DEVELOPMENT OF A SIMPLE DESIGN RULE FOR SUBSONIC TANDEM-AIRFOIL AXIAL-FLOW COMPRESSOR ROTOR BLADES

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ABSTRACT

Tandem-airfoils have demonstrated the ability to provide more work per blade row than a conventional airfoil while not suffering from higher losses. Tandem blades are employed as stators in production axial-flow compressors, but not as rotors.

By making several simplifying assumptions, a design rule has been developed that allows the designer to choose the best geometric parameters for each blade (i.e. camber, metal angles) prior to performing time-consuming CFD analysis. The goal is to ensure that both blades are producing minimum aerodynamic loss.

In a series of test cases, the design rule favorably captures on-design performance trends of the tandem airfoil when compared to CFD.

KEYWORDS

tandem-airfoil, rotor, stator, design rule, compressor, CFD

NOMENCLATURE

AB	Aft Blade
AO	Axial Overlap of tandem blades
C	chord
D	Lieblien diffusion factor
FB	Forward Blade
LE	Leading Edge
P	pressure
PP	Percent Pitch of AB LE relative to FB spacing
PS	Pressure Side
r	radius from axial centerline
s	tangential spacing between FB rows
SS	Suction Side
t	tangential spacing between FB Trailing Edge and AB Leading Edge
TE	Trailing Edge
w	velocity in frame of reference relative to rotor passage

Greek

β	flow angle relative to axial direction
Δx_1	axial distance between FB TE and AB LE
Δx_2	axial distance between AB TE and FB LE
θ^*	boundary layer momentum thickness
κ	blade metal angle
Ω	rotational speed in radians per second
σ	solidity
ω_C	stagnation pressure loss coefficient
ω_P	momentum thickness loss parameter

Subscripts

eff	effective
ov	overall
z	axial direction
0	stagnation conditions
11	FB inlet station
12	FB exit station
21	AB inlet station
22	AB exit station
θ	tangential direction

MOTIVATION

One of the oldest challenges faced by axial-flow compressor designers is using as few stages as possible to achieve the desired pressure rise without compromising efficiency. The obvious benefits of this are improved engine power-to-weight ratio and reduced manufacturing parts. Tandem-airfoils incorporated into a compressor rotor offer the possibility of more work without incurring higher losses, thus requiring fewer stages.

The purpose of the ten-week UTSR Industrial Fellowship was for the author to work at Rolls-Royce Corp. on a computational study already in progress on the tandem-airfoil.

BACKGROUND

In an axial-flow compressor blade row the amount of work is proportional to the turning of the working fluid by the blade ($\beta_{11} - \beta_{22}$). Figure 1 shows the 2-D profile view of a conventional blade row that is highly loaded. Note the onset of boundary layer separation towards the trailing edge (TE). However, in the tandem configuration (Figure 2) the individual blades are loaded below the point of separation, so that together they produce high turning without incurring large losses.

The tandem-airfoil is currently used in production for stators, examples of which include the GE J-79 compressor[1] and an advanced single-stage LP compressor built by Honeywell[2]. However, the tandem-airfoil has been slow to find application in rotors. While several experimental studies have been conducted on tandem rotors[3 – 10], none are known to be in production.

The early stages of rotor design consist of evaluating aerodynamic performance in the 2-D realm. A fully 3-D blade with radial twist can be designed from 2-D data. When performing a 2-D analysis---experimental or computational---the flow is usually examined in the frame of reference relative to the blade, i.e. the flow field within the blade passage is the same whether it is a rotor or a stator.

A number of experimental and analytical studies have been conducted on subsonic tandem blades in the 2-D relative frame[11 – 26]. While these studies vary widely in scope (e.g. different airfoil families, blade orientations, incompressible vs. compressible flow) there is one result that is consistent throughout. Namely, the subsonic tandem-airfoil will provide the most turning---work in a rotor---and the least losses when the following two conditions are met:

1.) There should be little, if any overlap between the Forward Blade (FB) and the Aft Blade (AB)
2.) The leading edge (LE) of the AB should be placed near the pressure side (PS) of the FB

The precise optimum values of overlap and AB pitchwise placement vary from study to study. Furthermore, nearly all of the previous studies on tandem blades in 2-D were conducted over a relatively narrow range of loading. It is of great interest to a designer to have 2-D results over a wide range of loading in order to evaluate the point at which the tandem configuration becomes a viable option over a conventional blade row. One recent computational study[27] has examined how the tandem blade performs in 2-D over a wider range of loading, as well as sensitivity to blade overlap and AB pitchwise position.

It is evident from all previous work that a tandem-airfoil does offer performance benefits over a conventional airfoil in the 2-D realm. The major shortcoming of the most recent computational study[27] was that losses were not as low as they could have been. In particular, it was found that the AB was not operating at its minimum loss condition, i.e. the incidence angle that produces the least aerodynamic loss. The primary reason for this was that the airfoil geometric parameters were chosen arbitrarily. It was thus thought that better performance could be achieved by development of a design rule for the tandem blades that would provide for both the FB and AB to be operating at minimum loss.

A second benefit of having a simple design rule is that it could potentially be used as a time-saving measure prior to the CFD analysis. In order for this to work, however, the design rule would have to demonstrate reasonable agreement with CFD solutions in test cases.

OBJECTIVES

1.) Develop a simple design rule for tandem blades that ensures minimum aerodynamic loss
2.) Compare the design rule predictions to CFD results

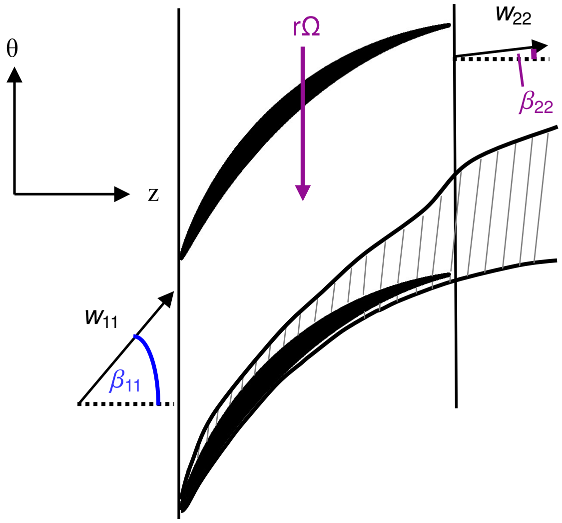

Figure 1: Highly Loaded Conventional Blade Row

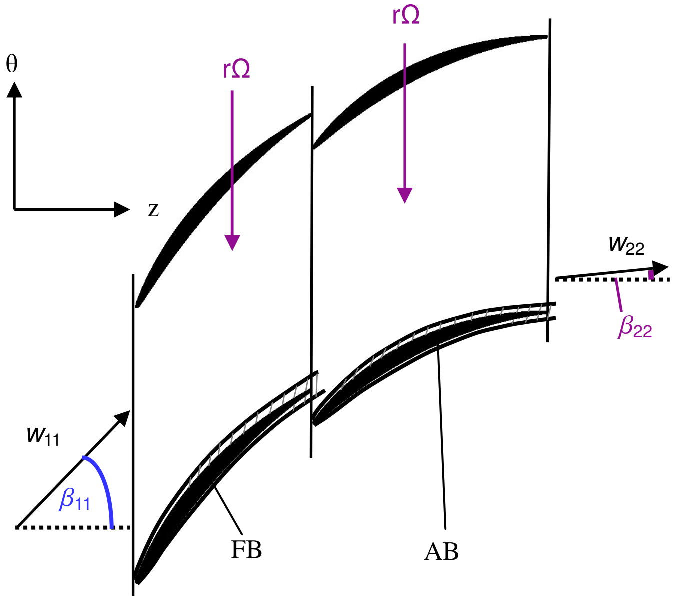

Figure 2: Highly Loaded Tandem Blade Row

ANALYTICAL APPROACH

Tandem Blade Geometric Parameters

There are several geometric parameters that must be specified for a tandem-airfoil. Referring to Figure 3, they are:

1.) Airfoil family (e.g. Double Circular Arc, Controlled Diffusion)
2.) Cambers:
    a. FB: $\varphi_{FB} = \kappa_{11} - \kappa_{12}$
    b. AB: $\varphi_{AB} = \kappa_{21} - \kappa_{22}$
    c. Overall: $\varphi_{ov} = \kappa_{11} - \kappa_{22}$
3.) Solidities:
    a. FB: $\sigma_{FB} = C_{FB} / s$
    b. AB: $\sigma_{AB} = C_{AB} / s$
    c. Effective: $\sigma_{eff} = (C_{FB} + C_{AB}) / s * (1+AO)$
4.) Axial Overlap: $AO = \Delta x_1 / \Delta x_2$
5.) Percent Pitch: $PP = t / s$

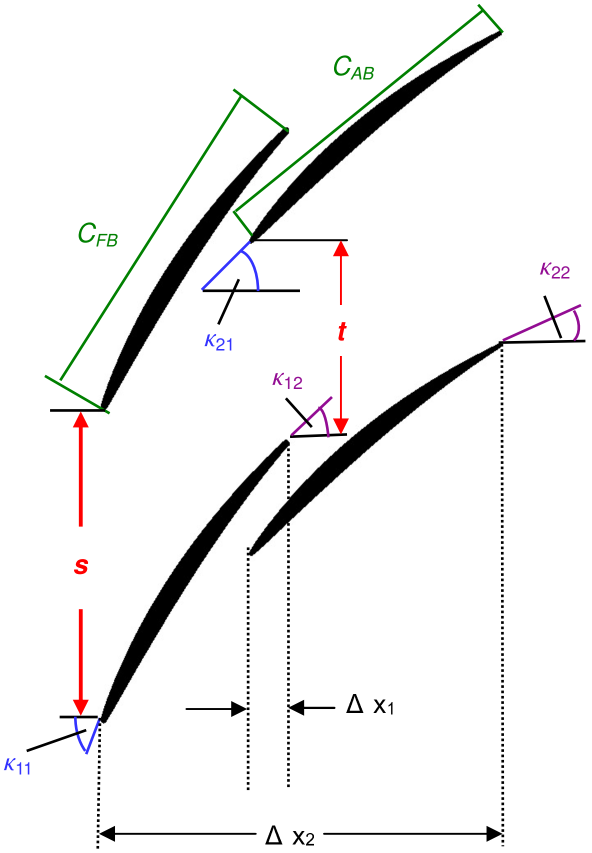

Figure 3: Tandem Blade Geometrical Parameters

As previously mentioned, the effects of Axial Overlap and Percent Pitch are well known. The purpose of the design rule is to specify the best blade angles---and consequently cambers---for a given airfoil family.

Tandem Blade Performance Parameters

When working in the 2-D relative frame of reference it is appropriate to compare the level of loss versus loading through a blade row. Lieblein[28] developed two generalized parameters for loss and loading that are based upon geometry, velocities, and flow angles. To measure loading, the Lieblein diffusion factor for a tandem-airfoil is defined as

$$D \equiv \left(1 - \frac{w_{22}}{w_{11}}\right) + \left(\frac{w_{\theta,11} - w_{\theta,22}}{2\sigma_{eff} w_{11}}\right) \qquad (1)$$

where the first term represents the velocity diffusion from inlet to exit, and the second term represents turning in the tangential direction. D-Factor in the relative frame is analogous to pressure rise in the absolute frame of reference. The D-Factor is derived such that it is a valid measure of loading only at minimum loss incidence, which goes along with the performance requirement of the design rule.

The associated loss parameter is a representation of the boundary layer momentum thickness at the trailing edge normalized by the blade chord length, defined for a tandem-airfoil as

$$\omega_P \equiv \left(\frac{\theta^*}{C_{eff}}\right) \approx \omega_C \frac{\cos\beta_{22}}{2\sigma_{eff}} \left(\frac{\cos\beta_{22}}{\cos\beta_{11}}\right)^2 \qquad (2)$$

where ω_C is the stagnation pressure loss coefficient, defined as

$$\omega_C \equiv \frac{P_{0,11} - P_{0,22}}{P_{0,11} - P_{11}} \qquad (3)$$

Figure 4 shows an example plot of the loss parameter versus D-Factor taken from experimental data of a NACA-65 airfoil[28].

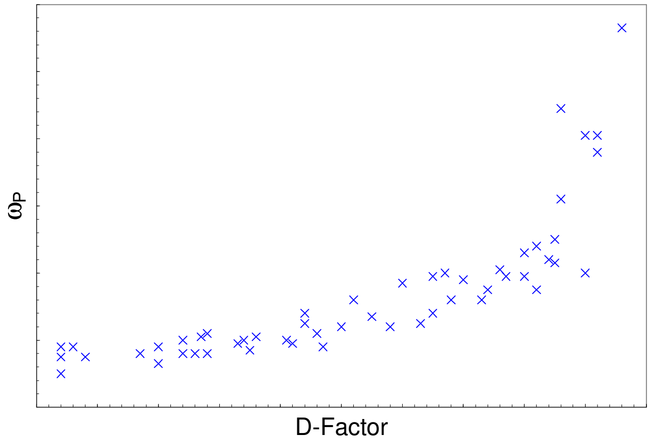

Figure 4: Example Loss versus Loading Chart

Design Rule Development and Use

A chart such as Figure 4 is one of the desired outputs from the design rule. Other outputs are the appropriate blade metal angles. Table 1 summarizes the inputs and outputs of the design rule.

	Inputs	Outputs
Flow	β_{11}	β_{12}, β_{21}, β_{22}
Loading	D_{FB}, D_{AB}	D_{ov}
Geometric	σ_{FB}, σ_{AB}	κ_{11}, κ_{12}, κ_{21}, κ_{22}
Losses		$\omega_{P,FB}$, $\omega_{P,AB}$, $\omega_{P,ov}$

Table 1: Design Rule Inputs and Outputs

Two initial assumptions are made that allow for easy development of the design rule. The first is that there is no interaction between the flow fields of the two blades. This eliminates the parameters of Axial Overlap and Percent Pitch from the design rule, although it makes it necessary to determine performance sensitivity to these parameters using CFD analysis. The second assumption is that the flow field is incompressible. While not completely accurate for most turbomachinery applications---the typical inlet Mach number to a compressor stage is above 0.30---it does allow the D-Factor to be expressed entirely in terms of effective solidity and flow angles:

$$D = \left(1 - \frac{\cos\beta_{11}}{\cos\beta_{22}}\right) + \left(\frac{\cos\beta_{11} * (\tan\beta_{11} - \tan\beta_{22})}{2\sigma_{eff}}\right) \quad (4)$$

Equation 4 can be used for the individual blades by making the appropriate substitutions for flow angles and individual blade solidity. The flow and loading parameters can now be found by the following procedure:

1.) Specify the desired FB and AB D-Factors, D_{FB} & D_{AB}
2.) Specify the desired inlet flow angle, β_{11}
3.) Calculate β_{12} using Equ. (4) modified for the FB
4.) Set the AB inlet flow angle equal to the FB exit flow angle, i.e. $\beta_{21} = \beta_{12}$
5.) Calculate β_{22} using Equ. (4) modified for the AB
6.) Calculate overall D-Factor, D_{ov}, using β_{11} and β_{22} in Equ. (4)

The above procedure for finding overall loading and blade flow angles is valid for any family of airfoils. Information on losses and required metal angles are family-specific, and can be found either experimentally or computationally. Since one of the motivations behind developing this design rule was to avoid time-consuming CFD analysis, it was decided to use the NACA-65 family of airfoils due to the large amount of experimental data on them that is available in the open literature[28].

The literature on NACA-65 airfoils contains loss versus loading correlations similar to that shown in Figure 4. Since the FB and AB D-Factors have already been specified, the loss parameter (ω_P) for the blades can be individually determined from the available correlation. The respective stagnation pressure loss coefficients, $\omega_{C,FB}$ and $\omega_{C,AB}$, can then be found by substituting the appropriate flow angles for the FB and AB in Equ. (2) and solving for ω_C. The loss in stagnation pressure due to the individual blades can be superposed to form the overall loss coefficient of the tandem configuration:

$$\omega_{C,ov} = \omega_{C,FB} + \left(\frac{\cos\beta_{11}}{\cos\beta_{21}}\right)^2 * \omega_{C,AB} \quad (5)$$

The cosine-squared term in Equ. (5) accounts for the change in dynamic head between the FB inlet and the AB inlet. The overall loss parameter can then be calculated using Equ. (2).

The final output from the design rule is the metal angles for each blade: κ_{11}, κ_{12}, κ_{21}, κ_{22}. The NACA-65 experimental data are presented in such a way that if the individual blade solidity and inlet flow angle are known, one can easily read the required metal angles from a chart.

RESULTS AND DISCUSSION

Design Rule vs. CFD

The design rule was tested against the R-R CFD package, which is a fully viscous Reynolds-averaged Navier-Stokes solver. Turbulence was simulated by the one-equation Spalart-Allmaras model. Losses were calculated using the design rule over a wide range of loadings, as shown in Figure 5. Two sets of CFD results are also shown, one for a tandem-airfoil at zero overlap and 50 Percent Pitch (PP), and another at zero overlap and 95 PP, both at an inlet Mach number of 0.60.

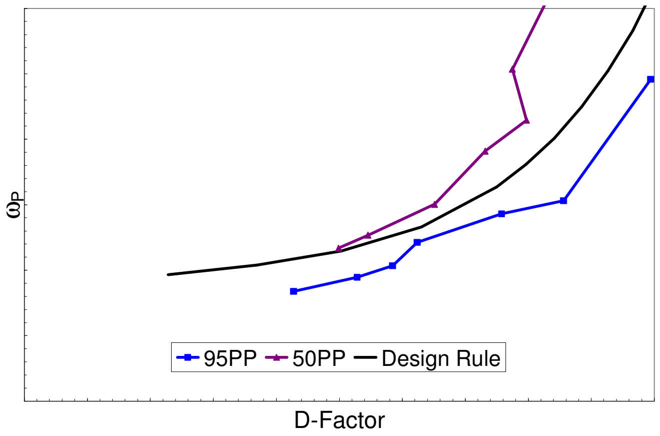

Figure 5: Design Rule vs. CFD Loss / Loading Chart

It can be seen from Figure 5 that the design rule does a good job of capturing the trend of tandem-airfoil performance in the 2-D realm. Discrepancies can be attributed to the two initial assumptions of incompressible flow and non-interacting flow fields.

It is well known from previous studies that a tandem-airfoil with a high Percent Pitch value (i.e. 80 or greater) will be more loaded than a tandem-airfoil with a lower Percent Pitch value. This increase in loading at high Percent Pitch is largely due to the interaction of the individual blade flow fields on one another. Henceforth the design rule under-predicts the D-Factor when compared to the 95 PP tandem.

Positioning the Aft Blade at 50 Percent Pitch results in the least interaction effect, yet the design rule over-predicts the loading compared to a CFD-analyzed 50 PP tandem. This is not surprising since the incompressible D-Factor equation (4) predicts a value as much as 35% higher than the general D-Factor equation (1) at an inlet Mach number of 0.60.

The obvious benefit of presenting the data as shown in Figure 5 is that it gives an indication of how much the design rule assumptions vary from the CFD code that more closely matches physical reality.

Metal angles (κ) are determined by the design rule based upon predicted minimum loss flow angles (β). For comparison, a CFD analysis was used to find the actual minimum loss flow angles for several cases of a highly loaded tandem-airfoil, some of which are shown in Table 2. As can be seen, the design rule generally gives a prediction that comes within a few degrees of minimum loss.

	Forward Blade		Aft Blade	
Tandem Configuration	Design Rule	CFD	Design Rule	CFD
0 AO, 95 PP	58.0	55.9	41.8	40.4
0 AO, 85 PP	58.0	56.0	41.8	41.3
0 AO, 50 PP	58.0	55.0	41.8	48.3

Table 2: Some Minimum Loss Inlet Flow Angles (β_{11} & β_{21})

Finally, it must be noted that a single point on the loss vs. loading chart can be calculated in about 15 minutes using the design rule, whereas the CFD cases required to accomplish the same task can take several hours to set up, execute and post-process.

Improvements to Tandem-Airfoil Performance

As mentioned earlier, a previous CFD study[27] on tandem-airfoils resulted in losses that were higher than they could have been due to blade metal angles being chosen arbitrarily, as opposed to designed for minimum loss. One subset of the test matrix from that study was recomputed (CFD) using the design rule metal angle predictions to determine how much improvement could be realized in tandem-airfoil performance. Figure 6 shows the best case from the previous study versus the best case using the design rule.

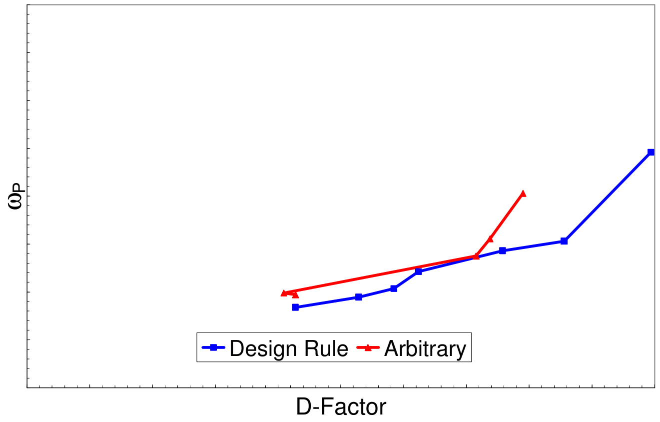

Figure 6: Arbitrary Metal Angles vs. Design Rule Metal Angles (both CFD results)

CONCLUSION

A simple design rule has been developed for tandem-airfoil compressor blade rows in the 2-D relative frame. The major conclusions are summarized as follows:

1.) The design rule predictions accurately capture the loss versus loading trend as compared to CFD results.
2.) The design rule closely predicts the required blade metal angles for minimum loss.
3.) Using the design rule prior to CFD analysis saves enormous amounts of time and computational resources in addition to providing for the best tandem-airfoil performance in 2-D.

It must be emphasized again that while the procedure for calculating loading (i.e. D-Factor) is universal, the loss predictions are dependent upon the family of airfoils used. Extending this design rule beyond NACA-65 would require that loss data be available for the chosen airfoil family.

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