Enhancement of thrust reverser cascade performance using aerodynamic and structural integration

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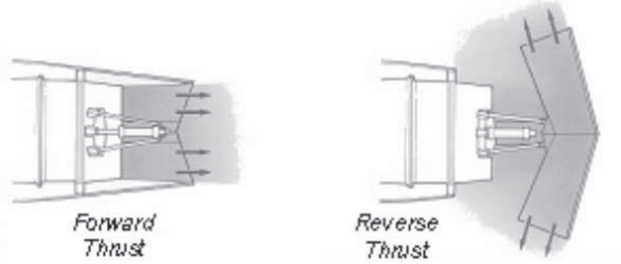
ABSTRACT

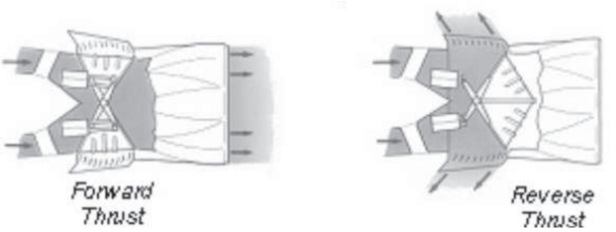
This paper focuses on the design of a cascade within a cold stream thrust reverser during the early, conceptual stage of the product development process. A reliable procedure is developed for the exchange of geometric and load data between a two dimensional aerodynamic model and a three dimensional structural model. Aerodynamic and structural simulations are carried out using realistic operating conditions, for three different design configurations with a view to minimising weight for equivalent or improved aerodynamic and structural performance. For normal operational conditions the simulations show that total reverse thrust is unaffected when the performance of the deformed vanes is compared to the un-deformed case. This shows that for the conditions tested, the minimal deformation of the cascade vanes has no significant affect on aerodynamic efficiency and that there is scope for reducing the weight of the cascade. The pressure distribution through a two dimensional thrust reverser section is determined for two additional cascade vane configurations and it is shown that with a small decrease in total reverse thrust, it is possible to reduce weight and eliminate supersonic flow regimes through the nacelle section. By increasing vane sections in high pressure areas and decreasing sections in low pressure areas the structural performance of the cascade vanes in the weight reduced designs, is improved with significantly reduced levels of vane displacement and stress.

NOMENCLATURE

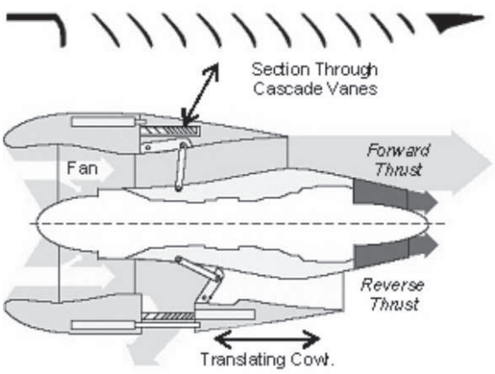
V	volume	
A	surface area	
ρ	density	
$\vec{u}$	velocity	
E	total energy per unit mass	
p	pressure	
τ	viscous stress	
q	heat flux	
H	enthalpy	
W	vector term	$\begin{Bmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \end{Bmatrix}$
F	vector term	$\begin{Bmatrix} \rho\vec{u} \\ \rho\vec{u}u + p\vec{i} \\ \rho\vec{u}v + p\vec{j} \\ \rho\vec{u}E + p\vec{u} \end{Bmatrix}$
I	vector term	$\begin{Bmatrix} 0 \\ \tau_{xi} \\ \tau_{yi} \\ \tau_{ij}u_j + q \end{Bmatrix}$



(a) Bucket target type thrust reverser[4].



(b) Clamshell type thrust reverser[4].



(c) Cold stream (cascade) type thrust reverser[2].

Figure 1. Jet engine nacelle with cold stream thrust reverser engaged[2].

1.0 INTRODUCTION

Airline operators are constantly striving to reduce operational costs in order to remain competitive. Although cost reductions are possible with administrative, organisational or logistical changes, the most effective savings are made by technical developments and improvements[1]. A significant proportion of the manufacturing and operational costs of an aircraft are determined during the design phase of the product development process. Up to 80% of final component cost is determined during the conceptual design phase alone[3].

One way of improving the design process with a view to reducing final component cost, is the development and application of more efficient tools and methodologies for better simulation of component behaviour[4]. The use of computer aided methods to simulate the behaviour of aircraft components, can be difficult and time consuming due to the inherent complexity of aerospace systems and the differing approaches taken by aerodynamic and structural designers to predictive modelling. The efficiency of the design process during the cost critical conceptual design stage, can be improved by using idealised simulation models and by employing a more integrated approach to component design. The real cost of each design iteration is reduced allowing the designer to analyse a greater number of component designs. The resulting designs are better and more efficient which results in long term savings as operational costs come down.

This paper looks at the development of effective and efficient methodologies for the simulation of aircraft component behaviour. A weight reduction exercise for a thrust reverser cascade was chosen as a test case for these methodologies. A reduction in the weight of any aircraft system will reduce fuel consumption resulting in lower operational costs. Although a component within a jet engine nacelle has been chosen as the subject for this work, the methodologies developed are equally applicable to any complex part where structural performance is a key requirement and multi-disciplinary simulation is heavily used.

In modern aircraft the thrust reverser is built in to the nacelle system and uses the power of the jet engine as a deceleration force during landing, by reversing the direction of the hot or cold stream airflows which generate forward thrust in flight[4]. There are a number of thrust reverser types including the bucket target, clamshell door and cold stream reverser systems, see Fig. 1. Figure 1 (c) shows a cold stream thrust reversal system which is used as the subject for this work. When the thrust reverser is engaged, the translating cowl moves back and a blocking mechanism is introduced to the cold airflow generated by the fan. This cold stream flow is then redirected through a series of cascades placed circumferentially around the nacelle thereby producing the deceleration forces that slow the aircraft down. The cascade used for this work is manufactured in aluminium alloy by the process of investment casting. When the thrust reverser is engaged the cascade manages the reversed airflow as it exits the nacelle. Cascade vane configurations vary around the circumference of the nacelle so that reverse thrust is maximised and the resulting flows do not cause problems with other aspects of the aircraft's performance.

Potential problems include engine stability issues due to re-ingestion of reversed flows, foreign object damage if ground debris is lifted into the engine inlet flow, efficiency losses on control surfaces if flow characteristics around the aircraft are changed and control issues resulting from buoyancy due to reversed flow from engines mounted on opposite sides of the aircraft, meeting below the fuselage. The vane configuration used for this work is for a cascade box located on the outboard part of the nacelle where the air flow is directed back in the direction of aircraft movement.

Thrust reversers increase nacelle weight and result in higher manufacturing and operational costs. The benefits which can be gained through the use of thrust reversers outweigh these disadvantages. The use of wheel brakes is reduced which prolongs brake life and reduces tyre wear. Safer landings can be achieved on wet, icy or snow covered runways where wheel breaks can have difficulty achieving traction[5]. Thrust reversers can also provide additional safety and control margins for aircraft operation during take off, landing and movement on the ground. The standing time required to allow breaking systems to cool down is reduced which in turn, reduces aircraft turn around times. Reduced landing distances allow aircraft to exit runways sooner which can increase airport throughput. Simulations have suggested that the time associated with the taxi-in of a typical heavy transport could be reduced by up to 12%[6] by using thrust reversal as a means of slowing an aircraft down when it lands.

The high pressures and airspeeds within the nacelle system during reverse thrust can lead to supersonic and turbulent flow regimes within the structure. These factors can lead to issues with the strength and durability of nacelle components such as the cascade and there has been a tendency in the past to 'over design' which adds weight and increases cost. The cost reductions achievable by using leaner designs are one of the practical motivations behind this work.

To illustrate how component design can be improved, a thrust reverser cascade is analysed using computational fluid dynamics (CFD) and finite element analysis (FEA) methods. A methodology is identified for the structural analysis of the cascade to determine levels of vane displacement and stress. Static pressure loadings on the vanes are determined using realistic operating conditions in a two dimensional CFD simulation. Methodologies for structural analysis have been examined showing that beam, shell and solid elements can effectively determine displacement levels on the cascade vanes[8].

In this paper design methodologies identified for the development of a thrust reverser cascade, are put into practice with a view to reducing weight. CFD and FEA simulations are linked so that the affect of deformed cascade geometry on aerodynamic performance can be determined. The effects of weight reduction achieved by varying cascade vane configurations, are then examined in terms of aerodynamic and structural performance.

2.0 METHODOLOGY AND PROCEDURE

Having determined the deformed shape for the cascade vane configuration shown in Fig. 1, a finite element model generated using 3D solid elements, was used to extract a deformed, 2D cascade section so that the CFD analysis could be repeated, see Fig. 2.

The purpose of this was to determine changes in aerodynamic performance when the vanes were displaced by the operational pressures. This was achieved by isolating the displaced elements and nodes through the central cascade section, in PATRAN during post processing of the structural model. The displaced nodes and elements were then output to a PATRAN results report file. The data in this file was then re-formatted to the NASTRAN neutral file format which is compatible with the FLUENT CFD solver. Earlier work showed that higher levels of geometric idealisation used with shell and beam element representations of the cascade, meant that the outputs from these element types was not as suitable for translation to a form that could be used in the CFD model[8]. Having examined the aerodynamic and structural performance of the original cascade section, known as Design 1 (Fig. 3(a)), two modifications were made to the vane section to determine if cascade weight could be reduced while at the same time maintaining or improving aerodynamic and structural performance. Both of these changes involved making vane sections 9 and 10 in predicted high pressure areas, larger and heavier and making vane sections 1 and 2 in predicted low pressure areas, smaller and lighter. Two slots were introduced through vane 11 in Design 2 to reduce the pressure build up at this point. The net effect was a reduction of 5% in weight (Fig. 3(b)). As well as introducing the slots in vane 11, the section of vane 0 was also reduced in Design 3 which resulted in a total weight reduction of 10% (Fig. 3(c)).

2.1 Aerodynamic model

An idealised, two dimensional representation of the nacelle geometry was used for the aerodynamic analysis. Thrust reverser performance was determined using a freestream flow of mach 0·2 and a temperature of 288K. The Fluent CFD solver was used to simulate the time dependent, viscous, compressible flows through the nacelle section[9]. The governing equations were solved by

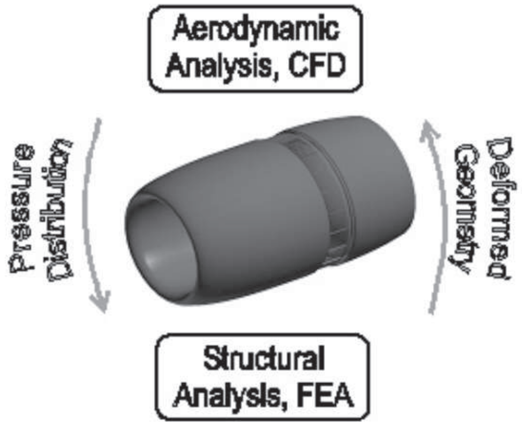
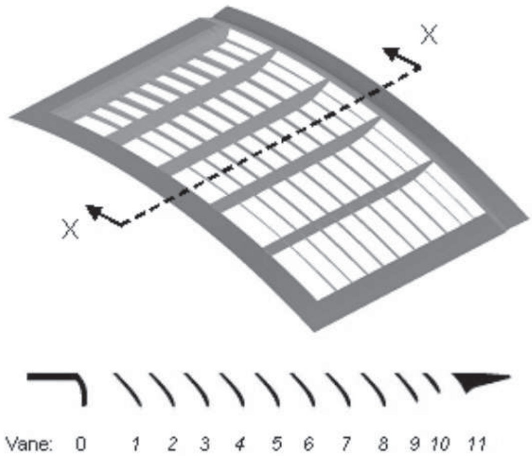


Figure 2 Simulation of aerodynamic and structural performance for a thrust reverser cascade.



(a) Cascade Design 1,original.

(b) Cascade Design 2, 5% weight reduction.

(c) Cascade Design 3, 10% weight reduction.

Figure 3. Section XX through thrust reverser cascade box for three design options.

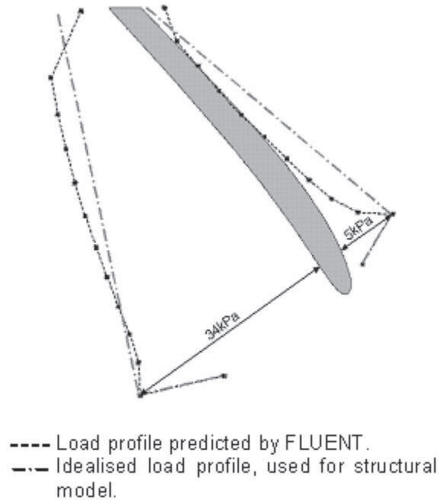


Figure 4. Schematic diagram showing magnitude of nodal pressures relative to surface of single cascade vane.

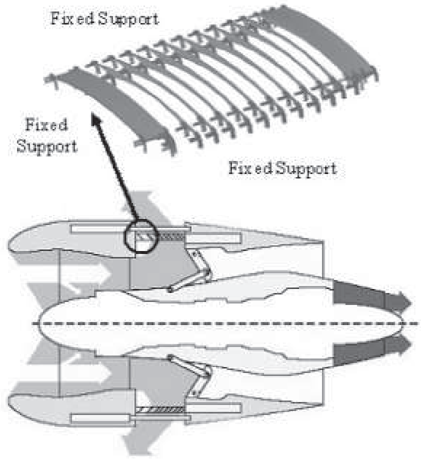


Figure 5. Support detail for structural model representing thrust reverser cascade.

FLUENT using the finite volume method. The system of equations used was cast integral, Cartesian for an arbitrary control volume V, with differential surface area A, as follows:

$$\frac{\partial}{\partial t}\int_V \mathbf{W} dV + \oint [\mathbf{F} - \mathbf{G}] \cdot dA = 0 \quad \ldots (1)$$

where the vectors **W**, **F**, and **G** are defined as;

$$\mathbf{W} = \begin{Bmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \end{Bmatrix}, \mathbf{F} = \begin{Bmatrix} \rho \vec{u} \\ \rho \vec{u} u + p\vec{i} \\ \rho \vec{u} v + p\vec{j} \\ \rho \vec{u} E + p\vec{u} \end{Bmatrix}, \mathbf{G} = \begin{Bmatrix} 0 \\ \tau_{xi} \\ \tau_{yi} \\ \tau_{ij} u_j + q \end{Bmatrix}$$

Here ρ, = $\vec{u}(u,v)$, E, and p are the density, velocity, total energy per unit mass, and pressure of the fluid, respectively. τ is the viscous stress tensor, and q is the heat flux. Total energy E is related to the total enthalpy H by

$$E = H - p / \rho \quad \ldots (2)$$

where

$$H = h + |\vec{u}|^2 / 2 \quad \ldots (3)$$

The Reynolds-Averaged approach with the RNG (renormalization group) k - ε model has been used to model the effect of turbulence. The RNG $k - \varepsilon$ model is derived from the instantaneous Navier-Stokes equations, using a mathematical technique called 'renormalization group' methods. Total reverse thrust was derived in FLUENT by the integration of pressure through the nacelle section.

Mesh adaptation (use of higher element concentrations in areas of interest) and mesh convergence studies were used to ensure that simulation errors were kept to a minimum. There is no significant difference in the results obtained for 30,000, 50,000 and 90,000 cell models indicating that the solution had converged to an acceptable level at 30,000 cells.

2.2 Structural model

2.2.1 Geometry & mesh

The only area common to both the CFD and FEA models is the geometric boundary of the cascade, where the outer surfaces of the individual vanes meet the surrounding air. For the CFD analysis a mesh was applied to the area outside the geometric boundary so that the airflow through the cascade could be examined, see Fig. 2. For the structural analyses the area inside the geometric boundary was represented by a mesh so that the effect of the resulting pressures on the vanes could be examined. The starting point for both simulations was CAD data transferred into the analysis packages in IGES format. For the aerodynamic analysis a 2D model was generated from the CAD data. For the structural model the 2D CAD data was swept to form a 3D, 20° cascade section.

2.2.2 Load application

The results from the 2D aerodynamic analysis yielded a load distribution for the cascade which took the form of a resultant pressure for each of the nodal positions around the perimeter of the individual vanes, see Fig. 4. For the structural model, pressures were applied to the cascade using individual load tables for each vane. The process of creating and applying pressures using load tables was carried out manually. The pressure distributions around each vane were idealised to the simple linear forms shown in Fig. 4.

2.2.3 Support conditions:

The cascade as a whole was fully restrained at the point where it is joined to the rest of the nacelle assembly, see Fig. 5. The process of geometric idealisation meant that, symmetry was used to reduce modelling and processing times. Fixed supports were applied to the areas where the symmetrical idealisations were made, see Fig. 5. These simulated the supporting affect of the lateral members between the sets of cascade vanes.

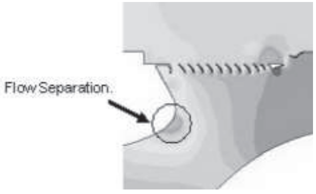


Figure 6. Design 1, Original:
static pressure distribution through nacelle section.

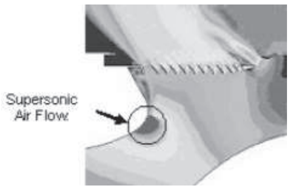


Figure 9. Design 1, Original: weight reduction:
air speed contours through nacelle section.

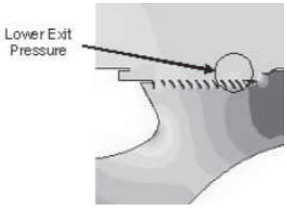


Figure 7. Design 2, 5% weight reduction:
static pressure distribution through nacelle section.

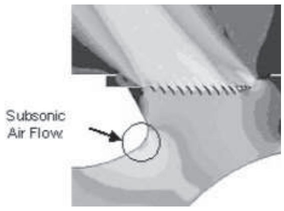


Figure 10. Design 2, 5% weight reduction:
air speed contours through nacelle section.

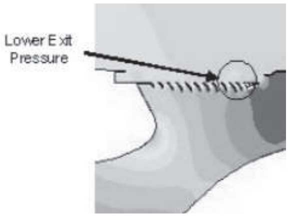


Figure 8. Design 3, 10% weight reduction:
static pressure distribution through nacelle section.

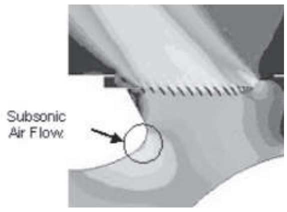


Figure 11. Design 3, 10% weight reduction:
air speed contours through nacelle section.

2.2.4 Material properties

The structural analyses were carried out using the material properties for an aluminium alloy with a Young's modulus of 72GPa and a density of 2,790kg/m^3.

2.3 Coupling of FEA model to CFD simulation

Having carried out the aerodynamic analysis on the original cascade geometry of Design 1, an idealised version of the pressure distribution around each vane was transferred manually to the structural model using load tables within PATRAN[5]. The deformed nodal positions for a section through each of the cascade vanes was isolated and the displaced nodal positions were output to a separate text file. To make this data compatible with the FLUENT CFD package, it was re-formatted to the NASTRAN neutral file format. The aerodynamic analysis was then repeated for the deformed cascade geometry.

2.4 Reduced weight vane configurations

The structural analysis of Design 1 revealed that vane deformations were greatest in the areas of high pressure predicted by the aerodynamic analysis, around vanes 9, 10 and 11 (see Fig. 3(a)) for vane numbers). The maximum displacements also corresponded to the positions where the vane sections were smaller than those elsewhere in the cascade. The aerodynamic analysis also revealed that there was a significant pressure build-up around vane 11. The results for the aerodynamic and structural analyses will be outlined in greater detail in Section 3.

For Design 2, the smaller vane sections 9 and 10 were replaced with larger sections and the larger sectioned vanes 1 and 2 were replaced with smaller sections. Slots were also added to vane 11 to relieve the predicted pressure build up. The net result of these changes was a 5% reduction in cascade weight.

An additional 5% weight reduction was achieved in Design 3 where vane 0 and vane 10 were reduced in section. The tip of vane 0 was now equivalent in section to the original vane 10 and the vane section in position 10 was now equivalent to the original vane 9. The net result of this exercise was a 10% reduction in cascade weight when compared to the original Design 1.

3.0 RESULTS

3.1 Aerodynamic analysis.

3.1.1 Static pressure distribution through nacelle section

The aerodynamic analyses were carried out on the three cascade configurations shown in Fig. 3. Figures 6, 7 and 8 show the

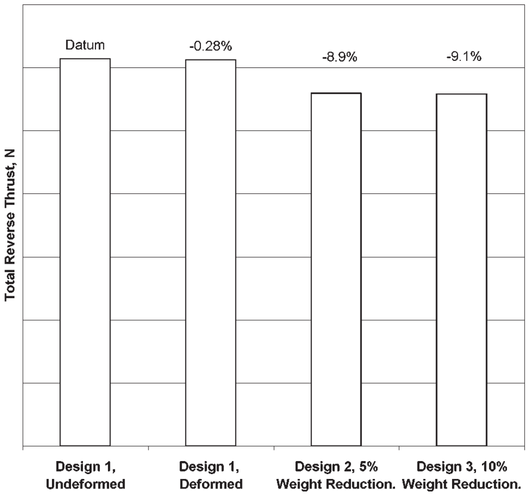


Figure 12. Comparison of total reverse thrust for three cascade configurations.

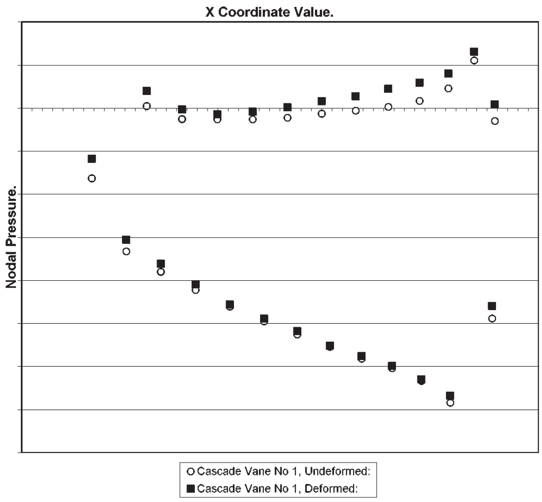


Figure 13. Comparison of pressure distribution around vane Number 1 for un-deformed and deformed cascade geometry.

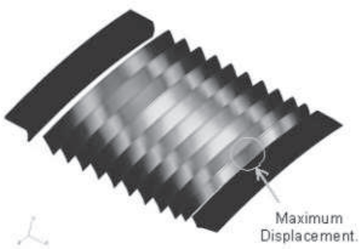


Figure 14. Design 1: Displacement contours.

predicted static pressure distributions which were subsequently used as the basis for the loads applied to the structural models. It is worth noting the area of low pressure associated with the separation of flow in Design 1, see Fig. 6. In Figs 7 and 8 the exit pressures, downstream from the cascade are lower than those for design 1. This is a result of the sectional changes at vanes 9 and 10 as well as the introduction of the slots to vane 11, which have increased the area through the cascade.

3.1.2 Air speed through nacelle section

Figures 9, 10 and 11 show contour plots representing air speed through the nacelle for cascade Designs 1, 2 and 3 with the thrust reverser engaged. The supersonic air speeds predicted for Design 1 are highlighted on Fig. 9. Air speed plots for Design 2 and Design 3 are shown in Figs 10 and 11. The same contour range has been used for Figs 9, 10 and 11. Despite a reduction in total reverse thrust for the weight reduced designs, the maximum airspeed through the nacelle is sub-sonic in both of the reduced weight cases. This reduction in the upstream airspeed is due to the increase in the area ratio between the cascade and the throat of the nacelle. The elimination of supersonic airspeeds means that there is a reduced risk of the cascade being subjected to the shock waves associated with the conditions predicted for Design 1.

3.1.3 Total reverse thrust

Figure 12 shows how total reverse thrust dropped by only 0·28% when deformed cascade geometry was used to re-examine aerodynamic performance for Design 1. This shows that for the conditions tested, the operation of the thrust reverser is not significantly affected when the cascade vanes deform under that action of the operational pressures used for this work. Figure 12 also shows that when the cascade configurations were changed to reduce weight by 5% for Design 2 and 10% for Design 3, total reverse thrust was reduced by around 9% in both cases. This is due to the reduction in the exit pressures downstream from the cascade which have resulted from the modifications made for Designs 2 and 3.

Figure 13 shows the affects of vane deformation on the static pressure distribution on vane number 1 for Design 1. The plot shows that the pressure distributions around vane 1 are similar for the un-deformed and deformed cases. This trend was repeated for the other vanes in the cascade. This result as well as the fact that the total degree of reverse thrust only changed by 0·28%, means that for the conditions tested, there is no significant change in thrust reverser performance when the cascade vanes are deformed after reverse thrust is engaged.

3.1.4 Deformation

Figure 14 shows a contour plot representing the deformations predicted for Design 1 using the operational pressures shown in Fig. 6. The maximum displacements, correspond to the areas of high pressure as predicted by the aerodynamic analysis. The maximum deflection occurs on vane 10 which has the smallest section of all of the cascade vanes.

As already discussed in Section 2.4, this outcome influenced the vane configurations used for Design 2 and Design 3 where the vane sections in high pressure areas were increased and the sections in the low pressure areas were reduced. In all three cases the maximum displacement occurs in the vane 10 position. The maximum displacements for Designs 1, 2 and 3 are illustrated in Fig. 15. The vane configurations used for designs 2 and 3 have lead to significant reductions in the maximum vane displacement when compared to Design 1.

3.1.5 Stress

Figure 16 shows a contour plot representing the Von Mises stresses predicted for Design 1 using the operational pressures shown in Fig. 6. The maximum mid vane stresses correspond to the areas of high pressure as predicted by the aerodynamic analysis. The maximum mid-vane stress occurs on vane 10 for all of the design configurations tested. Vane 10 has the smallest section of all of the cascade vanes. The maximum mid-vane stresses for Designs 1, 2 and 3, are illustrated in Fig. 17. Again, the vane configurations used for designs 2 and 3 have lead to significant reductions in the maximum vane stress when compared to Design 1.

3.2 Sources of error

3.2.1 Aerodynamic simulation

Experiments have been carried out on a 40% scale, 30° sector model of the Bombardier Aerospace Shorts thrust reverser design[9]. For the case where the thrust reverser was fully opened, the results showed that the resultant axial force on the trans-cowl was within 7·5% of the value predicted using the CFD simulation. One reason for the difference between the experimental and simulated results is the assumption of symmetry i.e. the use of a 2D CFD model to simulate a 3D fan air flow. Another source of error is the decrease in the accuracy of the CFD solution as the turbulence model struggles to capture the physics of the supersonic flow which arises due to flow separation in the throat of the nacelle. Other possible sources of error are rounding and truncation errors during the CFD calculations, the accuracy of the CAD data relative to the final geometry of the test rig. The level of agreement between the simulated and experimental data was considered to be good enough to conclude that the CFD model could predict thrust reverser performance with an acceptable level of accuracy.

3.2.2 Structural simulation

The structural model representing the thrust reverser cascade was idealised to include a 20° section of the vanes. Symmetrical idealisation is a common method used to reduce modelling times when using FEA. As long as the symmetrical support conditions are applied correctly, there is little or no effect on the final result when compared to the outcome of an analysis carried out on a complete structure.

For the purposes of this work the load distribution around the cascade vanes was also idealised. The maximum vane displacements predicted using the idealised, six point load distributions on the structural models, differed by less than 5% when compared to the values obtained using the full twenty five point load distribution.

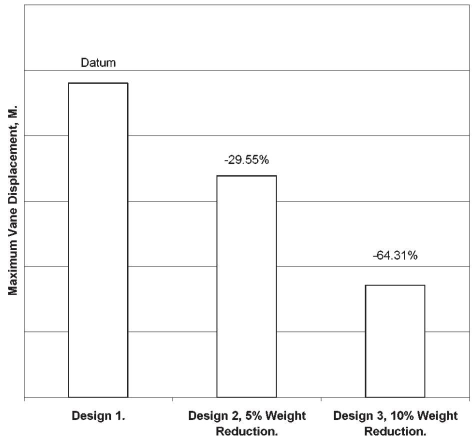


Figure 15. Comparison of maximum vane displacement for three cascade configurations.

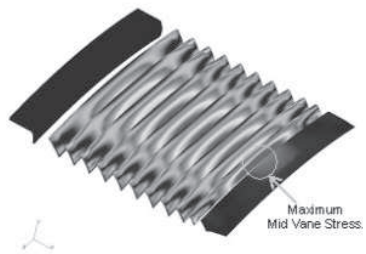


Figure 16. Design 1: Von Mises stress contours.

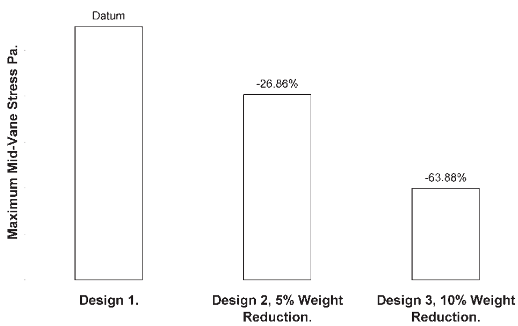


Figure 17. comparison of maximum mid vane stresses for three cascade configurations.

4.0 DISCUSSION

This paper details the outcome of an investigation into the aerodynamic and structural performance of a thrust reverser cascade with a view to reducing weight while at the same time, maintaining or improving aerodynamic and structural performance. Any reduction in the weight of aircraft components will result in financial savings as operational costs come down. Improved design efficiency can also lead to financial benefits as design lead times are reduced and the final product is introduced to the marketplace sooner. The methodology presented uses low level aerodynamic and structural models to achieve these weight reductions. The number of design configurations used for this work is not exhaustive but the methodology presented serves to illustrate how low level aerodynamic and structural models can be linked so that geometric and performance data can be transferred for the purposes of enhancing cascade design using a more integrated approach. Three cascade configurations involving minor design changes, have been examined however, the methodology could easily be applied to any number of cascade configurations or indeed any other structure where structural performance is a key requirement and multi-disciplinary simulation is heavily used. Some of the ways in which thrust reverser performance could be improved include a more detailed study of the aerodynamic section of the vanes, varying vane numbers and sizes or looking at the blocker configuration and nacelle throat section with a view to turning the reversed air flows more efficiently.

Aerodynamic and structural cascade models have been linked using neutral file formats, so that geometric and load data could be exchanged between the aerodynamic and structural simulations. In this case the integration of FLUENT and PATRAN facilitated a comparison between the aerodynamic and structural performance of the deformed cascade and the behaviour of the un-deformed structure. The results show that total reverse thrust was not affected by the levels of displacement on the vanes for the conditions tested, thereby demonstrating that there is scope for changing the cascade design to reduce weight.

The cascade configuration was modified based on the outcome of the simulation carried out on the existing design. The aerodynamic analyses identified areas of high and low pressure across the cascade section. Smaller vane sections are placed in low pressure areas and larger vane sections are used in high pressure areas. Slots are introduced to Vane 11 for both Design 2 and Design 3 (see Fig. 3). The sectional area of vane zero was also reduced for Design 3. Further aerodynamic simulations showed that having modified the cascade section, total reverse thrust was reduced by around 9% for both Design 2 and Design 3 as the exit pressures from the cascade, were reduced. Supersonic air speeds were eliminated from the nacelle section during reverse thrust due to the increase in area through the cascade which has the effect of reducing upstream airspeed. The risk of structural issues due to the occurrence of shock waves within the structure has therefore been reduced. This is the case for both of the reduced weight designs. Although levels of vane displacement and stress were significantly reduced for Design 2, optimum structural performance was achieved with the 10% weight reduction applied to Design 3. The maximum vane displacement on vane 10 was reduced by 64·31% and the maximum vane stress was reduced by 63·88%. Having already shown that the levels of vane displacement predicted for Design 1, had no affect on aerodynamic performance, it was concluded that no additional CFD analysis was required for Designs 2 and 3 because the levels of vane displacement were even less than those on Design 1.

This work has shown that total reverse thrust is maximised using the heaviest cascade configuration in Design 1, however, both of the reduced weight designs used for Design 2 and Design 3, show improvements in structural performance with significantly reduced levels of stress and deformation. The reduction in cascade weight will reduce operational costs as fuel consumption is reduced and the elimination of supersonic flow regimes is another benefit of the revised vane geometries. Ultimately, the decision as to whether or not the performance of the cascade has been enhanced will depend on a trade off between the higher levels of reverse thrust achievable with the heaviest Design 1, and the reduction in operational costs achievable with the lighter Designs 2 and 3. Although the reduced weight designs have shown improved structural performance, it would be important to consider the implications of the design changes on manufacturing costs, before the design is finalised.

5.0 CONCLUSIONS

Geometric and load data can be transferred between aerodynamic (Fluent) and structural (Patran/Nastran) simulations by re-formatting output from the structural analysis during post processing, to suit the Nastran neutral file format This is supported by both the aerodynamic and structural simulation packages.

For the cascade configurations and operational conditions used for this work, the resultant displacements on the cascade vanes had no affect on thrust reverser performance with total reverse thrust changing by 0·28% for the deformed case.

5% and 10% cascade weight reductions achieved by changing vane configurations, resulted in reductions in total reverse thrust of 8·9% and 9·1% respectively. This was due to the reduction in the exit pressure of the reversed air flow when the cascade configuration was changed.

The supersonic flow through the nacelle section with cascade Design 1, was eliminated after the 5% and 10% weight reductions were made by changing vane configurations. This reduction in upstream air speed is due to the change in area ratio between the cascade and the throat of the nacelle.

Structural performance was significantly improved for both of the reduced weight designs with reductions in both maximum vane displacement and mid-vane stress levels. Optimum structural performance was achieved with the 10% weight reduction.

The affect of any design changes on lifecycle cost and ease of manufacture will also have to be taken into consideration before any firm conclusions are drawn regarding the final cascade configuration

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