td>
<td>blade chord</td>
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<td>D</td>
<td>Lieblein diffusion factor</td>
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<tr>
<td>F</td>
<td>Force</td>
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<tr>
<td>FB</td>
<td>Forward Blade</td>
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<tr>
<td>PP</td>
<td>Percent Pitch of AB LE relative to FB spacing</td>
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<td>PR</td>
<td>Pressure Ratio</td>
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<tr>
<td>PS</td>
<td>Pressure Side</td>
</tr>
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<td>s</td>
<td>pitchwise spacing between FB</td>
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<tr>
<td>SS</td>
<td>Suction Side</td>
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<tr>
<td>t</td>
<td>pitchwise spacing between FB TE and AB LE</td>
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<td>U</td>
<td>free stream velocity</td>
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<tr>
<td>w</td>
<td>velocity in frame of reference relative to rotor</td>
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<tr>
<td>y⁺</td>
<td>dimensionless distance from viscous surface</td>
</tr>
<tr>
<td>Δx₁</td>
<td>axial distance between FB TE and AB LE</td>
</tr>
<tr>
<td>Δx₂</td>
<td>axial distance between AB TE and FB LE</td>
</tr>
<tr>
<td>Γ</td>
<td>circulation constant</td>
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<tr>
<td>θ</td>
<td>circumferential (pitchwise) direction</td>
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<tr>
<td>ρ</td>
<td>density</td>
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<tr>
<td>σ</td>
<td>solidity</td>
</tr>
<tr>
<td>ωₚ</td>
<td>momentum thickness loss parameter</td>
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Subscripts

eff   effective
L     lift
1     inlet station
2     exit station

Introduction

One of the oldest challenges faced by axial-flow compressor designers is that of using as few stages as possible to achieve the desired pressure rise without compromising efficiency. The obvious benefits to using fewer stages are improved engine power-to-weight ratio and a reduction in manufacturing parts. For example, a typical stage in a 9-stage subsonic compressor will have a pressure ratio (PR) of around 1.22. By using dual airfoils in the last two stages, it may be possible to increase their individual PRs to a level such that only eight stages—six conventional and two dual—are required instead of nine. It is with this ultimate goal in mind that the present research has been undertaken.

Previous research, along with intuition, indicates that under certain flow conditions, two airfoils working together can better accomplish the necessary task than a single airfoil. The flaps and slats on aircraft that are extended to improve lift during takeoff and landing are an excellent example. However, this dual-airfoil concept has been slower to find application in axial-flow rotors.

While there is a fair amount of literature on the subject, much of it focuses on a particular geometry or very specific flow conditions. From the designer’s standpoint, it is desirable to have information available that summarizes more general airfoil geometries and
flow conditions that are found in a compressor. Also of equal importance is to understand the governing fundamental physics. This paper presents some of the results of an ongoing project that will ultimately deliver both fundamental and practical knowledge of the dual-airfoil rotor.

Prior to any discussion of the dual-airfoil, it is necessary to have basic understanding of the lexicon used to describe it. Figure 1 shows a 2-D view of a dual-airfoil configuration. The two pertinent parameters are the percent pitch (PP), defined as $t / s$, and the axial overlap (AO), defined as $\Delta x_1 / \Delta x_2$.

**Figure 1: Dual-Airfoil Configuration**

When AO is large, the configuration is called a “splitter” since the aft blade splits the main flow path of the forward blades (Fig. 3). When AO is small, the configuration is called a “tandem” (Fig. 4). It is imperative that the reader remember this distinction to avoid confusion. Also of note is that while the aft blade (AB) shown in Fig. 1 is smaller than the forward blade (FB), it does not necessarily have to be for either a splitter or a tandem configuration.

**Dual Airfoil Background**

**Splitter Configuration**

**Centrifugal-Flow**

The splitter configuration is commercially employed only in centrifugal compressors (Figure 2). Fortunately, their use as such has been prevalent for quite some time, allowing for a plethora of published research on the subject. Ogawa & Gopalakrishnan (1987 & 1991), Bhargava & Gopalakrishnan (1978), and Fabri (1978) performed computations on splitted centrifugal rotors based upon potential flow models. Millour (1988) examined the same configuration using a 3D Euler analysis with simplified viscous forces. All noted that the primary effect of the splitters (aft blades) is to decrease the loading on the main blades, as well as to reduce the jet/wake effect at the rotor exit.

An important point to note is that the size and position of the splitters relative to the main blades can have a profound effect on overall performance. Gui et al. (1989) performed a series of incompressible flow regime experiments on two centrifugal fans: one with no splitter and one with variable geometry splitters. They examined the effects of splitter length, percent pitch, and splitter stagger angle. Results indicated that while splitters do reduce the load and velocity gradients on the main blades, they also introduce additional losses that are greatly dependent upon their geometry.

**Figure 2: Centrifugal Rotor with Splitter Blades**

**Axial-Flow**

The first axial-flow rotor incorporating the splitter configuration was built and tested by Wennerstrom et al. (1971, 1974, & 1975). The ultimate goal was to construct a single transonic stage capable of a 3.0 PR and an isentropic efficiency of 0.82. Upon testing, the constructed stage fell dramatically short of the design goals. Drawing on experience with centrifugal rotors, a splitter was added in the hopes of improving performance (Figure 3).

The result of adding the splitter was that the rotor performance improved, but was still short of the design goals: PR was 2.76, and efficiency was 0.68. However, the stage was much less sensitive to incidence variations at off-design conditions, indicating that the
splitter improved flow control within the rotor flow passage.

Later work by Dodge (1975) and Tzuoo et al. (1990) involved 2-D and 3D computations, respectively, on Wennerstrom’s splitter geometry. Results indicated a more complex flow field---particularly a more complicated system of passage shocks---than had originally been envisioned. These computations offered some explanation as to why the configuration did not perform as expected.

Here it should be reiterated that the current study focuses on fully subsonic flow fields. However, due to the very limited published work on axial-flow splitter configurations, it is useful to bear in mind the results of Wennerstrom, Dodge, and Tzuoo as a starting point.

**Tandem**

The tandem configuration, currently used only in stationary outlet guide vanes, has been very slow to find rotating turbomachinery application. However, it has been used extensively in aircraft design for decades. Slats and flaps on external wings are simple tandem blades by virtue of having little overlap in the axial direction. Two key physical effects that are of interest to compressor designers are given by Smith (1975).

The first is the circulation effect. Whenever an object---even a blunt one such as a cylinder---is placed downstream of an airfoil, the effect of that object is to increase the circulation around the airfoil. The Kutta-Joukouski law, expressed as

\[ F_L = \rho U \Gamma \]  

indicates that lift force is proportional to circulation. In terms of a tandem compressor rotor, this means that the aft blade will increase the loading on the forward blade, resulting in a greater combined pressure rise between both blades.

The second effect is the fresh boundary layer that is formed on the aft blade. Ideally, the aft blade would be placed such that it relieves the forward blade just prior to the point of separation, as shown in Figure 4. This allows for greater overall turning of the airflow, hence more work (i.e. pressure rise) while not incurring substantially higher losses.

**Figure 3: Wennerstrom’s Axial-Flow Splitter Configuration**

**Figure 4: Fresh Boundary Layer Effect of Tandem Configuration**
However, the tandem blades also tend to be susceptible to very high losses at off-design conditions.

Only two known major studies have been conducted on tandem rotors. Bammert et al. (1979 & 1980) produced a fully operational subsonic axial compressor. Their design computations indicated that at optimum percent pitch and axial overlap profile losses for a tandem arrangement can be 10 to 18 percent below those two fully independent blades. They also indicated that losses can be as high as 100 percent if the blades are poorly positioned.

The major pitfalls of the subsonic tandem compressor were narrow surge margin and rapid loss of efficiency when operating at off-design flow conditions. The given explanation is that this is due to poor adaptability of the tandem rotor blades to pressure and mass flow variations, which is consistent with the previously mentioned results on tandem stators.

A second single-stage tandem compressor was built recently in Japan by Hasegawa et al (2003). However, that study was in the transonic flow regime, putting it beyond the scope of this paper.

**Analytical Approach**

**Mesh Generation and CFD Solver**

Much of the software for this project was provided by the industrial sponsor, Rolls-Royce Corporation. The computational mesh generator is capable of producing structured meshes from airfoil geometries in two and three dimensions. Meshes ranged in size from 37,000 points (single airfoil) to 181,000 points (tandem), an example of which is shown in Figure 5.

The CFD solver employed is a viscous, Navier-Stokes code that was specifically developed by Rolls-Royce to analyze ducted turbofan engines. Time-marching is carried out by the explicit, 4-stage Runge-Kutta scheme. The turbulence model used in this study is Baldwin-Lomax (algebraic) with wall functions. In order to accurately use wall functions, the maximum value of $y^+$ was kept below 5.0 in all but a very few cases.

**Airfoil Geometries**

**Single**

Before computations could begin on dual airfoils, it was necessary to have some basis for comparison. Accordingly, a series of cases were first computed on single airfoils. For simplicity, NACA 65 profiles were chosen as the base geometry. Blade cambers ranged from $17^\circ$ to $37^\circ$, while solidities ranged from 0.76 to 3.04. This represented a wide range of blade loading conditions. See Figure 6 for an illustration of geometrical parameters.

![Figure 6: Single Airfoil Geometric Parameters](image)

**Dual**

There are several geometrical parameters that must be specified in order to define a 2-D dual-airfoil configuration. They are:

1. Airfoil shape (e.g. NACA, controlled diffusion, etc.)
2. Overall camber (i.e. blade turning)
3. Camber distribution per chord length of each airfoil
4. Solidity
5. Percent pitch
6. Axial overlap
One of the stated goals of this work is to glean the fundamental flow physics; therefore it is essential to determine how each individual parameter affects overall performance. Because a comprehensive picture was desired, the proposed method was to vary each parameter separately within a specified range while holding the others constant. This at first seems daunting, since a matrix approach of six parameters would mean running thousands of cases at a huge expense of human and computing resources.

When faced with a similar problem, Lieblein (1965) developed a procedure to collapse the parameters of camber and solidity into a single loss vs. loading chart that serves even today as a basis for compressor blade element design (Fig. 7). While originally derived for single airfoils, this method is easily adapted to the dual configuration by defining effective chord and effective spacing.

\[
C_{\text{eff}} = \frac{C_{FB} + C_{AB}}{1 + AO}
\]  
\[
s_{\text{eff}} = (1 - 0.5 * AO) * s_{FB}
\]

A further simplification can be made by using the same profile for all cases. This is reasonable at first since the blade shape is thought to have less of an impact on dual performance than camber, solidity, percent pitch, and axial overlap. As with the single blade, NACA 65 profiles were selected for the dual configuration. Both airfoils were assigned the same camber distribution, regardless of other parameters. This is not necessarily the best approach, but served as a practical simplification during the initial stages of the project.

At this point only the parameters of percent pitch and axial overlap were left to define a particular configuration. Percent pitch ranged from the aft blade being near the forward blade SS (PP ~ 20%) to the aft blade being near the forward blade PS (PP ~ 80%). Axial overlap was varied throughout a large enough range to cover both the splitter and tandem configurations.

Results

Flow Physics

The initial dual-airfoil cases run were in the splitter configuration, i.e. high axial overlap. Beginning here the Percent Pitch was varied from 20 to 80 (Figure 7) in order to determine what effect that parameter has on loss and loading.
The green shaded area represents positive FB loading. The lift plots indicate that at 20 PP, the FB has almost as much negative loading as positive. However, as the AB is moved away from the FB SS, the FB becomes more positively loaded. From a physical standpoint, positioning the AB near the SS of the FB is like placing a wing directly over a wing: the flow interference from the AB is unloading the FB. Hence moving the AB to a higher percent pitch allows the FB to act more independently. And since the AB loading changes little (it is always fully positive), the 80 PP configuration has the highest overall loading.

Figure 9 shows the typical downstream wake profiles for the 20 PP, 50 PP, and 80 PP configurations. At 50 PP, there are two distinct wakes, whereas at both 20 PP and 80 PP the wakes are beginning to merge. Data indicates that the lowest losses are achieved with merged wakes.

At 80 PP, there is a combination of minimum loss and maximum loading for the splitter configuration. However, from the bottom chart of Figure 8 it is evident that there is still a large portion of the FB that is unloaded. This begged the question of what would happen if the AB were moved downstream, reducing the overlap.

Figure 9: Pitchwise sweep typical wake profiles

Figure 10 shows typical lift plots at 80 PP for several axial overlaps, ranging from splitter to tandem configuration. As the overlap is reduced, the positive loading on the FB gets larger. While not yet confirmed, the trend suggests that at zero overlap the FB would be fully loaded. Data also indicates that as the overlap is reduced the losses either remain constant or decrease, depending upon the exact flow situation. Furthermore, Figure 10 indicates that there is not a substantial decrease in AB loading as the overlap is reduced. This gives a situation where both blades are fully loaded (or nearly so, in the case of the FB) and losses are not high.

Figure 10: Typical Variable AO lift plots
**Overall Performance**

It is desirable to present results in terms of losses vs. loading, as per Lieblein. Figure 11 shows this loss-loading chart for a single airfoil and a tandem (10% AO, 80PP), which at this writing was the best dual configuration. The loading parameter is the Lieblein D-factor, while the loss parameter is a measure of wake momentum thickness relative to chord, each respectively defined for dual airfoils as

\[
D = \left(1 - \frac{w_2}{w_1}\right) + \frac{\Delta w_{D}}{2\sigma_{eff} w_i}
\]  

(4)

\[
\omega_p = \frac{\cos \beta_2}{2\sigma_{eff}} \left(\frac{\cos \beta_2}{\cos \beta_1}\right)^2
\]

(5)

From Figure 11 it can be seen that the tandem configuration outperforms a single blade starting at D-factor of about 0.55. This is perhaps the most useful piece of information from the designer’s standpoint: it shows the point at which a dual airfoil becomes viable.

Future work will focus on further refining the tandem configuration with the ultimate goal of having a dual airfoil that will outperform the single airfoil at all loading conditions (i.e. pushing the blue curve in Fig. 11 down and to the right).

As indicated, greater overall loading could be achieved by reducing the overlap to zero, possibly even to small values of negative overlap (i.e. an axial gap). Also, the limitations on high percent pitch have yet to be fully explored. It was noted that at 80 PP the wakes were merging, but not fully so. Increasing the percent pitch to values greater than 80 could lead to a further increase in FB loading and a reduction in overall losses. These possibilities will be explored prior to the conclusion of the project.

The final step will be to perform wind tunnel tests on select configurations for the purpose of data validation.

**Conclusions**

Results thus far have demonstrated that the dual airfoil can deliver more work than a single airfoil without incurring higher losses, provided that compressor is operating above a certain loading range.

For the fully subsonic flow field, the dual airfoil functions best when in the high percent pitch tandem configuration, which allows the two blades two act nearly---though not incompletely---independent of one another.

**References**


Beelte, H., 1979, “Untersuchungen an einem Tandemgitterverdichter.” Dissertation Univ. Hanover


Ohashi, H., 1959, “Theoritische and experimentell Untersuchungen an Tandem-Pumpengittern starker Unlenkung”, ing.-Archiv 27 Nr.4, S. 201-226


Wennerstrom, A. & Hearsey, R., 1971, “The Design of an Axial Compressor Stage for a Total Pressure Ratio of 3 to 1,” Aerospace Research Laboratories report AR 71-0061, Wright-Patterson AFB, Dayton, Ohio

Wennerstrom, A., Frost, G., DeRose, R., 1974, “Test of an Axial Compressor Stage Designed for a Total Pressure Ratio of 3 to 1,” Aerospace Research Laboratories report ARL 74-0001, Wright-Patterson AFB, Dayton, Ohio
