

AN INVESTIGATION TO IMPROVE GAS TURBINE ENGINE PERFORMANCE THROUGH THE USE OF SPLITTERED ROTORS

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Abstract

Splitter vanes are additional, smaller airfoils that are placed circumferentially between the main blades of a compressor rotor. They have been used for decades in centrifugal rotors, and have been shown to improve overall performance in terms of pressure ratio and efficiency. Wennerstrom (circa 1974) was the first to use the splitter concept in an axial-flow rotor. His experiments indicated that in addition to the known benefits from centrifugal rotors, the splitters would also improve flow control in the axial flow when operating at off-design conditions. In spite of these potential benefits, there has been no known commercial application of the splittered axial rotor. The goal of this project is to determine if splitter vanes can be successfully utilized in a commercial gas turbine engine. If so, it would allow designers to use fewer stages in a compressor, thus reducing both manufacturing and operating costs of the engine. The first portion of the project will involve an extensive numerical study of various 2-D geometries. Pertinent parameters include the shape and position of the splitter vane relative to the main rotor blades. 3-D meshes will be used in the latter stages of the project.

Background on Splittered Rotors

Introduction

One of the greatest concerns to designers of compressors is boundary layer separation within the blade passages. Variations of incidence at off-design conditions can lead to high losses due to separation, particularly on the suction side (SS) of a blade. Two key geometrical parameters in a blade row that influence separation are the turning angle ($\beta_1 - \beta_2$) and the ratio of blade chord to spacing (C/s), often called solidity. The specifics according to Hill & Peterson (1992) are as follows.

As the turning angle increases, so does the maximum velocity on the suction side. Consequently, there will be a high adverse pressure gradient, which can lead to separation.

Decreased blade spacing (i.e. increased solidity) reduces the difference between the minimum pressure and the trailing edge pressure on the suction side. This dependence on solidity is recognized in the Lieblein diffusion parameter (D-factor), defined as

$$D \equiv 1 - \frac{w_2}{w_1} + \frac{w_{\theta 1} - w_{\theta 2}}{2 \left(\frac{C}{s} \right) w_1}$$

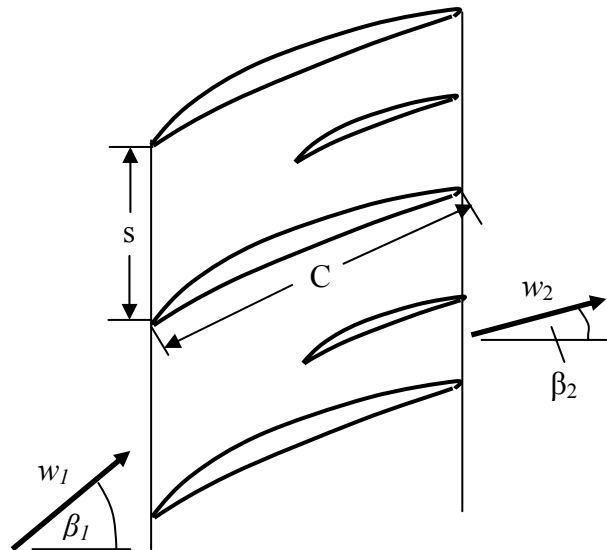


Figure 1: Axial Flow Rotor Cascade with Splitter Vanes

The D-factor is used by compressor designers as a first order indicator of the propensity of the flow to separate; a typical maximum allowable value ranges from 0.50 to 0.55.

While increasing the number of blades lowers separation losses, the additional metal in the flow path reduces the compressor's flow capacity and introduces additional profile losses. One solution to this dilemma is to insert a smaller airfoil, a splitter vane (Figure 1), in the flow path aft of the entrance plane. The result is a

higher effective solidity that has the potential to lower separation losses without seriously compromising flow capacity. Splitters also offer the ability to better control the flow, particularly when operating at off-design conditions.

Splitters have been commonly used in centrifugal compressor rotors for decades. Wennerstrom (1974b) was the first to investigate their application in an axial-flow compressor rotor. Since then, very few studies have been published on the subject. To the author's knowledge, splitters have never been commercially employed in axial rotors.

Splitters in Centrifugal Rotors

As previously mentioned, splitters have been used in centrifugal compressor rotors (Figure 2) for quite some time. Ogawa & Gopalakrishnan (1977 & 1981), Bhargava & Gopalakrishnan (1978a & 1978b), and Fabri (1978) performed computations on splintered centrifugal rotors based upon potential flow models. Millour (1988) examined the same configuration using a 3-D Euler analysis with simplified viscous forces. All noted that the primary effect of the splitters is to decrease the loading on the main blades, as well as to reduce the jet/wake effect at the rotor exit. Fradin (1987) demonstrated experimentally that the flow field at the discharge of a transonic rotor is more homogenous when the splitters are used.

The potential flow calculations of Ogawa & Gopalakrishnan (1981) indicated that the position and size of the splitter could have a profound effect on its overall performance. Gui et al. (1989) performed a series of incompressible flow regime experiments on a centrifugal fan with variable geometry splitters. They examined the effects of splitter length (Figure 3), circumferential position (Figure 4), and stagger angle (Figure 5).

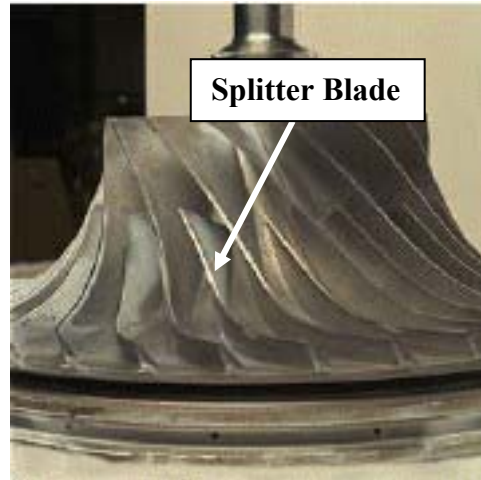


Figure 2: Centrifugal Rotor with Splitter Vanes

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. Increasing the length of the splitter can raise the pressure coefficient with little or no effect on efficiency. However, they indicated no rule of thumb as to the limit on splitter length, which would certainly have to be taken into account in a transonic flow field where shocks are present. It was shown that the pressure coefficient increases when the splitter is placed closer to the suction side of the main blade.

More recent experimental work on transonic rotors by Oana et al. (2002) focused on the fraction of mass flow in the two splitter channels. Splitters are typically located at mid-pitch between the main blades. Maintaining this circumferential position, the stagger angle was adjusted such that there was even mass flow distribution between the two channels. This proved to increase the overall efficiency of the rotor at a given pressure ratio.

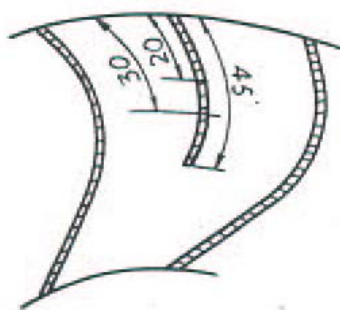


Figure 3: Variable Length Splitter

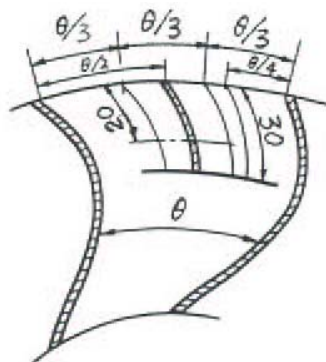


Figure 4: Variable Circumferential Position Splitter

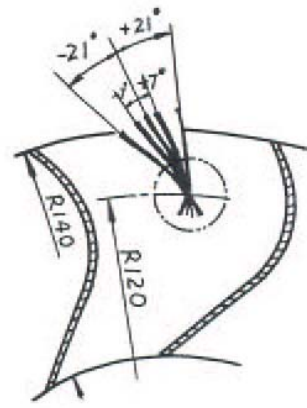


Figure 5: Variable Splitter Stagger Angle

Splitters in Axial Compressors

In the early 1970s the US Air Force undertook research to build a supersonic axial flow stage with a pressure ratio of 3.0 and an isentropic efficiency of 0.82 (both from stagnation conditions). Inlet Mach number ranged from 1.28 at the hub to 1.52 at the tip, with a tip velocity of 1,600 ft/s [Wennerstrom & Hearsey (1971)]. Upon testing, the constructed stage fell dramatically short of design. This was blamed largely upon poor flow control within the rotor passage. Recognizing that splitters had long been used to improve the performance of centrifugal rotors, the decision was made to use a splitter, in the hopes that better flow control could be achieved without incurring additional losses [Wennerstrom et al. (1974a)]. Due to time constraints, many decisions regarding the splitter were based upon engineering judgment in lieu of thorough analysis. These are described below.

The trailing edge (TE) of the splitter was located in the same plane as the TE of the main blades. The leading edge (LE) of the splitter was positioned in a region of subsonic flow. Recognizing that there would be a shock near the entrance region, the splitter LE was placed far enough downstream so as not to have a significant influence on the shock shape. The splitter camber line was identical to the main blade at the same axial location, and was circumferentially positioned at mid-pitch of the main blades, which was noted as not necessarily being optimum. Span was the same as the main blades [Wennerstrom et al. (1974b)].



Figure 6: Shock System as Visualized by Wennerstrom

The result of adding the splitter was that the rotor performance improved, but the overall stage performance was still short of 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 [Wennerstrom et al. (1975)].

A 2-D, inviscid computation was performed afterwards. Although limited in usefulness, the results did indicate that the lower passage of the splitter was choked at design conditions, resulting in higher losses than anticipated [Dodge (1975)].

Since then few known studies have been done on splitters in axial rotors. Tzuoo et al. (1990) performed both inviscid and viscous 3-D computations on Wennerstrom's rotor. They determined that additional shocks exist, as shown in Figure 7. It was also noted that by moving the splitter closer to the main blade SS, the likelihood of choking one of the splitter passages was reduced.

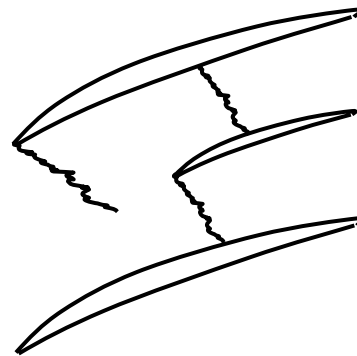


Figure 7: Shock system as calculated by Tzuoo et al. (1990)

Summary of Splitter Background

The most important points regarding the use of splitters in compressor rotors are summarized as follows:

1. Greater stage loading can potentially be achieved without incurring heavy losses
2. Splitters offer greater flow control at off-design conditions
3. Splitter geometry has a profound influence on overall rotor performance:
 - a. Splitters should be no closer to the main blade PS than mid-pitch
 - b. There is evidence to suggest that positioning the splitters closer to the main blade SS offers benefits in both subsonic and transonic flow
4. Splitter LE should be in a subsonic region, if possible
5. Careful attention should be paid to the mass flow distribution in the two splitter passages

Project Goal

While the potential benefits of splitters are evident in centrifugal rotors, the question remains as to how practical they are to use in an axial-flow machine. The goal of this project is to answer that very question using the work of Wennerstrom as a spring board.

As engine designers are ever concerned about power-to-weight ratio, the logical approach is to determine if the splitter configuration can improve single stage performance well enough to reduce the number of stages required for a given pressure ratio and efficiency. Removing even one stage from a 10-stage compressor would translate into millions of dollars in long-term savings for both manufacturers and operators of gas turbine engines.

Method of Investigation

Computer Code

Computational fluid dynamics (CFD) will serve as the primary method of the investigation. The particular solvers are the Advanced Ducted Propfan Analysis Codes (ADPAC) developed in the late 1990s by Allison Engine Company---now Rolls-Royce, plc---under contract from NASA. ADPAC is an Euler/Navier-Stokes solver that is capable of computing 3-D, multiple-block grids, for both steady and time-dependent flow fields. Available turbulence models include the Prandtl Mixing-Length, Baldwin-Lomax, Spalart-Allmaras, and Goldberg k-R.

Due to the large number of splitter configurations being investigated, the first portion of the project involves solving 2-D flow fields in order to save resources. The idea is to take the total number of possible splitter configurations and through 2-D analysis determine a substantially smaller subset which can then be optimized using 3-D grids.

Baseline Configuration

As previously mentioned, the project goal is to reduce the number of stages in a compressor. For a baseline configuration, two generic rotors are considered, each having an average pressure ratio (PR) of 1.19. Because the first portions of the project involve 2-D simulations, the airfoils are modeled after typical rear engine stages where radial variations in the flow field are minimal. Requiring that the same amount of work be done in a single rotor results in a PR of 1.42 and D-factor of 0.60. While these values are too high for typical standard blading, the computational results

serve as a basis of comparison for the splitter configuration.

Splitter Configurations

Geometrical Considerations

There are several geometrical parameters that will be investigated to evaluate the performance of the splitter configuration. They are:

- main blade airfoil shape (e.g. camber, chord, point of maximum thickness)
- splitter airfoil shape
- splitter circumferential position relative to main blades
- splitter axial position
- splitter stagger angle

As has been previously discussed, each of these will have a profound effect on the overall flow field. The project has begun by holding both airfoil shapes constant and varying the position and orientation of the splitter. These analyses are being conducted on a 2-D basis. Once a set of optimum splitter positions have been determined, the 3-D computations will commence. At that point, airfoil shape will also be allowed to vary.

Evaluation Criteria

In order to gain the maximum benefit from this project, it is necessary to have a clearly defined set of parameters by which the splitter configuration is evaluated compared to standard blading. In other words, how can we tell if a splitter is helping?

Overall performance criteria are pressure ratio and efficiency (both from stagnation conditions) as functions of mass flow and rotational speed. These are typically plotted on a stage map (Figure 8), and can be used to make a direct comparison with the baseline configuration.

Two subcategories are work and losses. For evaluating work, the criteria are overall turning ($\Delta\beta$) and blade loading. The work done to the airfoil is directly proportional to the total turning, therefore this will serve as an excellent indicator of splitter performance. It is also of importance to examine the loading of the main and splitter blades to determine if the splitters fulfill their promise of reducing the load on the main blades.

To consider losses, first recall that splitters reduce the jet/wake effect in centrifugal compressors. Wake profiles will be examined to determine if splitters are equally helpful in an axial-flow machine. Another loss

parameter is deviation (δ), which is the difference between exit flow angle and exit metal angle. A well-performing rotor will have a deviation near zero. Since one of the primary offerings of splitters is improved flow control---especially in off-design operating conditions---the deviation is an important parameter to consider.

Also of importance when considering losses is the loss coefficient, defined as

$$\omega = \frac{P_{02,ideal} - P_{02,actual}}{P_{01} - P_{s1}}$$

where the subscript 0 denotes stagnation conditions and s denotes static conditions.

Preliminary Results

To date, reportable computational results are available only for the baseline configuration. Figure 8 shows the overall performance (i.e. rotor map) at a design speed of 10,250 rpm. The design point (mass flow = 20.6 lb_m/s, PR = 1.42 & $\eta = 0.925$) is designated by a red dot. As can be seen, while the baseline airfoils very nearly reach the desired pressure ratio, they fall short on overall efficiency. This can be

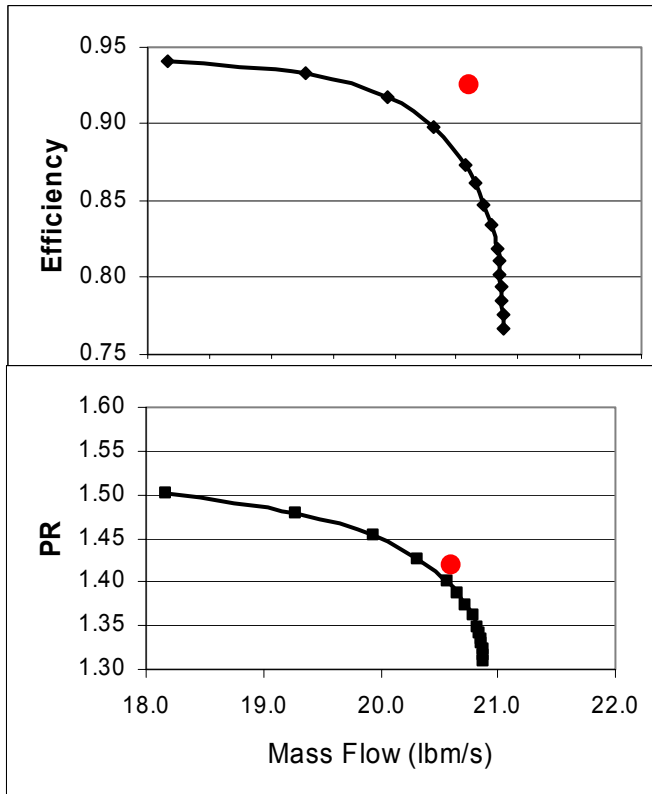


Figure 8: Baseline Rotor Design Speed Line

explained by examining the streamlines at the design mass flow (Figure 9). The colors indicate Mach number, with red being near sonic and blue near zero. Notice that the streamlines closely follow the metal angle up to about 60% of the chord. Further downstream they begin to diverge, with the end result being large deviation at the passage exit. This indicates that the flow is not being sufficiently turned. Also, notice the separation zone near the trailing edge of the suction side.

These problems are precisely what the splitter vanes pose to correct through improved turning and flow control. Extensive results of the splintered configuration should be available beginning summer 2005.

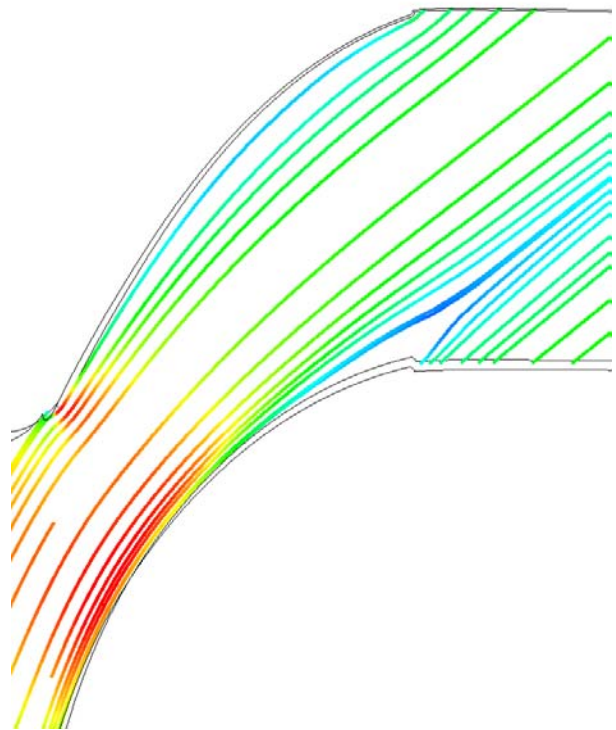


Figure 9: Baseline Streamlines at Design Mass Flow

Conclusion

Due to the very limited amount of previous work done on axial splitters, it is safe to say that there is much room for future improvement. Knowledge from centrifugal compressor application is being used in conjunction with the pioneer work of Wennerstrom to develop an axial flow stage with a high pressure ratio, high efficiency, and small loss penalties at off-design conditions. The most advanced computational tools available are being utilized to provide accurate solutions of the splintered flow field.

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