Numerical Investigation of Leaned Strake in the Ram-rotor

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Abstract. The concept of lean commonly adopted in conventional compressors is introduced into the design of the ram-rotor strake, and numerical simulation of the effect of lean on the aerodynamic performance of the ram-rotors has been conducted in this paper. Three types of leaned strake schemes are modeled and analyzed first to investigate the effect of lean on pressure rise and loss characteristics, and then based on C-mid scheme, different amounts of leaning angle are chosen for further research so as to improve the performance of leaned ram-rotor. Results show that the application of lean can affect the intensity and position of shock system. Radial transport and accumulation of low momentum fluid in the boundary layer of suction surface is suppressed. Compared to baseline, C-cas scheme increases total pressure ratio by 2.338 %, however, C-hub scheme improve the adiabatic efficiency by 0.462%. For C-mid scheme, a slight reduction of performance is observed.

1. Introduction

Axial flow compressor is an important power equipment in industrial production, but also an important energy consumption equipment. In the current situation of worldwide energy shortage, it is an important problem to save energy and reduce the consumption of axial flow compressor with high energy consumption[1]. In modern aeroengine and land gas turbine, compressors stages are required to operate with high compression ratio and efficiency, which helps to minimize the fuel consumption and make a compact component configuration. If the Mach number of the flow passage is high, a slight change in flow will cause congestion[2]. Transonic and supersonic compressors have been gradually developed to achieve this goal. Conventional supersonic axial compressor rotors have many blades and the blade surface produces a shock system with low efficiency, resulting in a large loss in the compression process[3]. Transonic compressor with good performance is one of the main components of high performance turboshaft engine. In order to reduce the compressor class, reduce the overall quality and improve the thrust-to-weight ratio of the engine, it is necessary to carry out the design and experimental research of the compressor with high pressurization ratio, high load and wide stability range [4]. Kantrowitz, et al [5] and Klapproth, et al [6] proposed two types of supersonic compressor rotors which are named the shock-in-type rotor and the impulse-type rotor, and demonstrated that supersonic compressor has a more preferable aerodynamic performance. With the development of transonic and supersonic compressors, a new kind of supersonic compressor rotor named ram-rotor or ram-pressor was presented recently, which has high hub-to-tip ratio and shallow stagger angle. As pointed out by Lawlor, et al [7], initial proof-of-concept of the ram-rotor was designed and tested to demonstrate the basic operational characteristics. Numerically predicted results and experimental
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study are reported by Grosvenor, et al [8][9], which obtained the measured pressure ratio of 7.8:1. Steele, et al [10] and Lawlor, et al [11] investigated the potential prospect of shock compression technology into micro turbines and CO₂ compressors. Many useful results also can be found by Han, et al [12-15] and Yang, et al [16] whose work focuses on the ram-rotor flow field and performance under the environment of whole stage system and single strake row respectively.

In order to improve the flow field in ram-rotors, many blades design means of conventional turbomachinery can be adopted into the strake of ram-rotor. Some successful efforts about the use of sweep on the strake and the consideration of the strake section shape in the ram-rotor were performed by Han, et al [17] and Yang, et al [18]. It is also known that blade curve or lean design has been demonstrated an effective flow control method to improve compressor performances, and many research efforts were spent on lean for compressor performance improvement. As pointed out by Bruges man, et al [19] that dihedral(lean) influenced strongly the development of the secondary flow. The overall loss and loss distributions in the spanwise direction were also modified by the lean effect. Bergner, et al [20] reported an investigation of the impact of various amounts of lean on the aerodynamic behavior and found that lean controlled the radial distribution of the mass flow and changed the shock pattern. The work by Benini, et al [21] showed that a substantial increment in the overall efficiency was obtained by using forward lean. Neshat, et al [22] drew his conclusion that blade lean was clearly more effective than blade sweep and it increased both the stage efficiency and the chocking flow rate.

From the published literatures, one of the main drivers for using lean in axial compressors is to add a radial blade force to the fluid cell, so that the original radial pressure field is modified for good control of secondary flow. Moreover, it has been found by the authors that in ram-rotors there exists massive flow separation near suction surface of strake aft part, which is one of the dominant sources of loss and detrimental to get a high aerodynamic performance. The challenge is to limit the loss and blockage produced by the flow separation. Hence, in view of the beneficial effect of lean in improving secondary flow and flow separation, the lean design is introduced into the strake of ram-rotors, with the purpose of controlling the flow separation and blockage near the strake aft part. Meantime, the impact of lean design on the aerodynamic behavior of the ram-rotor is obtained for further flow field and performance improvement.

2. Model and numerical method

2.1 Basic Ram-rotor Model

The basic three-dimensional ram-rotor model in present work is shown in Figure 1. On the ram-rotor rim configure three flow paths, and each path consists of two neighboring strake walls, hub wall and casing wall. The hub wall which consists mainly of the compression ramp, the throat surface and the diffusing ramp is the core part of the ram-rotor. Significant pressure rise is achieved across the shock...
system which is produced, reflected and held between the casing wall and hub wall. The specific geometric parameters of the ram-rotor model are listed in Table 1.

**Table 1. Geometric Parameters of Ram-rotor**

| Parameters                        | Values   |
|-----------------------------------|----------|
| Outer diameter/mm                 | 350      |
| Hub to casing ratio               | 0.9      |
| Throat to strake ratio            | 0.857    |
| Solidity at hub                   | 0.213    |
| Compression ramp angle/deg        | 6        |
| Diffusing ramp angle/deg          | 5        |
| Stagger angle/deg                 | 15       |
| Radius of LE and TE/mm            | 0.15     |
| Tip clearance height/mm           | 0.35     |
| Strake maximum thickness/mm       | 7.115    |

2.2 Geometric Leaning Definition
For baseline ram-rotor, the strake is radial stacked, and with respect to leaning model, there are different methods to create leaned blades such as shifting stacking line, leading edge line or trailing line in compressors. Shifting trailing edge is chosen in present work to make geometric modification in the ram-rotor, and the leaned strake is obtained by varying the strake profile perpendicular to the chord line direction, which is Y direction in Figure 2. The two points of O1 and O2 present the leading edge and trailing edge of strake, respectively. Point A and Point B separate the whole strake into such three parts as fore, middle and aft parts. In order to control the flow radial transportation near strake aft part and do not affect the incoming supersonic flow, the lean design is only applied into the design of the strake aft part. With keeping tip section unchanged to the baseline scheme, C-cas scheme is formed through moving the rest spanwise sections (strake aft part) from root to tip linearly perpendicular to the chord line (-Y direction in Figure 2). That is to say that the amount of movement is zero at tip section and highest at root section. Likewise, C-mid and C-hub schemes are obtained with keeping middle section and root section intact, respectively, to shift the rest strake sections. For C-mid scheme, strake sections from middle to tip are moved along +Y direction, with sections form middle to root sections along –Y direction. C-hub scheme moves the section from root to tip linearly along +Y direction.

Additionally, for the sake of smooth connection between middle part and aft part, the amount of section movement is zero at location B and highest at the trailing edge (location O2), which indicates no lean at the initial position of strake aft part and maximum lean at trailing edge position. Leaning angle in present work is defined as the acute angle between trailing edges of leaned ram-rotor and baseline ram-rotor.

![Figure 2. Schematic Diagram of Strake Lean Definition](image-url)
It is worth noting that the strake profile from leading edge (location O1) to location B of all three leaned ram-rotors maintain the same as that of baseline ram-rotor. Moreover, in order to investigate the impact of leaning angle on the flow characteristics in the leaned ram-rotors, six leaning angles are applied in C-mid scheme. The leaning angle varies in the range from 5 to 30 degrees, with the intervals of 5 degrees.

2.3 Grid and Numerical Method
The commercial CFD code FLUENT 6.3[23] was used to predict accurately the aerodynamic behavior of ram-rotors. Computations are performed on a single ram-rotor path for the purpose of reducing computational cost, and all simulations are steady-state solutions. Figure 3 shows the computational grid used for the analysis. Hexahedral grid of about 1.6 million cells are employed with fine mesh near the walls and the region where shocks occur. Grid independence study has been carried out to check the effect of the grid number on the convergence and calculation solutions in the previous research[13], and it is found that the solutions in terms of mass flow rate, total pressure ratio and adiabatic efficiency don’t show any appreciable variation with different grid precisions. The solutions show no correlation with grid size when grid number is above 1.41 million. Thus, the grid size of ram-rotor model employed in the current study is adequate.

![Figure 3. Grid of Computational](image)

![Figure 4. Boundary Conditions Setting of Ram-rotor](image)
The numerical method used for the current work is from reference [17]. The stability of Spalart-Allmaras turbulence model and the convergence of residual are better[24]. Density-based solver is chosen to solve Navier-Stokes (RANS) equations, and turbulence closure is achieved through S-A turbulence model. The second order unwind scheme is employed to spatially discretize convective term. The fluid is set as ideal gas and the Sutherland law is chosen for viscosity. The computational domain with given boundary conditions is shown in Figure 4. Total pressure, total temperature and flow direction are specified at the inlet of the computational domain, whereas static pressure is specified at the outlet of the computational domain. Hub and strake walls are defined as rotating wall with design rotating speed, and the casing wall is set as absolutely stationary wall. No-slip and adiabatic conditions are applied at all solid boundaries. The design rotational speed of the ram-rotor is 26728 RPM. Rotational periodicity is imposed on the circumferential boundaries. In the previous research [17], the case of NASA rotor 37 was used to validate the reliability of numerical method used in this paper. In terms of the relative Mach number distribution, the shock structure, shock strength and shock position obtained by numerical simulation agree well with the experimental data [25-27]. The numerical results of spanwise variation of adiabatic efficiency and total pressure ratio at outlet measurement station also match well with those of the experiment data. Hence, the numerical method in current work predicts overall flow pattern, including the shocks, reasonably well, and can be used to reliably capture shock and predict ram-rotor performance.

3. Results and discussion

3.1 Comparison of Ram-rotor Performance

The total pressure ratio and adiabatic efficiency of baseline and three types of leaned ram-rotors are plotted against mass flow rate in Figure 5. It can be seen that the performance curves produce distinct changes compared to the baseline. As a whole, C-cas scheme shows an increment in pressure rise, while C-hub scheme is beneficial in improving adiabatic efficiency of the ram-rotor. With respect to C-mid scheme, although this kind of lean exerts little impact on the improvement of pressure ratio and efficiency, the performance curve shows a little left displacement, which indicates that this scheme can work on lower mass flow condition and is believed to have a wider working range than the baseline.

![Performance Maps of Four Ram-rotors](image)

**Figure 5.** Performance Maps of Four Ram-rotors

For quantification analysis of aerodynamic performance of ram-rotors, the performance and corresponding increment of four ram-rotors at their peak efficiency conditions are listed in Table 2. Different levels of improvement and deterioration are conducted by the use of different lean schemes. It is shown that the C-cas scheme generates a significantly higher total pressure ratio that is 2.338%
larger than the baseline, while the adiabatic efficiency is decreased by 0.483%. For C-mid scheme, the pressure ratio and efficiency appear to be similar to that of baseline, with only a slight reduction of 0.169% and 0.025%, respectively. When it comes to C-hub scheme, the pressure rise capacity is worsened, with a total pressure ratio decrease of 3.163%, however, the adiabatic efficiency of this scheme is improved by 0.462% compared to baseline. Overall, different lean design schemes are appreciated for different application intention. For the purpose of higher pressure rise capacity, such lean design as C-cas scheme is preferable, and the C-hub scheme is more favorable for increasing adiabatic efficiency. As for C-mid scheme, the detailed analysis needs to be further studied.

### Table 2. Ram-rotor Performance At Peak Efficiency Conditions

| Schemes   | Total pressure ratio and variation | Adiabatic efficiency and variation |
|-----------|-----------------------------------|-----------------------------------|
| Baseline  | 2.835                             | 0.7229                            |
| C-cas     | 2.902                             | 2.338%                            | 0.7194 | -0.483%          |
| C-mid     | 2.831                             | -0.169%                           | 0.7227 | -0.025%          |
| C-hub     | 2.746                             | -3.163%                           | 0.7262 | 0.462%           |

3.2 Pressure Rising and Flow Loss Characteristics Inside Ram-rotor

The numerical results reveal that the shock pattern in the ram-rotor is similar, and the use of lean can give rise to little change in shock system structure. Figure 6 illustrates the relative Mach number contours in the baseline.

**Figure 6. Relative Mach Number Contours in The Baseline**

The numerical results reveal that the shock pattern in the ram-rotor is similar, and the use of lean can give rise to little change in shock system structure. Figure 6 illustrates the relative Mach number contours in the baseline.
distribution at peak efficiency point for the basic knowledge of shock system and flow feature in the baseline. There are two kinds of shock system that can be observed. One is the shock system featured by incident shock, reflected shock, the Mach stem (arising from low pre-shock Mach number under the effect of the tip leakage flow) and shock train on S2 stream surface, which is produced and held by hub surface (see Figure 6a), and most of the pressure rise occurs across this shock system. The other one is the shock system on S1 stream surface featured by leading edge shock which is induced by strake leading edge (see Figure 6b), and the pressure side leg of the leading edge shock spreads into the flow path which interacts with the shock system on S2 stream surface, while the suction side leg of this shock extends towards inlet which exerts an influence on the incoming flow. It is worth noting that these two kinds of shock system can both been viewed on the S1 or S2 stream surface. Moreover, in Figure 6c, two evident low momentum regions are formed near suction surface of strake aft part and near the middle region of flow path, which limit the aerodynamic performance of ram-rotors.

![Figure 7. Axial Distributions of Pressure Coefficients of Different Pitch Positions](image)

Despite the fact that the flow feature of the ram-rotors is not altered in essence, the application of lean does affect the intensity and position of shocks. Figure 7 shows the axial distributions of pressure coefficients in the ram-rotor path. Every sharp pressure rise corresponds to the occurrence of shock or shock train. It can be observed that the shock system location is moved at the whole span height of strake aft part when applying lean. The principal location change at 10% throat height is the reflected shock and the initial position of shock train (see Figure 7a). C-mid scheme shows little displacement of shock, which is characterized by the same shock or shock train position, and has almost the same pressure rise characteristics of the baseline in the flow path. As for the C-cas scheme, forward motion of reflected shock is observed with a higher pressure rise, compared to the baseline. It is also the same case for the shock train. The pressure rise after shock train is also higher for C-cas scheme than baseline. This effect is more evident near the pressure surface region of flow path, which corresponds to the position range between 10% to 50% pitch. The forward motion of reflected shock and shock train in C-cas scheme makes a more compact distance between shocks on S2 stream surface, and the scale and intensity of shock interaction is enhanced, which produces an adverse effect on the ram-rotor efficiency in spite of high pressure-ratio. However, different effect is obtained for the C-hub scheme, which has a more backward displacement of reflected shock and shock train. Correspondingly, the pressure rise through the C-hub scheme is also reduced more, just as shown in Table 2. When at 99% throat height (see Figure 7b), the effect is similar but with a slight difference. Due to close distance from the casing wall, the shock system on S2 stream surface at the front of shock train presents only one single shock, and once pressure rise is realized by the incident shock or the Mach stem of lambda-
shock. This pressure rise is hardly influenced by the use of lean. The variation of shock train at this throat height is just as that at the 10% throat height.

Figure 8. Limited Streamlines on The Suction Surface

Limited streamlines on the suction surface of strake wall and on the hub are given in Figure 8. Two main features are seen in the baseline, and one is that the flow in the boundary layer separates from strake suction surface at the region near compression ramp. This flow phenomenon is attributed to the occurrence of incident shock. The fluid in the region of strake suction surface can’t undergo the high pressure rise of incident shock so that they fail to maintain the attachment to the wall. The other feature is that when the fluid near the hub region flow into the region near the diffusing ramp, they are deflected towards the corner between suction surface and hub wall, and then climb up along the spanwise direction. Thus, another separation line is formed when these upward-fluid encounter the strake tip leakage flow. This separation line is a result of the great pressure gradient in the rear of the ram-rotor path. Because the large pressure rise is achieved after diffusing ramp, the fluid at the corner is influenced by the great pressure gradient, which explains the reason of streamlines behavior. For the three leaned ram-rotor schemes, an important variation is scope and scale of the first separation region. Due to forward motion and intensified strength of shock system on S2 stream surface, flow separation is shifted slightly forward in C-cas scheme and less streamlines run downstream, which means that the flow blockage is aggravated in the first separation region. In spite of the fact that there is a slight reduction in terms of the ram-rotor performance, C-mid scheme still has a positive effect to some extent on the streamlines behavior on the suction surface compared to the baseline. The first separation line on the suction surface extends more downstream, which is an indication of delaying separation. As for C-hub scheme, the beneficial effect is more obvious at the first separation region with a more backward separation line, and the flow capacity at suction surface is the strongest among the four schemes.

Figure 9 gives the low momentum fluid denoted by iso-surface of relative Mach number=0.2, which is colored with static entropy. There are two main high loss regions or low momentum regions at the corners between strake aft part suction surface and end-wall. The development of secondary flow is governed by the balance of forces acting on the fluid, and the introduction of lean may produce an additional blade radial force component, also the spanwise pressure gradient, on the fluid so that the
secondary flow evolution is under control to some extent, which weakens the flow migration towards strake tip.

![Figure 9. The Low Momentum Fluid Colored by Static Entropy (Iso-surface Of Rel-Mach=0.2)](image)

Under the beneficial effect of lean, C-mid scheme shows a slight reduction of extension of high loss region 1, in spite of the fact that the beneficial effect is not so obvious. Due to high pressure rise obtained by C-cas scheme, the flow loss is increased at region 1. Because the diverging degree of C-cas scheme is greatest at lower flow path near the hub region, the supersonic flow blows out some low momentum fluid to some extent. Hence, the flow loss is somewhat reduced at high loss region 2. As for C-hub scheme, the flow migration to the tip on the suction surface of strake is suppressed more to alleviate the low momentum fluid accumulating near the corner between suction surface and casing wall. The high loss region 1 is decreased much more compared to the baseline. However, a disadvantage is that relatively more low momentum fluid is accumulated at the corner between hub and suction surface, but the overall effect is positive according to Table 2.

Fifteen slices which are cut and numbered along streamwise direction of the ram-rotor are extracted in Figure 10. Slice positions numbered from 5 to 10 represent the shock system compression region near compression ramp, throat surface and diffusing ramp. The total pressure ratio and total pressure loss coefficient are plotted against stream position in Figure 11. Flow loss is increased remarkably at shock region with abrupt pressure rise in four schemes. It is shown that the use of lean affects the pressure ratio and loss characteristics along stream direction. C-cas scheme performs better in terms of total pressure ratio at the expense of high flow loss. C-mid scheme indicates little improvement at shock region and in front of shock region, however, there is a loss reduction in the region after shock train. Total pressure ratio maintains the same as baseline. As discussed above, the use of lean alleviates the radial transportation and shows an effective loss reduction along stream direction. It is also known that the pressure ratio of this scheme is decreased.
3.3 Flow Characteristics at Ram-rotor Outlet

The exit flow is important to the flow field of possible static blade row, and Figure 12 plots the radial distribution of flow parameters at outlet. The radial migration trend can be observed from Figure 12a. Compared to baseline, the radial velocity of three leaned schemes is reduced in the mid-span region, which is a beneficial effect on the suppression of low momentum fluid accumulation. The trend of streamlines towards the tip corner is reduced in three leaned ram-rotors. C-hub scheme shows a greater improvement in the bottom half of the strake height, which corresponds to the high efficiency of this scheme in Table 2. Different with C-hub scheme, great reduction of radial velocity occurs in the upper half of strake height in C-cas scheme, and the radial velocity below 30% strake height is even raised. The beneficial effect of suppressing radial migration can’t compensate the detrimental impact due to large pressure rise. As seen in Figure 12b, C-cas scheme gives rise to a significant increase of axial velocity density below 40% strake height, so more mass flow goes through near hub region. The C-mid scheme reveals almost the same distribution with baseline above 40% strake height, with a little increase below this height. For C-hub scheme, the redistribution of flow makes a reduction of mass flow below 40% strake height, and the opposite variation is seen above this height. Absolute flow angle at outlet is plotted in Figure 12c, and the flow angle in present paper is defined as the acute angle between flow direction and circumferential direction. It is found that the flow angle is increased above 20% strake height for C-hub scheme. It can be explained by the fact that the high loss region

Figure 10. Schematic Diagram of Slices Along Streamwise Direction

Figure 11. Flow Characteristic Distribution Along Streamwise Direction
located at the corner between suction surface and casing wall is suppressed compared to baseline (Figure 9d). The reduction of blockage in this region makes more amount of flow run through the upper part of flow path, with the result of larger flow angle. When it comes to C-cas scheme, an opposite trend is observed above 20% strake height. The flow blockage caused by high loss region 1(Figure 9a) makes a more non-uniformed distribution of flow angle, which is more unfavorable. From the distribution of pressure ratio, C-hub scheme performs a reduction of pressure rise from hub to tip. C-mid scheme indicates an obvious decrease at the tip region and a little improvement below 40% strake height. Under the influence of flow redistribution, the pressure rise of this scheme shows almost no change. As for C-cas scheme, the pressure ratio presents an increase almost covering the whole span except for the spanwise position above about 95% strake height. It is attributed to the severe tip blockage, which decreases the pressure rise capacity.

![Graphs](image)

**Figure 12.** Radial Distribution of Flow Parameters at Ram-rotor Outlet

### 3.4 Strake Tip Leakage Flow

The strake tip clearance leakage is one of the main flow features in ram-rotors, and Figure 13 provides the pressure coefficient distributions at 95% throat height of four ram-rotors. It is seen in Figure 13 that in C-cas scheme, the forward motion and intensified strength of shock train lead to an increase of static pressure on pressure surface at axial position from about 10% to 20%, which increases the aerodynamic load of strake fore part. Hence, the strake tip leakage is intensified at strake fore part. Great variation occurs at strake aft part (from about 80% axial position to trailing edge). Compared to baseline, C-mid and C-hub schemes both yield a decrease of strake load due to reducing pressure
difference between both sides of strake, and the resulting tip leakage extent is smaller. The improvement of tip leakage in C-hub scheme is more preferable. There is an opposite effect for C-cas scheme which causes more tip leakage.

Figure 13. Pressure Coefficient Distributions At 95% Throat Height

Figure 14 illustrates three dimensional streamlines and entropy distribution with a color bar range from 150 to 300. It is known from these figures that the tip leakage initiates near the leading edge, and the leakage vortex is formed and develops downstream. Strake tip loss arises from the mixing between leakage flow and main flow. The leakage is enhanced and more significant loss is generated when the low-momentum leakage flow encounters the pressure surface of adjacent strake (The encountering location is denoted with blue filled arrow in Figure 14a). C-cas scheme gives a more severe leakage loss compared to baseline due to higher pressure rise capacity, whereas there is a low leakage loss in C-hub scheme resulting from smaller strake load and pressure difference. As for C-mid scheme, the effect is a compromise between C-cas and C-hub schemes, which shows a similar loss to baseline.

![Figure 14(a) Baseline](image1)

![Figure 14(b) C-cas Scheme](image2)
3.5 Effect of Leaning Angle

As mentioned above, it is true that C-mid scheme performs better in terms of flow capacity near the suction surface of strake (see figure 8c) and the radial migration tendency of boundary layer fluid (see figure 12a), despite the fact that little positive effect is gained. Maybe the amount of lean is not enough to get a more optimized ram-rotor by using such leaned ram-rotor as C-mid scheme. Hence, in this section the impact of leaning angle on the aerodynamic characteristics of C-mid scheme is investigated. It can be observed in figure 15 that pressure ratio and efficiency both rise first and then drop with the increase of leaning angle, while the optimum angles are different. The total pressure ratio reaches maximum value of 2.831 at the leaning angle of 10 degrees, and 20 degrees of leaning angle can gain a more preferable adiabatic efficiency of 0.7235. For a better ram-rotor performance, there need to be a compromise selection of leaning angle.

Figure 14. Streamlines and Entropy Distribution

c. C-mid Scheme
d. C-hub Scheme

Figure 15. Ram-rotor Characteristic Parameters Variation with Sweeping Angles

Figure 16 gives the pressure coefficient distribution through the ram-rotor path at different leaning angles. The pressure rise characteristics is similar when using different leaning angles. The shock system ahead of throat surface (incident shock and reflected shock) is almost the same, and the
difference is mainly expressed by the strength and position of shock train. As a whole, large leaning angle makes a more downstream initial position of shock train, except that 10 degrees lean makes its position a little forward. Because the backward motion of shock system produces no benefit to the strength of shock train, the pressure rise resulting from shock train is reduced when applying overlarge leaning angle.

Figure 16. The pressure coefficient distribution through the ram-rotor path at different leaning angles

The pressure coefficient distributions at 95% throat height is plotted in figure 17, and figure 18 gives the axial distribution of normalized velocity density at mid-gap height of tip clearance region. Due to the weakened shock train and decreased pressure rise capacity at the strake aft part, the aerodynamic load promotes an almost descending trend. Correspondingly, there is a reduction of leakage mass flow especially in the shock train region near pressure surface (dotted oval box) and in the tip low momentum corner near the suction surface (dotted rectangle box). Overall, the beneficial effect is more positive when increasing leaning angle.

Figure 17. Pressure Coefficient Distributions at 95% Throat Height  
Figure 18. Axial Distributions of Normalized Velocity Density at Mid-gap Height of Tip Clearance
Figure 19 gives radial distribution of radial velocity and loss coefficient with different leaning angle at ram-rotor outlet. From Figure 19a, it can be seen that there is a significant reduction of radial velocity at midspan height when initially increasing angle from 5 to 15 degrees. The radial transport of high loss fluid is gradually inhibited, so is the separation area of reflux tip. Just as shown in Figure 19b, the total pressure loss coefficient presents a reducing trend above about 40% strake height. It is beneficial to reduce the flow loss and to further increase efficiency of ram-rotor. As the leaning angle varies from 20 degrees to 30 degrees the reduction of radial velocity is mainly realized in the region below 40% strake height, however the radial velocity above 85% height is even increased, which can reduce the beneficial effect of suppressing the accumulation of low momentum in the tip corner. It is necessary to point that large leaning angle leads to a large diverging S1 stream surface at hub section, and it is easy to induce more low momentum fluid accumulation at hub corner and raise the flow loss below about 30% strake height (see figure 19b). When at 25 or 30 degrees, the improvement of radial transport can’t compensate the detrimental impact caused by the increase of low momentum in the hub corner, which leads to a decrease of adiabatic efficiency in figure 15.

4. Conclusions
A detailed numerically investigation has been conducted to better understand the strake lean effect on the aerodynamic behavior of ram-rotors. Three types of leaned ram-rotors and one leaned scheme with six leaning angles are modeled and analyzed, respectively. It is found that the application of lean can affect the intensity and position of shock system, radial transport and accumulation of low momentum fluid in the boundary layer of suction surface.

The leaned ram-rotor which keeps tip section unchanged (C-cas scheme) performs better in pressure rise, with an increase of 2.338 % in terms of total pressure ratio compared to baseline. Reflected shock and shock train shift upstream with a high pressure rise, which worsens flow blockage and separation near suction surface of strake. The beneficial effect of lean can’t compensate the detrimental impact due to large pressure rise. The increase of strake load aggravates the tip leakage flow.

While the leaned ram-rotor which maintains identified sections of root (C-hub scheme) is more preferable in reducing loss, with an improvement of 0.462% in terms of adiabatic efficiency compared to baseline. It shows a more backward displacement of shock system and delays separation on the suction surface. The blockage at the tip corner of strake aft part is relieved. Loss is also reduced due to low strake load.

With respect to the leaned ram-rotor which has the same middle section with baseline(C-mid scheme), a slight reduction of 0.169% and 0.025% in terms of total pressure ratio and adiabatic efficiency is obtained, but it still has a positive effect to some extent on the streamlines behavior on the suction surface compared to the baseline. Different leaning angles are applied in C-mid scheme, and it is
concluded that there exist different optimal leaning angle values in terms of total pressure ratio and adiabatic efficiency as leaning angle rises. Large leaning angle makes the shock train more backward and reduces its strength. A gradually descending trend of tip leakage occurs when leaning angle rises. However, if overlarge leaning angle, such as 25 or 30 degrees, is introduced, the improvement of radial transport is not enough to compensate the detrimental impact of low momentum accumulation in the hub corner.

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