PERFORMANCE IMPROVEMENT OF FLUSH, PARALLEL WALLED AUXILIARY INTAKES BY MEANS OF VORTEX GENERATORS

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Abstract

An experimental and numerical investigation of the benefits of vortex generator (VG) control on the performance of a flush, parallel walled auxiliary intake has been conducted in air at a Reynolds number of 6,000 based on boundary layer momentum thickness, and at a free stream velocity of 45 ms^{-1}. The boundary layer thickness to intake depth ratio was 1.5, and zero external streamwise pressure gradient was imposed. In the experiments, a common flow down pair of vane type vortex generators of height 20 mm, chord 40 mm, apex separation 50.8 mm and angle of attack 22° was placed 400 mm upstream of the intake where the turbulent boundary layer was 10 mm thick. The control case without VGs was also investigated. A wider parameter space of VG size, lateral spacing, angle and type was investigated using computational fluid dynamics (CFD). Measurements and calculations showed a performance improvement of between 35% and 40% as a result of the application of the vortex generators. Performance was found to be most sensitive to lateral spacing of the VGs, with the best result obtained when the VGs were closest together, but not so close as to cause ingestion of the vortices.

1 Introduction

Auxiliary air intakes perform a variety of functions on aircraft, from cabin air supply, to engine component cooling and fire zone ventilation. The intakes come in a number of forms, including pitot designs, fared surface mounted blisters and flush (or submerged) intakes. Flush intakes are generally either parallel walled or of the NACA contoured diverging wall design (Fig. 1). The basic technology of submerged intake design was developed in the 1940s and 1950s [1-5]. Much of the work was performed on behalf of the NACA, and NACA inlets are commonly seen on the fuselage of commercial transport aircraft.

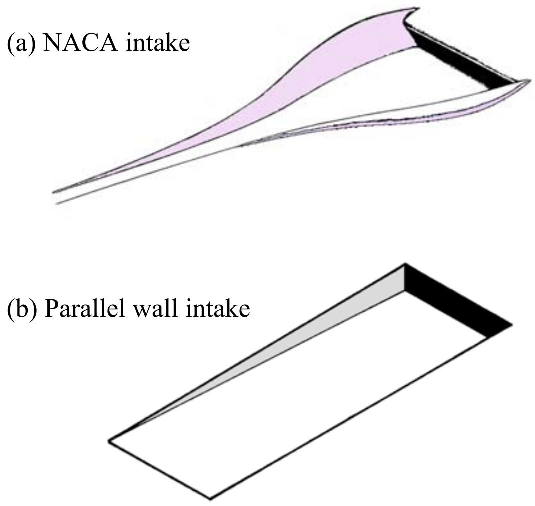


Fig. 1 Flush intakes: (a) NACA; (b) parallel wall

Intake performance is characterised by ram pressure recovery (RPR) and velocity ratio (VR). RPR is defined as,

$$\eta = \frac{\overline{P} - p_0}{P_0 - p_0} \qquad (1)$$

where P_0 and p_0 are the reference free stream total and static pressures, respectively, and $\overline{P}$ is the average total pressure recovered in the intake. VR is defined as the ratio of the mean velocity in the intake to the external free stream reference velocity. For turbofan nacelle ventilation, the volume flow rate ingested is a typical design requirement, expressed in terms of 'volume changes per minute' (VCPM). It is desirable to achieve the design VCPM with as small as possible an intake. For flush intakes it has been found that the relationship between RPR and VR is a function of the ratio of the boundary layer thickness (δ) to the intake scale, usually represented by depth (*d*). The performance of the intake is degraded as this ratio increases.

The parallel walled intake design is simpler, and less expensive to manufacture than the NACA, but has inferior performance, so that a larger, heavier intake, with a greater drag penalty is necessary to match the capacity of the equivalent NACA intake. The parallel walled intake has the advantage, however, that its performance is less sensitive to the velocity ratio at which the intake is operating [3]. The motivation for the research reported here was the improvement of the parallel walled intake performance to match that of the NACA design, without losing the advantage of its superior insensitivity to VR. This was attempted through the application of vortex generator flow control.

Vortex generators (VGs) have been used for decades to improve the high lift capability of aircraft wings [6]. Vane type generators are the most common form, but all types have much the same mode of operation: an embedded longitudinal vortex is generated with a diameter of the same order of magnitude as the boundary layer thickness. Because it is embedded within the boundary layer, the vortex draws high momentum flow from the external mainstream down into the lower third of the boundary layer, which enables the boundary layer to absorb the effects of adverse pressure gradients without stagnating and separating. Arrays of VGs are either co-rotating or counter-rotating; the latter are generally preferred and were used in the work described in this paper. The effect of a pair of counter-rotating vortices is observed as a thinning of the boundary layer in the 'common flow down' region, and a consequent increase in skin friction coefficient. The opposite occurs in the 'common flow up' region, but the net effect is favourable boundary layer control.

It is hypothesised that a pair of vortex generators placed upstream of a parallel wall intake, such that the intake lies in the vortex common flow down region, should reduce the local value of δ/d and improve the intake performance.

2 Methodology

2.1 Experiments

Experiments were conducted in a subsonic, closed loop wind tunnel with a test section 575 mm × 375 mm. An idealised model of a parallel wall auxiliary intake was mounted in a flat plate, 870 mm downstream of the plate leading edge (Figs. 2 and 3). Care was taken in the design of the plate leading edge and the plate mounting in the tunnel to ensure a streamwise pressure gradient as close to zero as was practicable. At the test speed of 45 m/s, the boundary layer was characterised by Re_θ = 6,000 and δ/d = 1.5 at the intake. The intake was manufactured from aluminium with a ramp angle of 10°, a width to depth ratio of 4 and a cross sectional area of 645 mm^2; the lip of the intake was a circular arc of radius 2 mm. The intake was 300 mm long and a traverse mechanism was installed so that total pressure could be surveyed in the plane 200 mm downstream of the intake lip.

To draw air through the intake, a plenum chamber 405 mm × 265 mm × 550 mm was placed beneath the intake and a flow meter and vacuum pump placed downstream of that. Throttling the flow to the vacuum pump allowed the velocity ratio (VR), defined as the ratio of the mean velocity through the intake to the reference free stream velocity, to be varied between 0.3 and 0.9.

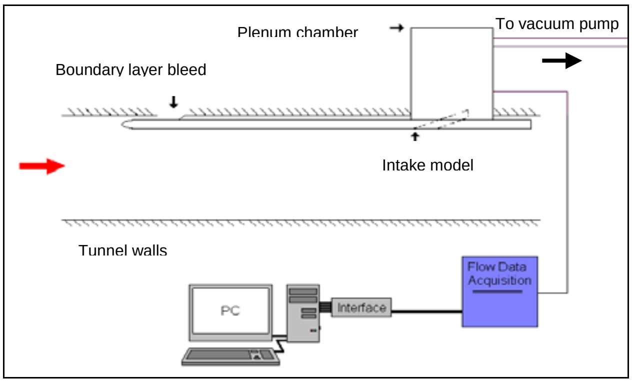


Fig. 2 Experimental set-up

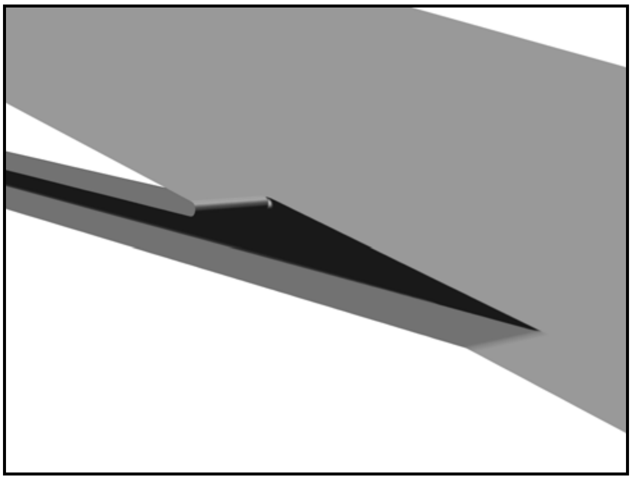


Fig. 3 Model intake split down centreline

Single wire hot wire anemometry was used to survey the boundary layer on the plate upstream of the intake; measurements were taken at positions 655 mm and 790 mm from the plate leading edge, both on and off the centreline. The boundary layer was confirmed to be turbulent, with a shape factor of about 1.3, and no significant cross-flow effects were observed. The total pressure inside the intake was measured using a pitot rake of 5 probes, which could be traversed normal to the intake wall and laterally, giving a coverage of 10 points normally by 50 laterally. Uniform spacing was used in both directions. The directional sensitivity of the pitot probes was shown to be 1% of total pressure for yaw angles of ±15°. Since the CFD studies predicted that the maximum yaw and pitch angles expected in the intakes were ±5°, this was regarded as sufficiently accurate.

It would be preferable to have calculated a volume flow rate averaged total pressure from the total pressure survey data. However, since axial velocity data was not available, an area average, $\overline{P}$, was obtained instead, i.e.

$$\overline{P} = \frac{\sum P\delta A}{\sum A} \qquad (2)$$

where P is the measured total pressure at a point surrounded by elemental area δA. The RPR was calculated using equation (1).

To investigate the effect of VG flow control, a common flow down pair of vortex generators was placed on the plate 400 mm upstream of the intake, where δ≈10 mm. The VGs were of height 20 mm, root chord 40 mm and the apex was cropped, of span 8 mm, such that the VG sweep angle was 73°; they were manufactured from aluminium sheet of thickness 1 mm. The VGs were positioned anti-symmetrically about the model centreline with an apex separation 50.8 mm and angle of attack 22°; the VG trailing edge was 400 mm upstream of the intake leading edge.

2.2 CFD

A wider range of VG configurations was investigated using the commercial CFD package Fluent 6™. The incompressible Reynolds-averaged Navier-Stokes equations were modelled. Tests for a single geometry indicated the superior performance of the k-ω turbulence model, and this was employed for all other cases. The software was run in its implicit segregated mode; the SIMPLE algorithm was used for pressure-velocity coupling and second order spatial discretisation was used for all the equations. Only steady state solutions were sought and calculations were iterated until all the residuals had 'flat lined'.

The basic computational domain measured 1210 mm long by 500 mm high by 500 mm deep and included the test plate and intake. Advantage was taken of the lateral symmetry of the geometry by employing a half-model with a symmetry condition applied on the centreline. Velocity and turbulence (k and ω) boundary layer profiles were obtained from a two-dimensional flat plate calculation and used as the inflow boundary condition, so that the intake could be placed 82 mm (about 6.5d) downstream of the inflow boundary. The plenum was not modelled since the discharge into the chamber was likely to be unsteady; instead, the modelled intake simply terminated at an outflow boundary. Varying the fraction of volume flow rate leaving via the intake outflow boundary allowed the velocity ratio to be controlled.

In addition to the uncontrolled case, eleven cases of VG control were considered, in which size (characterised by height), angle, lateral separation and shape were varied, as laid out in Table 1. Note that Case0 is the reference case which was also the subject of the experimental investigation. Case1 investigates the influence of the VG size; Case2 the VG angle; Case3 the VG spacing; and Case4 the VG shape. The rectangular VG had a chord of 40 mm, the same as that of the vane type VG used in Case0. The longitudinal position of the VGs relative to the intake was not varied.

Table 1 Vortex generator geometries

Case	Height (mm)	Angle (deg)	Separation (mm)	VG Type
Case0	20	22	25.4	Vane
Case1a	10	22	25.4	Vane
Case1b	15	22	25.4	Vane
Case1c	25	22	25.4	Vane
Case2a	20	7	25.4	Vane
Case2b	20	10	25.4	Vane
Case2c	20	15	25.4	Vane
Case3a	20	22	5.4	Vane
Case3b	20	22	10.4	Vane
Case3c	20	22	40.4	Vane
Case4a	20	22	25.4	Rectangle

Block structured meshes with approximately 250,000 (coarse), 500,000 (medium) and 1,000,000 (fine) cells were created for one case. The meshes were designed to maintain y^+ for the cell centre adjacent to the walls between 30 and 45 so as to accommodate the use of wall functions. The mesh spacing in the region of the VG was guided by the work reported in [7]. Comparison of the predicted RPRs on the three meshes (Fig. 4) shows that the maximum difference between the coarse and fine mesh results is about 2%. It was decided, therefore, to use coarse meshes for the remaining calculations.

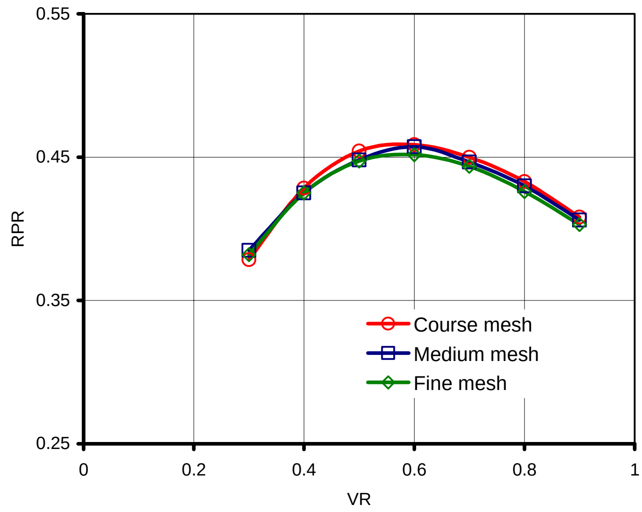


Fig. 4 Results of grid independence study

3 Intake Performance without Flow Control

The performance of the intake without flow control is illustrated by Fig. 5 which shows both the experimentally measured and numerically predicted RPR versus VR characteristic.

At low VR the performance of the intake is poor for two reasons. First, the low VR implies that the ingested fluid is taken from the lower regions of the plate boundary layer where there is low dynamic pressure. Secondly, as the flow approaches the intake throat (the throat is defined as the cross-section normal to the intake axis and lying underneath the lower surface of the intake lip) the streamlines diverge and the flow decelerates; the consequent adverse pressure gradient (Fig. 6) along the intake ramp upstream of the intake throat may cause boundary layer separation with all the usual penalties such as unsteadiness, strong mixing and loss of total pressure.

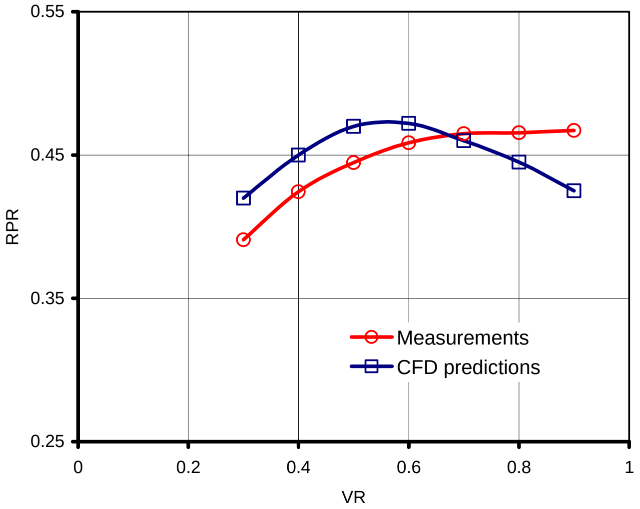


Fig. 5 Measured and predicted RPR, no flow control

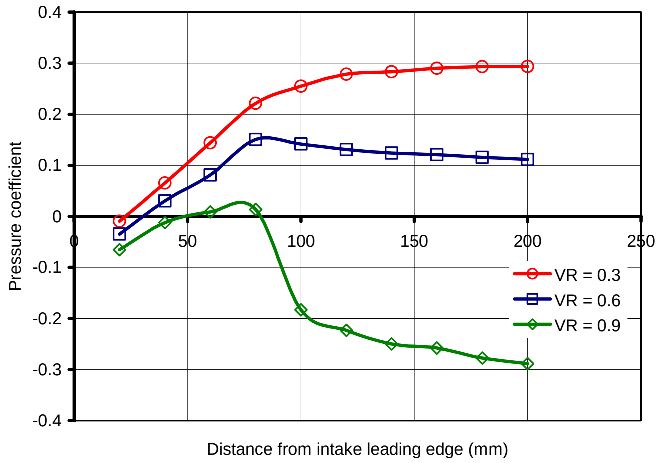
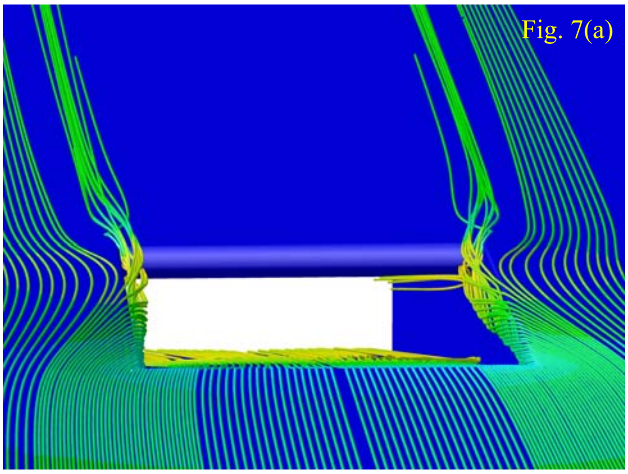


Fig. 6 Measured pressure distribution on centreline of intake lower wall

As VR is increased, more higher dynamic pressure boundary layer fluid is ingested by the intake and the intake performance improves. The improvement is limited, however; at the highest VRs investigated, the RPR achieved levels off. At high VRs the higher velocity in the intake is associated with increasing viscous losses as shear stress on intake walls increases. In addition, the stagnation point on the intake lip moves outward, and the streamlines negotiating the lip region see a drop in static pressure followed by a sharp rise, similar to the spike in pressure seen at the leading edge of an aerofoil operating above its ideal incidence. The rise in pressure may cause a bubble separation on the intake upper surface, just downstream of the lip, a thickening of the boundary layer and increase in total pressure loss. High VR is also associated with ingestion of longitudinal vortices generated at the streamwise edges between the plate and the intake ramp (Fig. 7). These vortices are generated as a result of the skewing of the boundary layer vorticity as the boundary layer is ingested. In fact, the NACA intakes are designed to make good use of the vortices. In the case of the parallel wall design, ingestion of the vortices results in additional losses.



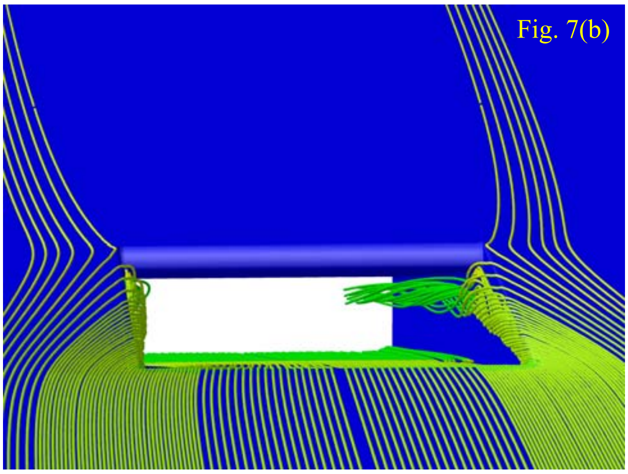


Fig. 7 Intake side wall vortices bypass the intake at VR = 0.5 (a) but are ingested at VR = 0.9 (b)

4 Intake Performance with Flow Control

4.1 Reference case

The reference case (Case0) was the subject of experimental and numerical investigation. A contour plot of the measured total pressure in a plane 200 mm downstream of the VGs and 200 mm upstream of the intake is shown in Fig. 8 (measurements were taken only in one half of the flow). Both the vortex and its influence on the boundary layer can be seen. In particular, note the significant thinning of the boundary layer in the common flow down region; the boundary layer thickness on the centreline has reduced from about 14 mm to about 7 mm.

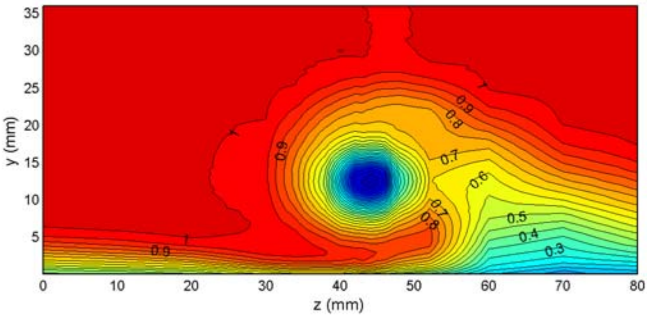


Fig. 8 Contours of normalised total pressure in a crossflow plane 200 mm downstream of the VG (Case0)

Since intake performance improves as δ/d decreases, an increase in RPR is to be expected. This is exactly what is found, as shown in Fig. 9, where an increase in RPR of between 0.15 and 0.2 (or about 40%) may be observed. The improved intake performance is also illustrated by the contour plots of measured normalised stagnation pressure in the intake shown in Figs. 10 and 11. The data in these plots was obtained 200 mm downstream of the intake leading edge. It is quite obvious that in each case, higher total pressure fluid was ingested by the intake with flow control than without.

Of course, this investigation has been constrained by the size of wind tunnel available, to use of a reference uncontrolled case with a relatively high value of δ/d, such that the reference performance is poor and the benefits of flow control stand out in sharp relief. Nevertheless, it is still significant that the performance improvement is maintained over the whole range of VRs considered, which is in stark contrast to the standard NACA intake performance which is quite design point specific.

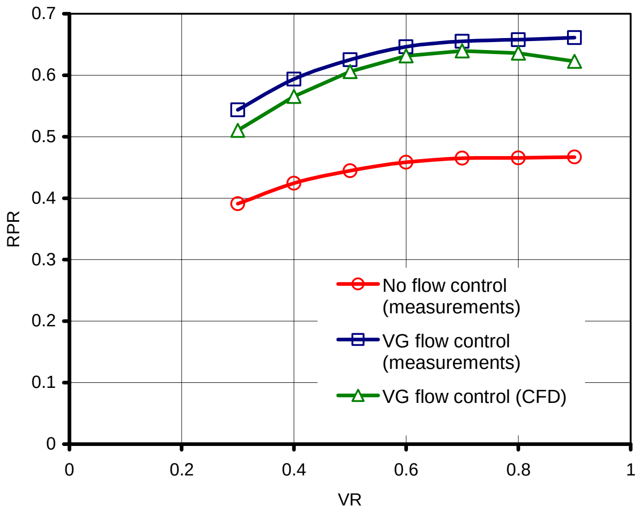


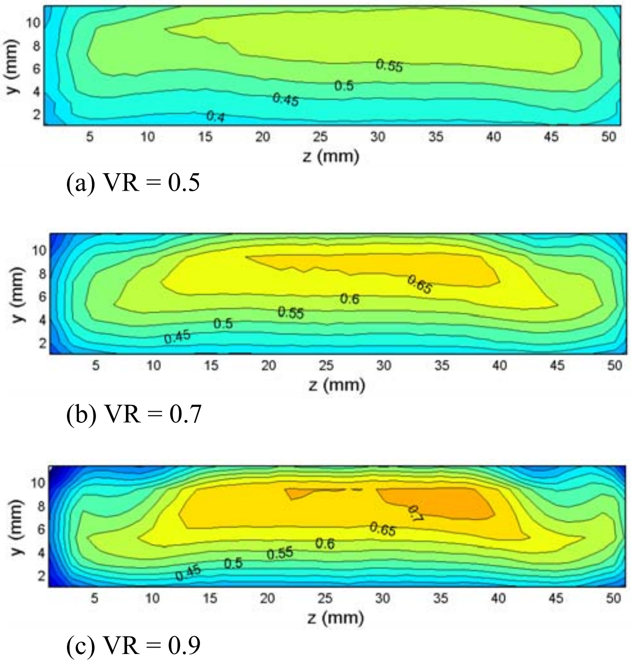
Fig. 9 Influence of control on intake performance

4.2 Results of parametric study

The parametric study detailed in Table 1 was conducted to investigate the dependence of the intake performance improvement on the design of the vortex flow control applied. The results are shown in Figs. 12 to 15.

The first thing to be observed is that increasing height caused an increase in performance (Fig. 12). The increase is obtained over the whole range of VR and does not appear to have been exhausted by the maximum VG height considered, though an asymptotic approach to a limit would be expected.

The influence of incidence angle is shown in Fig. 13. The optimum angle is apparently 10°. However, care must be taken in the interpretation of these results: the VG was rotated about its fixed apex and consequently reducing the incidence caused the VG trailing edges to come closer together. Hence the interaction between the vortices and the intake strengthened. The influence of VG spacing is shown in Fig. 14.

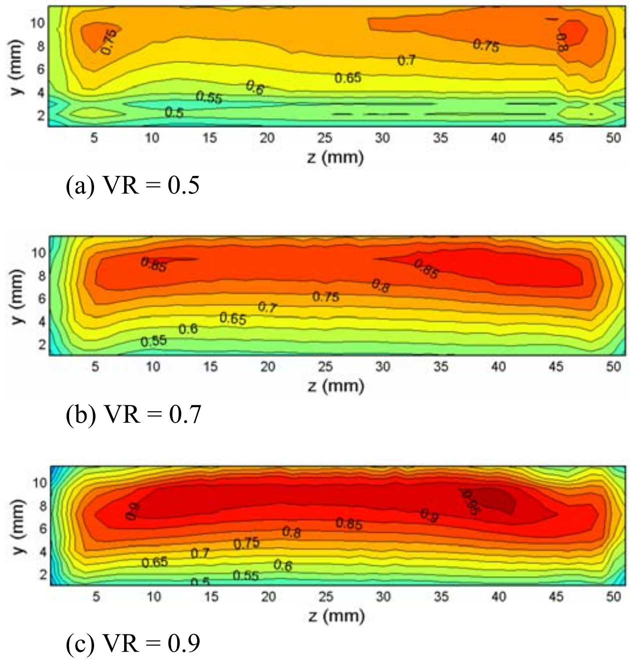


(a) VR = 0.5

(b) VR = 0.7

(c) VR = 0.9

Fig. 10 Normalised total pressure on plane 200 mm downstream of intake leading edge, without flow control



(a) VR = 0.5

(b) VR = 0.7

(c) VR = 0.9

Fig. 11 Normalised total pressure on plane 200 mm downstream of intake leading edge, with flow control

Fig. 14 shows that reducing the lateral spacing of the VGs caused an increase the intake performance. This is due to the stronger interaction between the vortices and the intake. Care would have to be taken that the vortices were not ingested (recall the performance drop observed for the uncontrolled case at high VR when the intake side wall vortices were ingested). However, common flow down vortex pairs tend to drift apart under the influence of their image pair, and so ingestion is unlikely.

Finally, there is almost no discernable difference in Fig. 15 between the performance enhancement accruing from the vane and rectangular VGs. The manufacturer might take advantage of this by using the simplest, and cheapest to manufacture, form of VG.

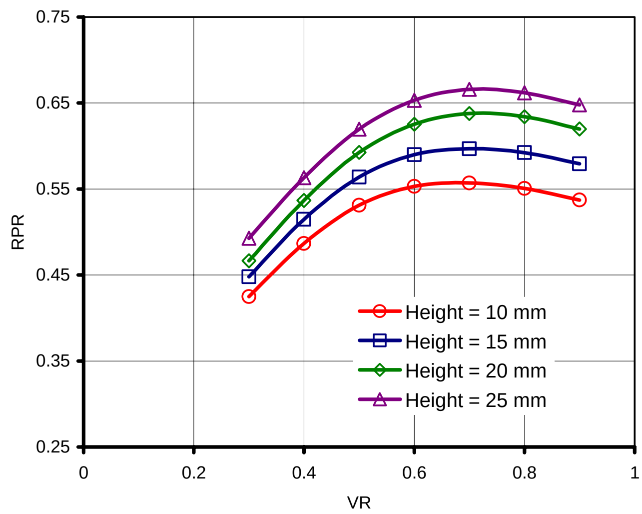


Fig. 12 Influence of vortex generator size

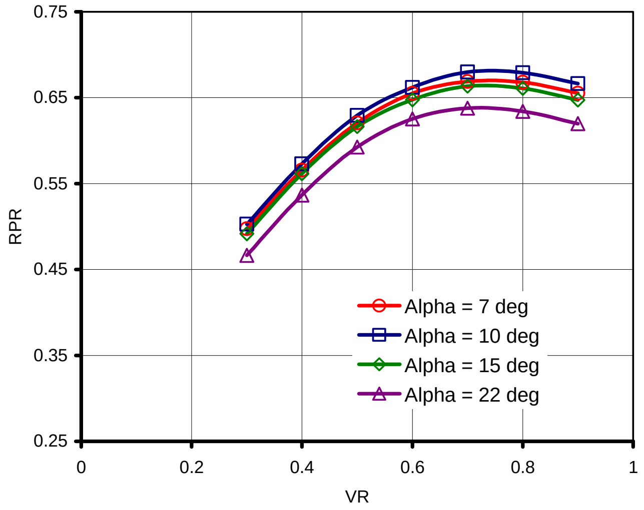


Fig. 13 Influence of vortex generator incidence angle

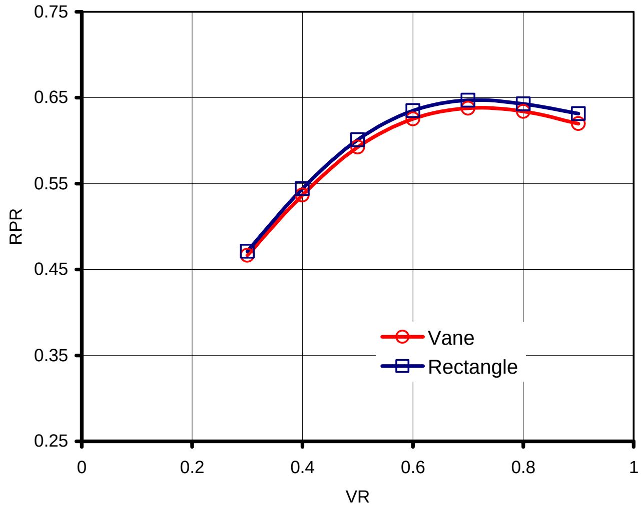


Fig. 15 Influence of vortex generator shape

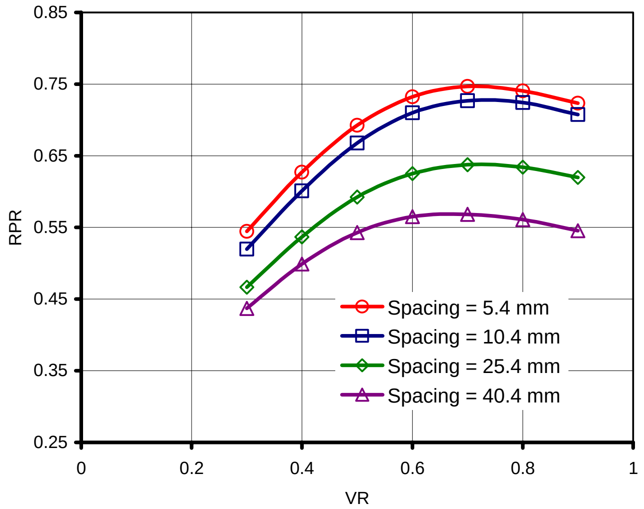


Fig. 14 Influence of vortex generator spacing

5 Conclusions

Measured and predicted ram pressure recovery was generally lower than reported in other texts. This is likely to be because of the higher value of δ/d employed in this work.

The flow around and into the intake is three-dimensional. Corner vortices are formed where the intake side walls meet the flat plate, and when these vortices are ingested by the intake at high velocity ratios, they create blockage, enhance mixing processes and degrade the performance. At VR greater than 0.7, the predicted performance of the intake was less than that measured, and this has been attributed to (a) premature swallowing of the corner vortices in the predictions and (b) over-predicted mixing of the vortical shear flow and the intake wall boundary layers. Designers who employ simple flush, parallel walled auxiliary intakes without taking the three-dimensional effects at high velocity ratios into account, will probably undersize the intakes.

The application of the vortex generators typically gave ram pressure recovery improvements of between 35% and 40%. Although ingestion of the vortex pair must be avoided, this does not appear to be a problem as the vortices naturally migrate away from the centreline of the intake. The treatment gives the intakes the potential for a peak performance similar to that of the more complex NACA intake. However, the vortices generated by the NACA intake are ingested at high flow rates and the intake's performance drops markedly. Hence, the treated parallel walled intake performs better over a wider range of flow conditions.

Designers/manufacturers may be able to use either smaller examples of the treated intake or smaller numbers of them. This would have benefits for aircraft weight, part count and maintenance.

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