THE EFFECTS OF LEAN AND SWEEP ON TRANSONIC FAN PERFORMANCE: A COMPUTATIONAL STUDY

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Abstract: The aerodynamics of transonic fans is discussed with emphasis on the use of three-dimensional design techniques, such as blade sweep and lean, to improve their performance. In order to study the interaction of these 3D features with the shock pattern a series of five different designs is produced and analysed by CFD. It is found that the 3D features have remarkably little effect on the shock pattern near the tip where the shock must remain perpendicular to the casing. Lower down the blade significant shock sweep, and hence reduced shock loss, can be induced by 3D design but this is usually at the expense of reduced stall margin and increased loss elsewhere along the blade span. Overall, very little change in efficiency is produced by blade sweep or lean. However, forwards lean of the rotor does produce a small increase in mass flow.

Radial migration of the boundary fluid on the suction surface behind the shock is shown to play a large part in the aerodynamics near the blade tip.

Keywords: transonic fan, transonic compressor, three-dimensional flow, shock waves, CFD

1. Introduction

Transonic fans are widely used as the first stage of large civil aero engines and as the first few stages of military engines. They typically operate with a blade speed in the range 1250–1600ft/s (380–490m/s) and with an axial Mach number at the fan face of about 0.7. The flow through them is made more complex by the fact that the hub:tip radius ratio is low, about 0.30, so that the inner part of the blades operate in the high subsonic regime. The stage stagnation pressure ratio achieved depends mainly on the tip speed but is in the range 1.5–2.2. Despite operating in the transonic regime with strong shock waves the efficiency achieved is often very high, it is likely to decrease with increasing pressure ratio and is typically in the range 88–92% for the fan rotor. Because the reaction of such designs is very high (except near the root) most of the losses occur in the rotor and it is usual to quote the efficiency for the rotor

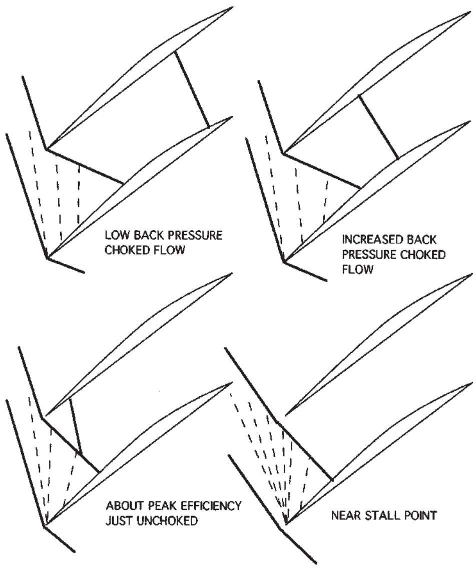

Figure 1. Shock patterns near the tip of a typical transonic compressor

alone. All the overall efficiencies quoted in this paper will be total-to-total isentropic efficiencies of the fan rotor alone.

A review of the aerodynamics of such fans is given by Calvert and Ginder [1]. In the tip region the blade camber is very low and most of the pressure rise occurs across the shock wave. The pre-shock Mach number is typically about 1.5 and so it can be shown that, for a normal shock, the shock loss accounts for about 10% loss of efficiency. In reality the shock is not quite normal and there are significant viscous losses, resulting in a rotor efficiency around 85%. Figure 1 shows the typical evolution of shock pattern with pressure ratio near the tip of such fans.

At mid-span the inlet Mach number is still supersonic, around 1.25, and the shocks are much weaker causing only a few percent efficiency loss, however, the pressure rise is almost the same as at the tip and so there is considerable subsonic diffusion and boundary layers losses. The resulting rotor efficiency is about 94%.

Near the hub the inlet Mach number is about 0.8 and the flow may just remain subsonic. As a result of the much lower blade speed the loading is very high and the pressure ratio is often reduced near the hub to allow for this. The reaction is low and so the static pressure rise through the rotor is small but there is considerable flow turning. The solidity is also high and this combined with the high turning leads to significant boundary layer losses and an efficiency about 95%.

The main design requirements of such a fan are high efficiency and high mass flow per unit frontal area. The latter implies high axial Mach numbers but these are limited by the danger of choking in the intake and so the axial Mach number at the fan face seldom exceeds 0.7. Good mechanical properties, especially resistance to bird strike, are also important, as is low noise in civil engines. The blade shapes are nowadays universally designed with the aid of CFD, usually 3D Navier-Stokes solvers, and a good example of the state of the art of such calculations is found in the ASME comparison of "blind" calculations on a typical highly loaded fan, NASA Rotor 37.

The full details of this comparison have never been published but a summary is given by the author in [2]. It was found that most methods predicted the overall flow pattern, including the shocks, reasonably well. The shape of the fan characteristic of pressure ratio and efficiency against speed was also well predicted but the flow details; such as the exit velocity profile, the depth of the wakes and the level of efficiency were not so well computed.

In recent years manufacturers have shown considerable interest in trying to improve the performance of such fans by using three-dimensional design techniques [3]. The most usual of these is to introduce blade sweep. The philosophy behind this is the same as that on a swept aircraft wing, *i.e.* to make the shock swept relative to the incident flow so that the component of Mach number perpendicular to the shock, and hence the shock loss, is reduced. [4] shows how strongly the shock loss depends on this Mach number, for example at a Mach number of 1.5 the loss of a normal shock is reduced by 22% by 15° of sweep. Some success has been claimed for this approach but little has been published. The most detailed results are given by Wadia *et al.* [5], who used a combination of experiment and CFD to investigate the effects of sweep and lean on a highly loaded military fan. They found that forward sweep produced better results than backward sweep despite the fact that the flow was expected to be less swept relative to the shock wave. In fact [5] finds that the efficiency of conventional, back swept and forward swept fans was very similar with the main differences being that the forward swept fan had better stall margin and the back swept one worse stall margin than the conventional fan. Wadia *et al.* also investigated a fan with tangential lean which can be regarded as another means of introducing sweep, the performance of this was not significantly different to that with backsweep.

The analogy of a swept fan with a swept aircraft wing is not an accurate one. The flow over the wing suffers no overall static pressure change and the pressure rise across the shock actually serves to reduce the lift. The flow through the fan must undergo the same overall static pressure rise for both a conventional and a swept fan designed for the same duty and the shock produces much of the useful pressure rise. Hence, if the pressure rise across the shock is reduced by sweeping the shock relative to the flow, then the pressure rise in the subsonic diffusion downstream of the shock must be increased to compensate for it. This will increase the boundary layer losses and may even lead to boundary layer separation. Hence, it is not obvious that the reduction in shock loss will lead to an overall improvement in performance. It was this argument that made the author decide to perform a series of calculations to try to understand the pro's and con's of sweep and lean on typical transonic fans.

2. CFD method

All calculations were performed with the author's 3D multistage viscous solver MULTIP. This is a very highly developed method which is widely used by industry for the design of all types of turbomachinery. The solution algorithm used in recent versions of this program is a very simple explicit scheme, which the author has called the "SCREE" scheme. All spatial differences are completely centred, using cell corner storage, and the time stepping is performed using

$$\Delta F_u = 2\Delta F^n - \Delta F^{n-1}$$

where ΔF_u is the change actually used to update the flow variables in the current time step, ΔF^n is the change calculated from the current values of the variables and ΔF^{n-1} is the change calculated in the previous time step. The name "SCREE" comes from "two steps forward and one step backward", as will be familiar to anyone who has climbed a scree slope on a mountain. This algorithm is very fast and simple, it works with extremely low levels of artificial viscosity in subsonic flow but like other second order methods needs some artificial viscosity to stabilise shock waves. It also has an advantage of working at extremely low Mach numbers (as low as 0.1) so that effectively incompressible flow can be computed.

The turbulence model is an extremely simple mixing length scheme with wall functions to obtain the surface shear stress. The turbulent viscosity is allowed to extend throughout the whole flow field rather than being confined to near wall regions, this is felt to be preferable for dealing with the large regions of separated flow which often occur in compressors. The only empirical inputs to the method are the boundary layer transition point and the limit on the value of mixing length. The later is typically taken as between 3 and 5% of the blade pitch with higher values implying higher free-stream turbulence. The program has been calibrated against a variety of fans including NASA rotors 37 and 67 and many commercial designs.

The blade geometry package used to generate and manipulate the fan geometry is the author's program STAGEN, an early version of which is described in [6]. This program generates blade sections on quasi-stream surfaces from user-specified values of camber line shape and blade thickness distribution and stacks them to form a 3D data set for MULTIP. The blade section geometry and stacking can be changed very easily so that new data sets can be generated and a calculation restarted in a matter of minutes.

3. Blade sweep and lean

Different definitions of sweep and lean are used in the literature. In fact the blade stacking may be defined on any two sets of perpendicular axes. A common choice is to define lean and sweep relative to the axial and tangential directions so that lean corresponds to moving the blade section in the circumferential direction and sweep to moving them in the axial direction. In the present paper, however, lean will be defined to be moving the blade perpendicular to the local chord line (*i.e.* the line joining the leading and trailing edges) and sweep to moving the sections along the chord line. This definition is illustrated in Figure 2. The reason for this choice is that, defined in this way, sweep does not introduce any spanwise blade forces. whereas lean does introduce such forces.

The effects of lean and sweep on the flow through blade rows are described by Denton and Xu [7]. The effects are best understood by considering that the pressure gradient acting perpendicular to the endwalls is usually very small compared to the blade-to-blade pressure gradient. This is because the streamline curvature in the blade-to-blade plane is much greater than that in the meridional plane and is also much greater than that due to the hub and casing radii. Because of the low spanwise pressure gradients near the endwalls the blade loading cannot change rapidly in the direction perpendicular to the endwalls. Consequently, the pressure distribution

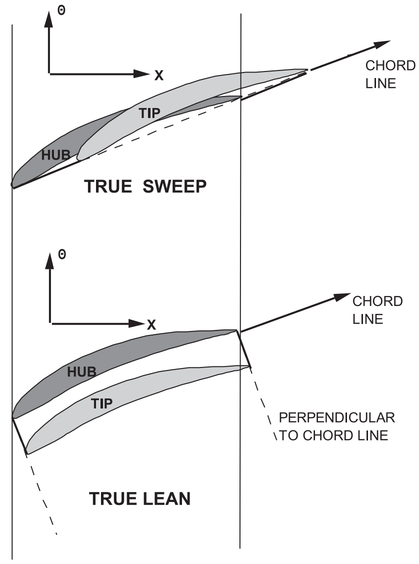

Figure 2. Definition of sweep and lean (view looking radially inwards on the blade)

acting some distance away from the endwall is imposed on the endwalls, irrespective of the local blade profile. Hence forward sweep reduces the leading edge loading and increases the trailing edge loading and vice-versa. On the same argument, lean with the pressure surface facing towards the endwall increases the pressure on the endwall and vice-versa. As a first approximation it can be considered that when local changes of blade stacking are made the blade sections are moved through a "frozen" pressure field.

For shock waves an important consequence of these ideas is that all shocks must intersect the endwall perpendicularly. Hence, any effects of shock sweep are inevitably lost at and near the hub and casing.

4. Baseline design

A baseline design of transonic fan was produced using STAGEN. This was designed for a typical tip speed of 1500ft/sec (457.2m/s) and a stagnation pressure ratio of about 1.8 at standard sea level conditions. The blade sections were tailored to achieve a good performance at the design point and they were stacked on their centroids so that no deliberate sweep or lean was introduced. A meridional view of the annulus is shown in Figure 3 and a view of the blade sections is in Figure 4. The latter shows 5 equally spaced blade sections viewed looking radially inwards on the lower blade. The stacking of the blade sections on their centroids is obvious.

In order to study the effects of 3D design on the blade performance it was decided to perform the calculations with no endwall effects. Hence, all calculations were performed with no tip clearance and with the viscous shear stress set to zero on both endwalls. The idealised results are not representative of the performance of a real fan but should illustrate the effects of 3D design on the shock sweep and blade performance without the complications of end effects. In reality it is known that the

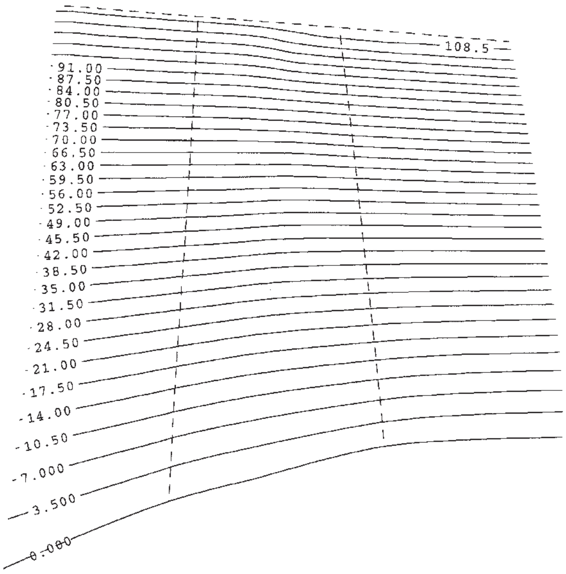

Figure 3. Streamlines through the baseline design

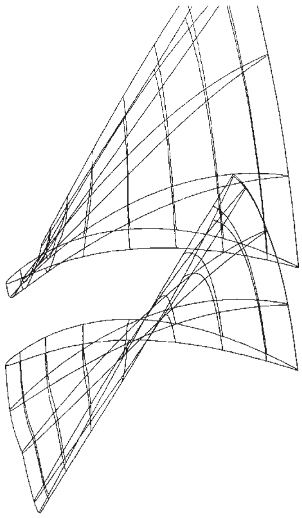

Figure 4. Blade sections of the datum design

tip clearance has a large effect on the fan performance near the tip as does the hub boundary layer on that near the root.

All calculations were performed with a $41 \times 141 \times 41$ point grid, which is relatively coarse by today's standards, but enabled rapid turn round of the calculations on a PC. Previous checks have shown that the overall performance is not significantly different if more grid points are used. The blade surface boundary layers were assumed to be turbulent from the leading edge.

The predicted stagnation pressure ratio and efficiency of this datum fan are plotted against mass flow rate in Figure 5. The characteristics are typical of such fans and the peak efficiency of 92.8% is only slightly above that achieved in practice. Figure 6 shows the shock pattern on the suction surface and at mid-pitch near the

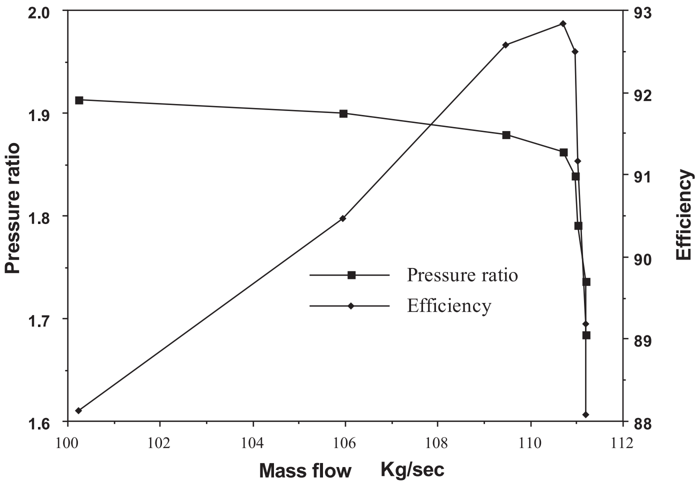

Figure 5. Datum fan characteristics

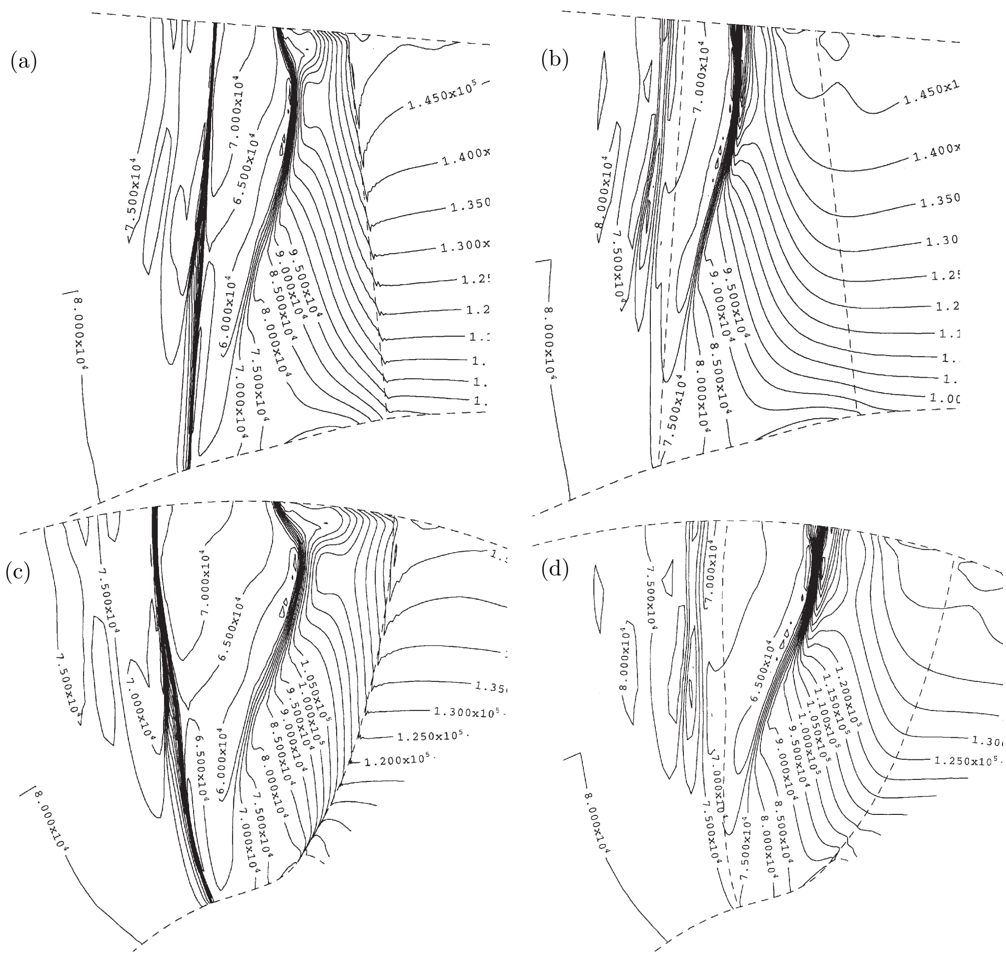

Figure 6. Pressure distributions on the suction surface and at mid-pitch: (a) meridional view, suction surface; (b) meridional view, mid-pitch; (c) view normal to the chord on suction surface; (d) view normal to the chord at mid pitch

peak efficiency point. A meridional view as shown in the upper two figures can be misleading in judging the shock sweep and a better view is one looking perpendicular to the chord line near the blade tip. This is shown in the lower two figures, and confirms that the shock has negligible sweep in this plane. It may, however, have sweep in the blade-to-blade plane. In fact it is extremely difficult to judge the true shock sweep from any surface plot and the best means of judging it was found to be by comparing the Mach number jump across the shock with the predictions of oblique shock tables. The Mach number jump may be judged from the contours on a quasi stream surface or from line plots along a streamwise grid line. Even this is made difficult in the region where the bow shock intersects the passage shock. Using this approach it was judged that the shock sweep over the outer 25% of span was about 15°, most of this was judged to be sweep in the blade-to-blade plane.

Figure 7. Efficiency contours behind the trailing edge

An alternative method of judging shock loss is to look at contours of local efficiency behind the trailing edge. Figure 7 shows these for the datum blade near its peak efficiency point. The contour interval is 1% efficiency and the pale blue area near the hub represents 100% efficiency, white represents 95% and the bright yellow colour represents 90%. These contours show high viscous loss in the blade wake but the mid-passage loss is zero in the subsonic part of the blade and so all the mid-passage loss over the outer part may be taken to be shock loss. Figure 7 then shows clearly how the shock loss increases from mid passage towards the tip and accounts for about 5% of lost efficiency over the outer 25% of span. An interesting feature of Figure 7 is the accumulation of loss in the suction surface-casing corner and on the casing. This "loss core" occurs despite there being no endwall boundary layer and is due to the strong radial transport of boundary layer fluid from the blade surface behind the shock towards the casing under the influence of the "centrifugal force".

This radial transport is a common feature of such fans and has a large influence on the performance of the tip region. In a real machine its effects are greatly influenced by tip leakage. Another interesting feature is an "island" of high efficiency near the suction surface just inwards from this loss core. This is a due to the strong shock-loss core interaction making the shock highly swept in both the hub-tip and blade-to-blade planes in this region. This can be clearly seen in Figures 6 and 8.

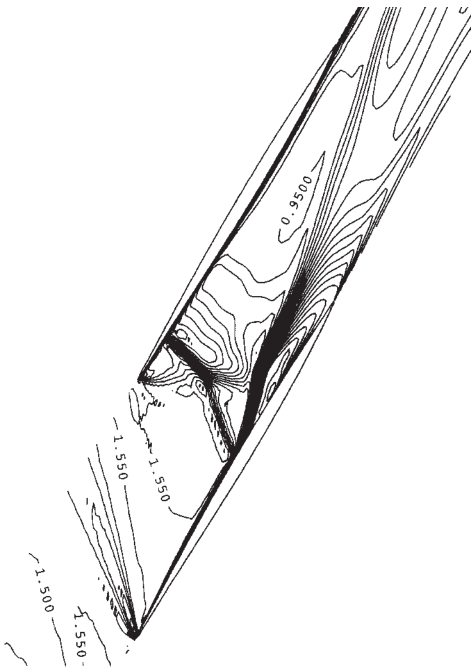

Figure 8. Interaction of the shock with the loss core

5. Swept cascades

A simple method of studying the effects of sweep and lean is to perform calculations on a three-dimensional cascade. This was done by taking the 3/4 span section from the datum fan and calculating it as a compressor with the same blade speed and with a hub:tip radius ratio very close to unity. The aspect ratio was chosen as 2 based on axial chord. The flow in the cascade will differ from that in the fan due to the constant stream tube thickness in the cascade (compared to about 25% reduction in the fan) as well as due to the different 3D effects. Because of the lack of stream tube contraction the static pressure ratio had to be reduced for these cascade calculations.

Figure 9a shows the shock pattern on a swept cascade at mid-pitch. The view is parallel to the endwalls and is very closely perpendicular to the blade surface. The upper part of the blade can be considered to be swept backwards and the lower part to be swept forwards. The figure shows clearly how the shock remains closely perpendicular to the endwalls and so is much closer to the leading edge (and hence to

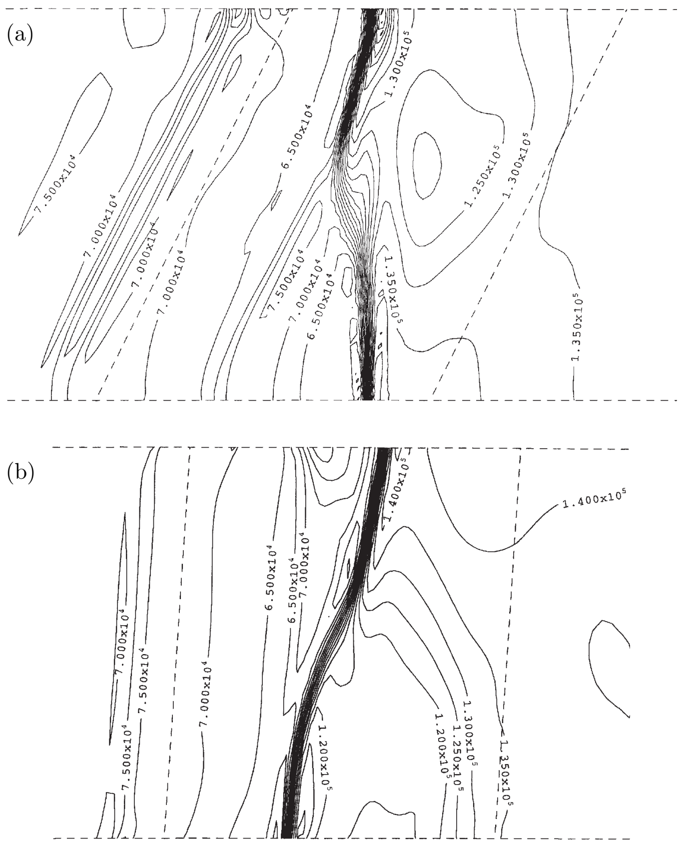

Figure 9. (a) Shock at mid-pitch in a swept cascade; (b) shock at mid-pitch in a leaned cascade

stall) at the casing than at the hub. Clearly in this case there will be little reduction of shock loss by sweep.

Figure 9b shows the corresponding view for the effects of blade lean. The blade is leaned so that the suction surface is inclined towards the lower endwall, *i.e.* in Figure 9b the upper part of the blade is moved into the page relative to the lower part. Again the view is parallel to the endwalls and perpendicular to the blade chord line but it is not perpendicular to the blade surface. The shock remains perpendicular to both endwalls, but in this case it is shifted upstream at the lower wall and downstream at the upper one. This effect is not easy to explain as one would expect the static pressure to be lowered near the hub and increased near the casing. The pressure contours in Figure 9b confirm that this is the case downstream of the shock, where the blade loading is high, but there is negligible spanwise pressure gradient upstream of the shock where the loading is low. One would expect the higher pressure behind the shock on the casing to move it further upstream but this is the opposite of the effect observed. Closer inspection of the solution shows that the upstream displacement of the shock on the hub is due to strong viscous effects, which create very high boundary layer blockage near the hub. The viscous effects may be expected to be larger in this cascade than in the datum fan because the lack of stream tube contraction creates higher diffusion. However, both cases confirm the strong tendency of the shock to remain perpendicular to the endwalls, irrespective of blade geometry.

6. Swept and leaned rotors

In order to study the effects of sweep the datum stage was modified by sweeping the blade sections forward or backwards along the local chord line. A backswept rotor was produced by moving the 25% section forwards by 1% of its chord, the 50% span section forwards by 3% its chord, the 75% section backwards by 20% of its true chord and the tip section backwards by 75% of its chord. It is important to note that the casing was moved with the tip section so that the tip speed remained the same. The effect is the same as keeping the tip fixed and moving the hub upstream, hence reducing the annulus area at the axial location of the tip sections and increasing it at the axial location of the hub sections. A forward swept rotor was produced by changing the signs of the above blade movements. In this case the effects on annulus area are the opposite of those for backwards sweep.

Leaned rotors were produced by moving the blade sections perpendicular to the local chord lines by the same amount as described above for sweep. The axial movement of the sections is actually greater than that of the swept rotors because of the high stagger. Radial inwards views of all rotors is shown in Figure 10. It is

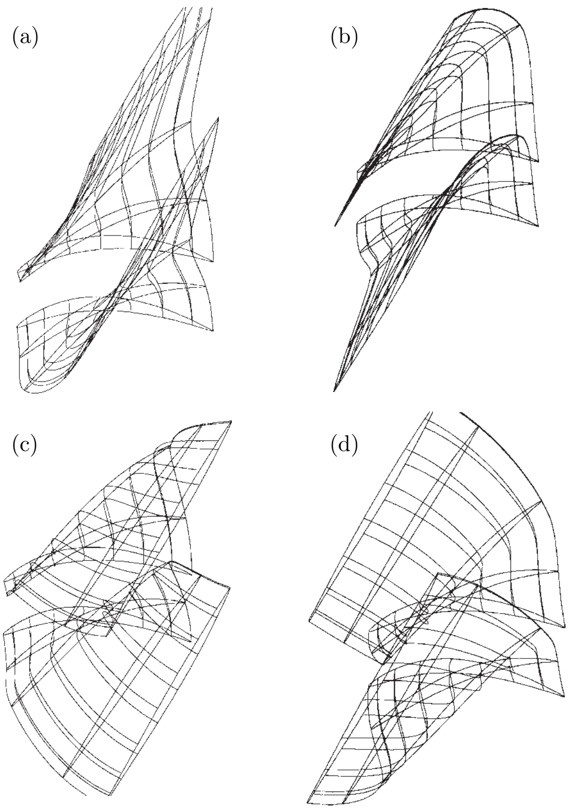

Figure 10. Radially inwards views of the 3D rotors:
(a) backwards swept; (b) forwards swept; (c) backwards leaned; (d) forwards leaned

recognised that not all of these modifications may be mechanically acceptable in a real fan as they will introduce significant bending stresses into the blade. However, it is worth examining these extremes in order to understand the aerodynamics.

All four modified designs were run at exactly the same conditions as the datum. In particular the exit static pressure at the casing was held constant. No attempt was made to find the optimum efficiency point of any of the new designs although some calculations were performed with different back pressures in order to get a feel for how close the blades were to stalling. The overall performance of all five designs is summarised in Table 1.

Table 1. Comparison of overall performance

	Datum rotor	Back Swept	Forwards Swept	Back Leaned	Forwards Leaned
Mass Flow kg/s	110.63	108.37	109.34	108.45	112.45
Stagnation Pressure ratio	1.86	1.86	1.85	1.86	1.85
Total to Total Efficiency	92.59	91.12	92.03	92.48	92.32

There is clearly little difference in the overall performance of the different designs. Static pressure contours at mid-pitch for all four rotors are shown in Figure 11.

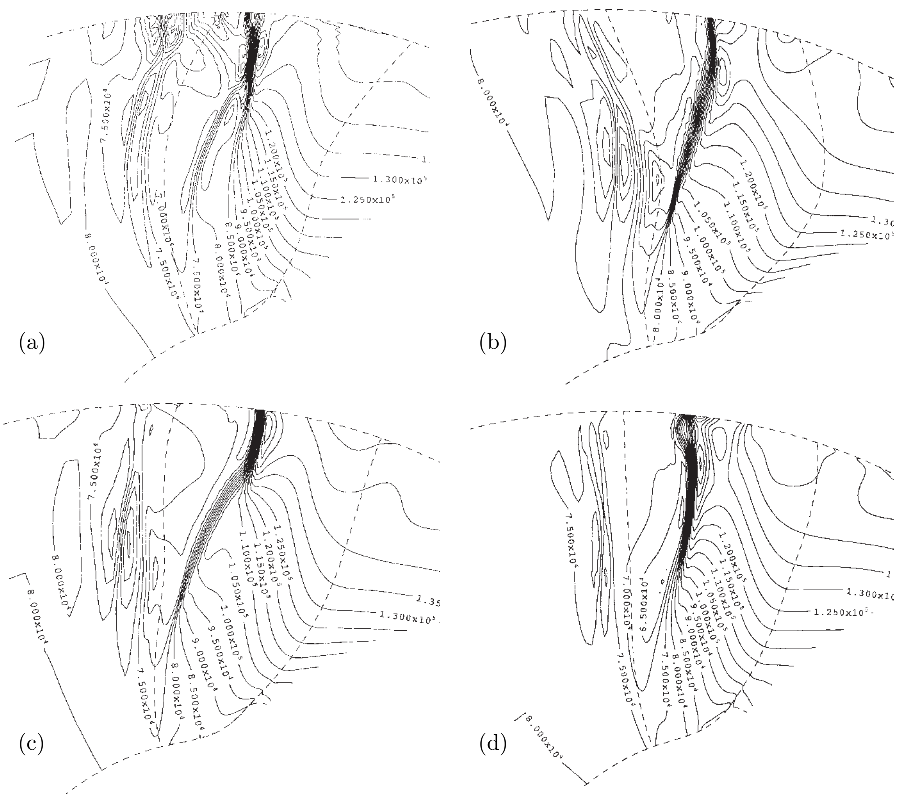

Figure 11. Static pressure contours at mid pitch (viewed perpendicular to the chord line at the tip): (a) backswept rotor; (b) forwards swept rotor; (c) backwards leaned rotor; (d) forwards leaned rotor

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These are viewed perpendicular to the chord line at the tip. The shock sweep in this view can be judged by remembering that the streamlines are roughly parallel to the line of the casing. However, the shock may be independently swept in the blade-to-blade plane and this can be judged from Figure 12 which shows Mach number contours at about 80% span.

7. Comparison of designs

7.1. Backwards swept rotor

Figure 11 shows that the shock is almost perpendicular to the flow near the casing, if anything being slightly swept forward. It is particularly strong at about 80% span where Figure 12 shows that the bow shock and passage shock have merged to form a single normal shock with an incident Mach number about 1.6. The high Mach number is as expected from a backswept tip. Further inboard the shock splits into two shocks, the bow shock and the passage shock, and this will greatly reduce the shock loss. Although not shown, near the suction surface the shock is pushed forward by the radial migration of boundary layer fluid from the suction surface and is actually swept forward near the casing. This causes it to become detached from the leading edge and the shock on the pressure surface can be seen in front of the leading edge very near to the casing in Figure 11. This implies that the blade is approaching its stalling point.

The shock loss can best be judged by contours of local efficiency behind the blade. These are shown in Figure 13 and should be compared with those for the datum blade in Figure 7, which has the same contour intervals. It is clear that loss is less than that of the datum from 50% to 75% span but is greater than the datum near the tip. The latter is due to the strong normal shock. It is interesting that the backswept rotor does not have as large an "island" of low loss due to interaction of the shock with the loss core although the loss core itself appears to be larger. The latter is probably due to the stronger normal shock producing more boundary layer separation.

Overall it seems that backsweep has reduced the loss between 50% and 75% span, due to the formation of a double shock system, but increased it between 75% and the casing. It has also moved the shock closer to the leading edge reducing the stall margin of the blade. The mass flow has slightly decreased, possibly because of the reduction in annulus area in the region of the blade throat.

7.2. Forwards swept rotor

Equivalent results for the forward swept rotor are also shown in Figures 11, 12 and 13. Figure 11 shows the shock at the tip is further back in the passage, implying a good stall margin. Figure 12 shows that the pre-shock Mach number is reduced which is as expected for a forwards swept tip. There is a significant backwards sweep of the shock between 50% and 85% span but near the tip it is swept forward by the interaction with the loss core. The shock can be seen to be detached from the blade leading edge around mid-chord and this implies that this part of the blade is closest to stall. Notice also how the shock appears to be much stronger around mid-span and extends to lower radii than in the previous case. The latter is confirmed by the

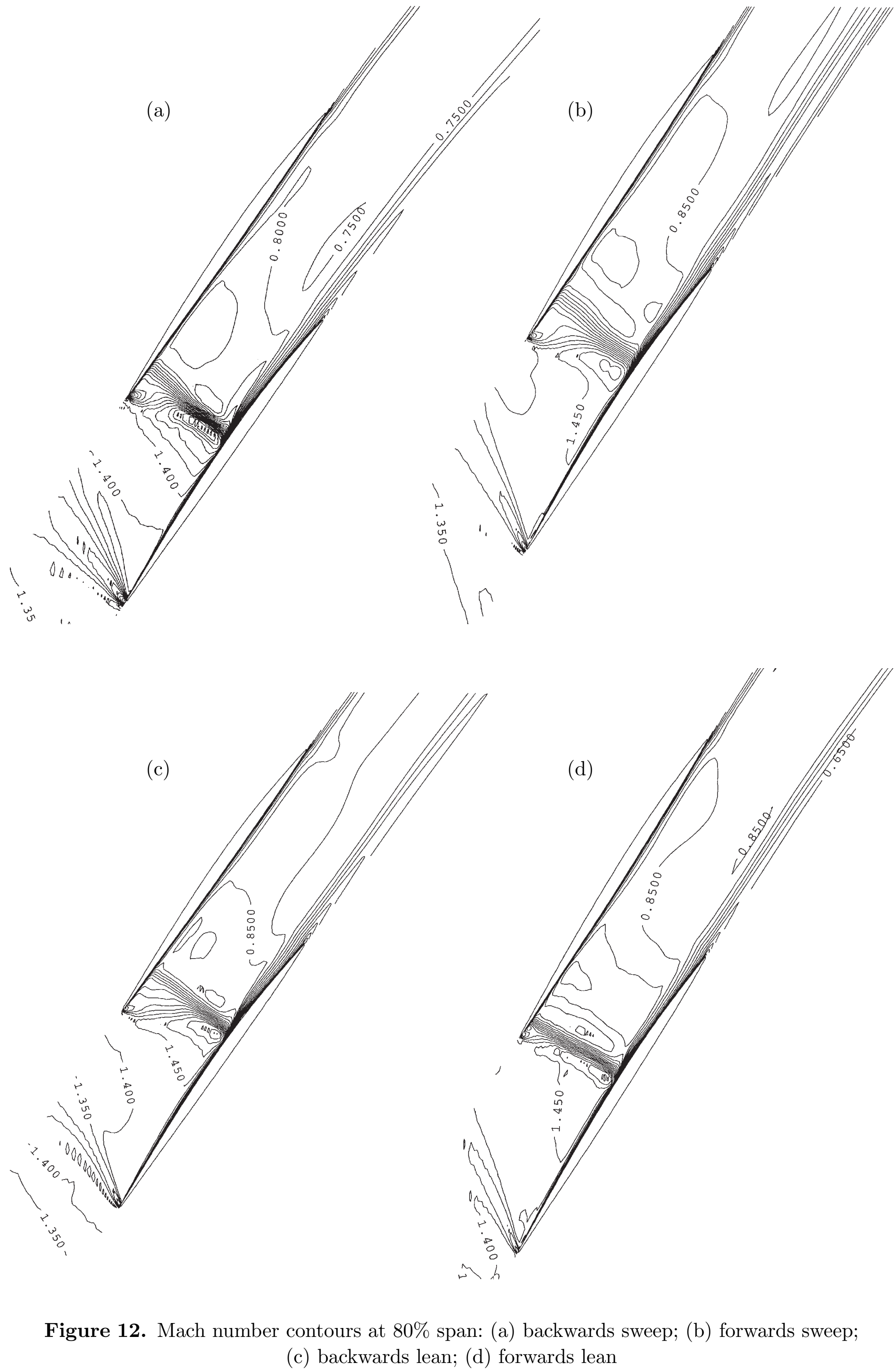

Figure 12. Mach number contours at 80% span: (a) backwards sweep; (b) forwards sweep; (c) backwards lean; (d) forwards lean

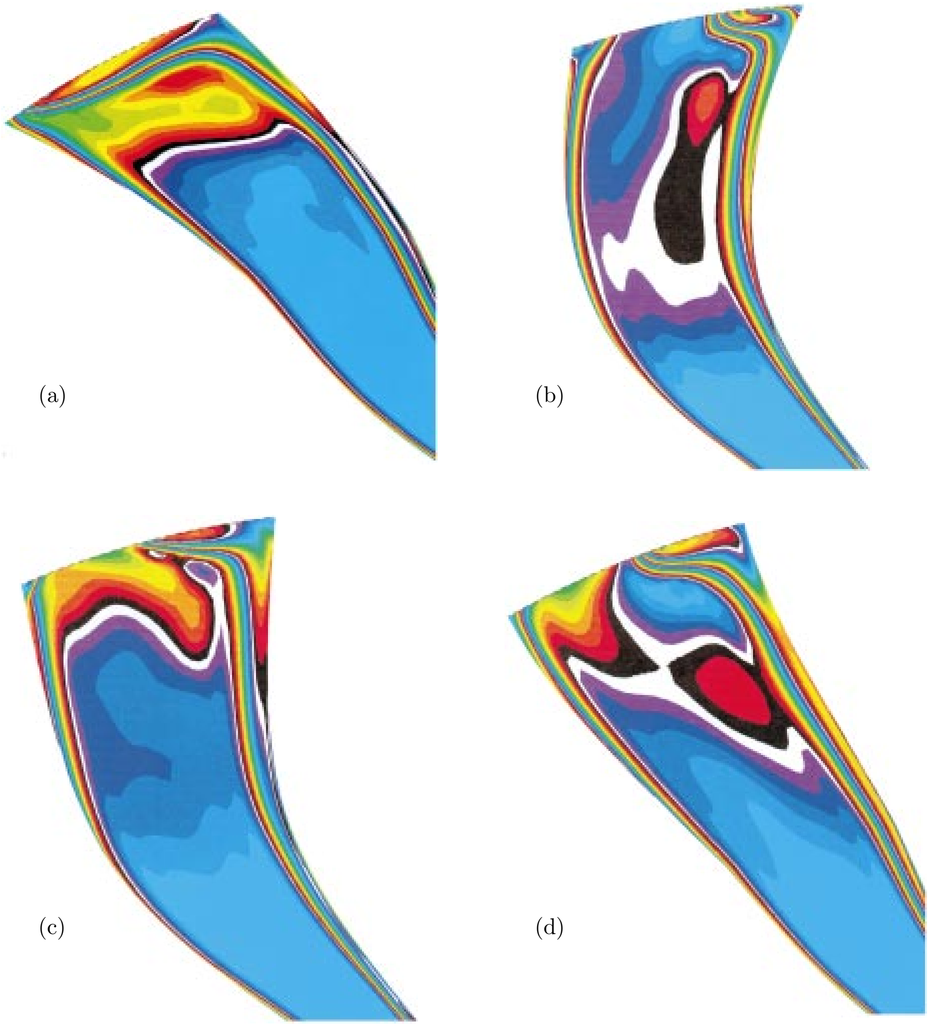

Figure 13. Contours of local polytropic efficiency just behind the trailing edge: (a) backswept rotor; (b) forwards swept rotor; (c) backwards leaned rotor; (d) forwards leaned rotor

efficiency contours, Figure 13, which show considerably more loss between 40% and 75% of span but much less loss near the casing. This is explained by the blade-to-blade view, Figure 12, which shows that the pre-shock Mach number is lower and the shock is further back so that more of it is weakened by the bow shock. This greatly reduces its loss. It is also significant that the loss core has not moved as far across the pitch, probably due to the shock being further downstream and swept forward relative to the leading edge so that less of the blade surface area is available for radially migrating fluid. Also, any fluid that does migrate does not run into the almost radial shock.

In summary forward sweep reduces the loss near the casing but significantly increases it around mid-span with very little effect on overall efficiency. The shock is pushed ahead of the leading edge at mid-span and it is likely that this part of the blade will stall first. The mass flow is slightly less than the datum despite the increase of annulus area at the axial location of the tip. This is because the shock is spilled around mid-chord so the blade is unchoked in that region.

7.3. Backwards leaned rotor

Figure 11 shows that the shock is well away from the leading edge at the tip but it has again moved in front of the leading edge near mid-span, this implies a poor stall margin. The shock has significant backsweep between 40% and 80% span, which should result in low loss. However, it changes suddenly to a strong normal shock beyond 80% span. The shock also extends to lower radii than the datum and appears stronger at mid-span. In fact the pre-shock Mach number at mid-span is considerably higher than the datum but because the shock has significant sweep its loss is similar to that of the datum between 50% and 80% span. One would expect back lean to lower the pressure and increase the Mach numbers over the whole of the tip region but there is no sign of that occurring. Near the tip, however, the loss appears greater than the datum corresponding to the strong normal shock. The "island" of low loss is considerably smaller than in the datum case. Overall the efficiency is very similar to the datum but the mass flow is reduced by 2% due to the lower annulus area at the axial location of the tip. The shock is detached from the leading edge around mid-span and this is likely to produce a poor stall margin.

7.4. Forwards leaned rotor

The forward leaned rotor has a shock with negligible sweep in either the blade-to-blade or perpendicular to the chord line view. The shock loss will therefore be high at the tip. However, the shock weakens considerably towards 50% span and becomes very weak after that. One would expect forward sweep to reduce the Mach number level over the whole tip region but again there is no sign of this occurring. Overall the loss contours, Figure 13, are quite similar to the datum with high losses about 75% span and a large "island" of low loss near the tip. Pressure contours near the suction surface (not shown) show that the "island" is again due to the shock at the tip being pushed upstream by the loss core, leading to considerable local shock sweep and reduced loss near the suction surface. The overall efficiency is very similar to the datum rotor. The mass flow is significantly higher than in any other case. This is because of the increased annulus area near the tip and the fact that the shock is nowhere in front of the leading edge so the blade remains choked. Although not checked, this design should have a good stall margin.

8. Conclusions

The main conclusion must be that blade sweep and lean have remarkably little effect on the shock pattern near to the casing. This must be because the shock always intersects the casing at right angles. The exact shock pattern and position in this region is determined by the blade profile (camber and thickness distributions) rather than by the blade stacking. In the region between mid-span and 80% span the shock position and sweep can be influenced by the blade stacking and shock sweep can produce significant reductions in loss. This is clearly seen by comparing the backwards swept and forwards swept rotors in Figure 13. However, features which tend to introduce backwards sweep of the shock in this region also tend to move it closer to the leading edge at mid-span, and hence reduce the stall margin.

The backswept rotor is most successful at keeping the passage shock well within the passage and so allowing pre-compression from the bow shock. This is a very desirable feature and greatly reduces the overall shock loss. However, it is likely to be more easily achieved by blade section design than by stacking. The forward leaned rotor is likely to have the best stall margin, although probably no better than the datum.

In terms of overall performance; none of the 3D designs are significantly more efficient than the datum radially stacked blade. Only the backswept rotor has a slightly lower efficiency. This is attributed to the increased pre-shock Mach number near its tip. However, both the forward leaned and the forward swept blades move the throat area to a region where the stream tube thickness is greater and so obtain a higher choking mass flow. This is most marked for the forward leaned blade, which did not spill the shock at mid-span.

The radial migration of boundary layer fluid in the separated region behind the shock has a very important effect on the flow in the tip region. It produces a large blockage, even with no tip gap and no annulus boundary layers. This blockage pushes the shock upstream and so reduces the stall margin but the resulting local shock sweep may give a significant reduction in shock loss very close to the tip. In reality this effect is likely to be considerably modified by the interaction of the loss core with the tip leakage flow. The radial migration must also thin the boundary layer behind the shock on the blade surface and so may help to prevent complete separation occurring in the shock-boundary layer interaction. The predicted magnitude of this effect is likely to be very dependent on turbulence modelling and the present results may not be quantitatively accurate, however, the trend is believed to be real and important in all transonic compressors and fans.

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