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Integrated Methods for the Design of a Thrust Reverser Cascade

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The design of a cascade box within a cold stream thrust reverser is studied with a view to establishing a methodology for the optimization of aerodynamic, structural, manufacturing, and cost parameters. Aerodynamic and structural simulations have been carried out for three different design configurations. When the weight of the original cascade design (design 1) was reduced by 5% (design 2) and then 10% (design 3) by modifying the vane configurations, it was found that although total reverse thrust was reduced by 9% for the reduced-weight designs, the structural performance of the cascade improved when compared to the original design. Cost analyses show that labor costs for the reduced-weight designs are reduced when compared to the original design, due to reduced casting times and improved component handling characteristics. Although material costs are lower for the reduced-weight designs, increased component complexity increases tooling costs. The total unit cost of cascade design 2 is 4.5% more than design 1, and the unit cost of design 3 is 0.14% higher than design 1. The increase in cost of two aircraft nacelle systems for a single aircraft using design 3 cascade boxes is $5.04. The increased expenditure on design 3 cascade boxes will be recovered in the first year of operation because the 10% weight reduction reduces operational cost by $260 over 12 months. Although only three cascade box configurations have been used, the methodologies developed will be equally applicable to further cascade designs or indeed any complex component where structural performance is a key requirement and multidisciplinary simulation is heavily used.

Introduction

IN an economic environment that shows no signs of rewarding performance, manufacturers must play their part in facilitating cost and development lead time reductions as well as profit maximization, in the aircraft industry. Any technology that reduces cost and time to market is of significant financial and strategic value to any aircraft manufacturer. Although cost reductions are possible with administrative, organizational or logistical improvements, the most effective financial savings can be made by technical developments.[1] Therefore, it is recognized that research spending can significantly aid the aerospace industry and shrink time to market.[2] This, in turn, offers opportunities for increased profitability (Fig. 1). Reduced product development cycles mean that an aircraft can enter the marketplace further upstream from the point where it becomes obsolete, thereby allowing opportunities for increased sales. When the point of obsolescence is eventually reached, relatively short product development lead times mean that aircraft manufacturers are in a position to react more quickly to any changes in the marketplace, and new aircraft can be introduced more efficiently.

The push by suppliers to reduce product development lead times must run simultaneously with the development of improved integration tools, otherwise final component efficiency could suffer resulting in heavier, less efficient aircraft. One area that has a significant bearing on both cost and time to market is the design process. Up to 80% of final component cost is determined during the conceptual design phase alone.[3] One way of lowering cost and time to market is to improve the product development process by using more efficient tools and methodologies for better simulation of component behavior.[1] Employing design tools such as finite element analysis (FEA) and computational fluid dynamics (CFD) will improve efficiency, but components that have been fully optimized in terms of aerodynamic and structural performance must also meet manufacturing and cost requirements. Good designs are worthless unless they can be manufactured efficiently, reliably, and within budget. By using costing software such as SEER™–DFM, the designer can make quick, accurate and early estimates of cost for a particular design scenario. By including manufacturing and cost considerations at all stages of product development, the designer can work easily within budget constraints and ensure that designs are fully optimized with minimum cost.

In the past, a lack of understanding of complex structural behaviors has meant that there has been a tendency to overdesign, which adds weight and increases cost. Compression of development flow times without the simultaneous improvement of integrated design tools could also lead to overdesigned, heavier structures. The development of fully integrated design methodologies using low-level models and analysis methods, including cost estimation, for use early in the design process, means that concept suitability can be determined relatively quickly. If simpler, lower level analyses can be used to eliminate unsuitable designs early on, then this will save time later in the design process when more complex analyses are carried out and changes become more expensive. Product development times and time to market will be reduced, thereby increasing profitability. A reduced-weight component, such as the cascade, will cost less, and the operational cost of the aircraft will also be reduced.

The thrust reverser cascade used for this work is currently manufactured in aluminium alloy by the process of investment casting. The vane configuration used was for a cascade box located on the outboard part of the nacelle where the airflow is directed back in the direction of aircraft movement. The number of cascade designs used to develop the design methodologies presented in this work is not exhaustive. The work represents a first step in the development of more efficient thrust reverser designs, where problems associated with the integration of key design technologies are addressed. The resulting integrated design methodologies can then be applied to new concepts that could, for example, examine the performance of cascade boxes on other areas of the nacelle where the reversed fan airflow is directed back and to the side, away from the fuselage. In this case, the added dimension to the air movement through the cascade would require a more complex, three-dimensional CFD model, resulting in the need for the transfer of greater quantities of data to the structural model. The basic principles of the design

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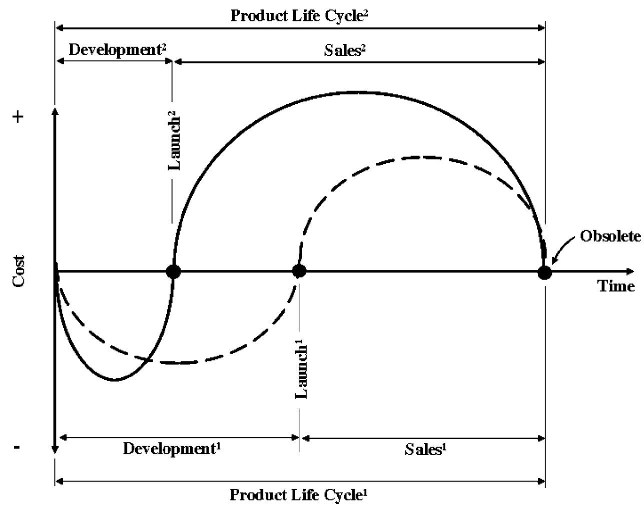


Fig. 1 Optimization of product life cycle to maximize profitability by reducing product development time: – – –, typical product life cycle and ——, optimized product life cycle.

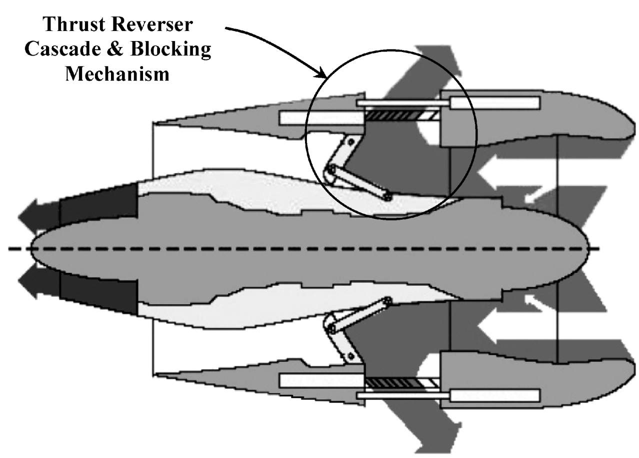


Fig. 2 Section through jet engine nacelle with cold stream thrust reverser operating in reverse thrust.

methodology would, however, be the same as those presented in this paper. The reduction of cascade vane numbers or the use of composite materials to reduce weight could also be examined as design alternatives. In these cases, the methodologies would also be the same in terms of the determination of structural and aerodynamic performance, as well as cost, but the geometry, material properties, and manufacturing methods would change.

In modern aircraft, the thrust reverser is an integral part of the nacelle system, and it uses the power of the jet engine as a deceleration force during landing, by reversing the direction of the airflow that generates forward thrust in flight. When reverse thrust is engaged (Fig. 2), the transcowl moves back and a blocking mechanism is introduced to the cold stream flow generated by the fan. The airflow is redirected through a series of cascade boxes placed circumferentially around the nacelle, forcing the flow back in the direction of aircraft movement, thereby reducing speed. The key design requirement for the thrust reverser is that it must be compatible with the engine in terms of managing reversed airflows safely and efficiently so that it can satisfy the stopping requirements for the aircraft.

Vane configurations vary depending on where the cascade is located on the engine nacelle. Although their primary function is to reverse the airflow coming through the nacelle from the fan, it is important that the reversed flow does not interfere with other aspects of aircraft performance. When the air flow exits the nacelle, it must be managed by and directed through the cascades, to avoid[4] the following problems: 1) engine stability problems due to reingestion of reversed flows, including surge, stall, inlet distortion, and noise; 2) foreign object damage to turbomachinery as reversed airflow lifts ground debris into the inlet flow; 3) efficiency losses on control surfaces if flow characteristics around the aircraft are changed; 4) vibration and deterioration of surface finish due to impingement of reversed airflows on aircraft surfaces; and 5) control issues resulting from buoyancy due to reversed flow from engines mounted on opposite sides of the aircraft, meeting below the fuselage.

Thrust reversers significantly affect nacelle design increasing weight and resulting in higher manufacturing and operational costs. Thrust reverser systems can account for up to 30% of total nacelle weight (not including engine),[3] and this added weight can increase fuel consumption by up to 2% (Ref. 4). Despite the disadvantages, thrust reversers offer several operational benefits. These include reduced landing runs, which allow the use of shorter runways and can increase airport throughput. The use of wheel brakes is reduced, which prolongs component life, reduces tire wear, and decreases the time that operators must wait for braking systems to cool down after use.[4] Safer landings can be achieved on wet, icy, or snow-covered runways where wheel breaks can have difficulty achieving traction. Thrust reversers can also provide additional safety and control margins for aircraft operation during takeoff, landing, and movement on the ground.

The high pressures and airspeeds within the nacelle system during reverse thrust can lead to supersonic and turbulent flow regimes within the structure and through the cascade. These factors can lead to issues with the strength and durability of nacelle components. Typically the various disciplines involved in aerospace product design and development are well equipped to iterate through multiple designs within their respective fields. The mechanisms for cross discipline iteration are less common, and they can be difficult to implement due to the nature and make up of the data that need to be integrated. Schedule pressures and organizational problems can also raise issues because a finished nacelle design may require inputs from several departments within a single organization or from a number of suppliers operating on different sites.

In this paper CFD, FEA, and cost-estimation methods have been used to illustrate how the design process for a cascade within a thrust reverser can be made more efficient. Previous work focused on the development of effective and efficient methodologies for the structural analysis of a thrust reverser cascade. Methodologies have been identified for the aerodynamic and structural analysis of the cascade.[5] Static pressure loadings on the vanes have been determined using realistic operating conditions in a two-dimensional CFD simulation. These pressure loadings were transferred and used for structural analyses, which have shown that beam, shell, and solid elements can effectively determine displacement levels on the cascade vanes. The methodologies identified for the design of a thrust reverser cascade have been used to reduce the weight of the cascade. Two-dimensional CFD and Three-dimensional FEA simulations have been linked so that the effect of deformed cascade geometry on aerodynamic performance could be determined. The effects of weight reduction achieved by varying cascade vane configurations have been examined in terms of aerodynamic, structural, manufacturing, and cost parameters.

The main aim of this work is to determine concept suitability using a fully integrated approach to the design of a thrust reverser cascade (Fig. 3). The approach includes aerodynamic, structural, manufacturing, and cost considerations.

Methodology

The starting point for the simulation of cascade performance was a CAD model for a Bombardier Aerospace, Shorts, thrust reverser design. A two-dimensional representation of the cascade region was extracted from a three-dimensional solid model of the nacelle. It has already been stated that vane configurations vary around the nacelle depending on where the cascade is located. For this work, the geometry used was representative of a cascade box located on the outboard side of the engine where the reverse airflow is simply thrown back in the direction of aircraft movement. The methodologies developed for this geometry are equally applicable to cascades located elsewhere on the nacelle. The two-dimensional CAD data were used as the starting point for both the aerodynamic simulation

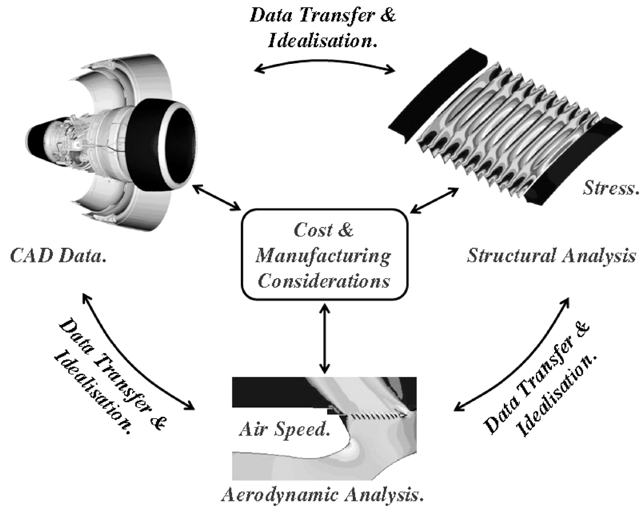
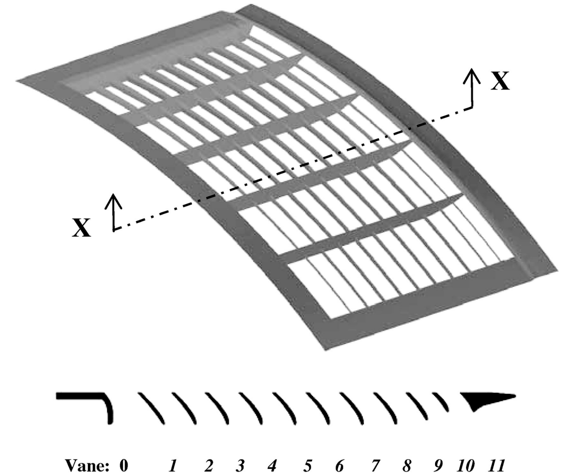


Fig. 3 Design of thrust reverser cascade using integrated, multidisciplinary approach.

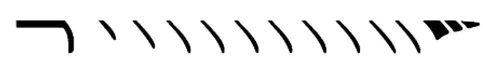
and the structural analysis. The aerodynamic simulation was carried out first using FLUENT to determine the loads on each of the vanes in the cascade for a realistic set of operating conditions. Structural models were then set up in PATRAN using, three-dimensional solid element representations of the cascade. The models were analyzed using NASTRAN. Cost analyses were carried out for each design configuration using SEER–DFM, which is an estimation and analysis tool that allows the designer to evaluate and manage the complex array of cost, labor, assembly, process, part design, and production variables that affect manufacturing operations. When used in parallel with other simulation methods, costing tools such as SEER–DFM can show how design and process decisions will affect production and final component cost. SEER–DFM was developed by the Galorath Corporation to predict and estimate the costs related to manufacturing activities primarily, in the aerospace industry. It is based on a parametric estimating methodology driven by a vast number of cost-estimating relationships. These relationships have resulted from detailed studies looking at the main factors that drive the costs associated with manufacturing activities. The cornerstone of the program is a series of knowledge bases for various manufacturing processes. Each knowledge base is a repository of data describing technology, environment, size, difficulty, and constraints of a particular development attribute.

When the deformed shape of the cascade vanes shown in Fig. 4a had been determined, a finite element model that was generated using three-dimensional solid elements was used to extract a deformed, two-dimensional cascade section so that the CFD analysis could be repeated. The purpose of this was to determine changes in aerodynamic performance when the vanes were displaced by the operational pressures. This showed that, for the original set of cascade design parameters, the vane deformations had a minimal effect on thrust reverser performance, thereby illustrating that there is, in fact, scope for reducing the weight of the cascade box without significantly affecting aerodynamic and structural performance.

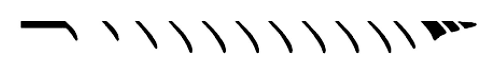
When the aerodynamic and structural performance of the original cascade section, known as design 1 (Fig. 4a) was examined, the vane configuration was changed to determine the effects of cascade weight on aerodynamic and structural performance, as well as manufacturability and component cost. Both of the design changes involved making the vanes in the high-pressure areas toward the right of the cascade larger and heavier and making the vanes in the low-pressure areas to the left smaller and lighter. The main purpose of this change was to improve structural performance by lowering maximum stress and displacement levels in areas with high operational pressures. Two slots were also introduced through vane 11. This has the effect of reducing the pressure build up that was predicted at this point, and the net effect was a reduction of 5% in weight for design 2 (Fig. 4b) and a reduction of 10% for design 3 (Fig. 4c).



a) Cascade design 1, original



b) Cascade design 2, 5% weight reduction



c) Cascade design 3, 10% weight reduction

Fig. 4 Section 20 through thrust reverser cascade for three design options.

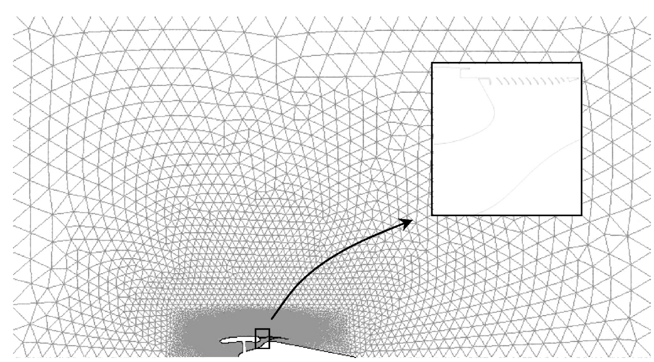


Fig. 5 Axisymmetric CFD mesh used to simulate aerodynamic conditions within nacelle section.

The following sections detail how the various simulation models were set up for the purpose of determining cascade performance parameters.

Procedure

Aerodynamic Model: FLUENT

An idealized, axisymmetric representation was used to simulate the aerodynamic performance of the thrust reverser when it was fully opened (Fig. 5). Each cascade configuration was analyzed for operating conditions that resulted from a freestream flow speed of Mach 0.2 and a temperature of 288 K. The pressure inlet condition was set at a total pressure P_t to ambient pressure P_a ratio of 1.4 and a total temperature of atmospheric temperature plus 40°C. The FLUENT CFD flow solver was used to simulate the time-dependent, viscous, compressible flows through the model representing the thrust reverser.[6] The governing equations were solved by FLUENT using the finite volume method. The system of equations used was cast integral for an arbitrary control volume V, with differential surface area A, as follows:

$$\frac{\partial}{\partial t}\int_V \boldsymbol{W}\,\mathrm{d}V + \oint [\boldsymbol{F} - \boldsymbol{G}]\cdot \mathrm{d}A = 0 \qquad (1)$$

where the vectors $\boldsymbol{W}$, $\boldsymbol{F}$, and $\boldsymbol{G}$ are defined as

$$\boldsymbol{W} = \begin{Bmatrix} \rho \\ \rho u_x \\ \rho u_r \\ \rho E \end{Bmatrix}, \qquad \boldsymbol{F} = \begin{Bmatrix} \rho \boldsymbol{u} \\ \rho \boldsymbol{u} u_x + p\boldsymbol{i} \\ \rho \boldsymbol{u} u_r + p\boldsymbol{j} \\ \rho \boldsymbol{u} E + p\boldsymbol{u} \end{Bmatrix}, \qquad \boldsymbol{G} = \begin{Bmatrix} 0 \\ \tau_{xi} \\ \tau_{ri} \\ \tau_{ij} u_j + q \end{Bmatrix}$$

Here ρ, $\boldsymbol{u} = (u_x, u_r)$, 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

$$E = H - p/\rho \tag{2}$$

where

$$H = h + |\boldsymbol{u}|^2/2 \tag{3}$$

The Reynolds-averaged approach with the renormalization group (RNG) k–ε model has been used to model the effect of turbulence. The RNG k–ε model is derived from the instantaneous Navier–Stokes equations, using the RNG mathematical technique. 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.

Structural Model: PATRAN/NASTRAN

Geometry and Mesh

The structural models representing the cascade were constructed in PATRAN using three-dimensional solid elements and analyzed using NASTRAN. Earlier work showed that higher levels of geometric idealization used with shell and beam element representations of the cascade meant that the outputs from these model types was not as suitable for translation to a form that could be reused in the CFD model.[5] Each structural model represented a 20-deg cascade section (Fig. 6).

Load Application

The results from the two-dimensional aerodynamic analysis yielded a load distribution for the cascade that took the form of a resultant pressure for each of the nodal positions around the perimeter of the individual vanes (Fig. 7). 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 idealized to the simplified linear forms shown in Fig. 7.

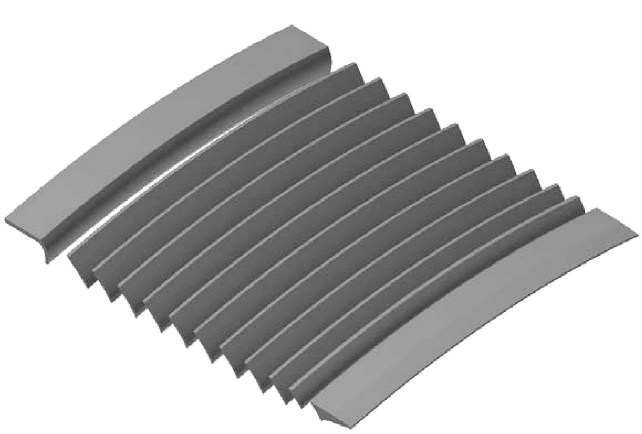


Fig. 6 Representation of cascade vanes using three-dimensional solid elements.

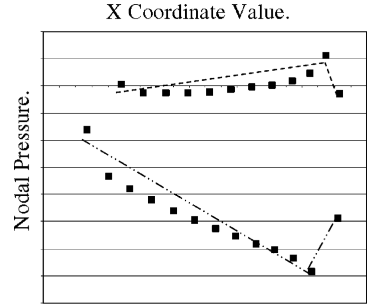


Fig. 7 Typical static pressure distribution around single cascade vane: ■, load profile from aerodynamic analysis; - - - -, idealized load profile, top vane surface; and —··—, idealized load profile, bottom vane surface.

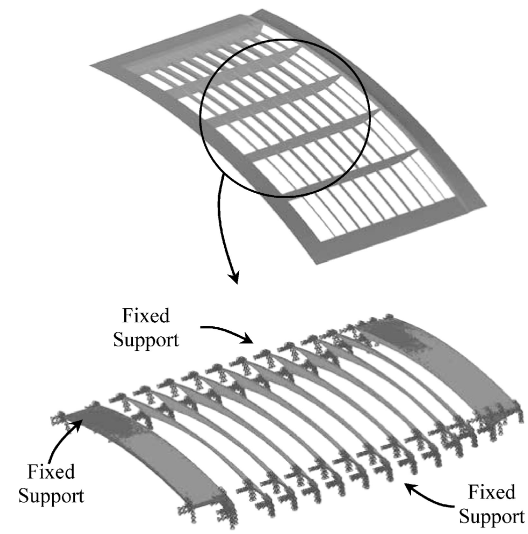


Fig. 8 Support detail for structural model representing 20-deg section of thrust reverser cascade.

Support Conditions

The cascade model was fully restrained at the point where it is joined to the rest of the nacelle assembly. Fixed supports were applied to the areas where the symmetrical idealizations were made (Fig. 8). These simulated the supporting affect of the transverse supports between the cascade vanes.

Material Properties

The structural analyses were carried out using the material properties for an aluminium alloy with a Young's modulus of 72 GPa and a density of 2790 kg/m^3.

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 (vane numbers in Fig. 4). 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 buildup around vane 11. Note that the results for the aerodynamic and structural analyses will be outlined in greater detail in the results section.

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 buildup. 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 also 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.

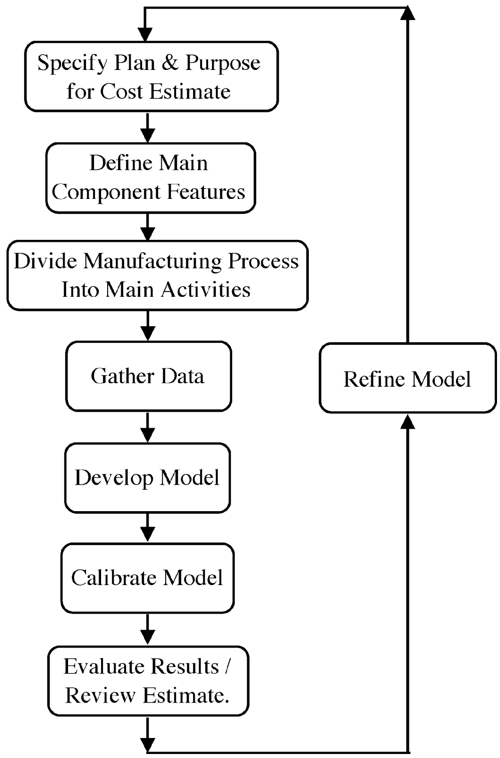


Fig. 9 Preliminary activities required for development of cost model in SEER–DFM.

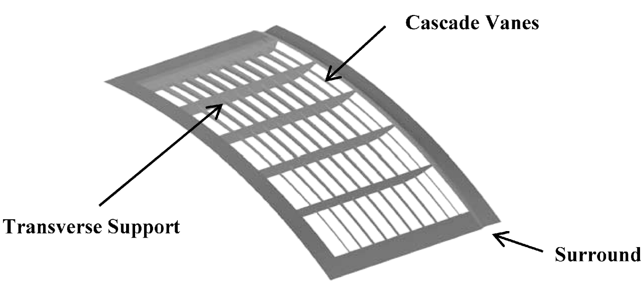


Fig. 10 Main features for cascade box.

Cost Modeling: SEER–DFM

Figure 9 shows a summary of the main steps required for the preparation of a cost model using SEER–DFM. The cost model is based on the parametric costing technique, which, for example, relates cost as a dependant variable to a number of design parameters that are treated as independent. This is typically carried out by using multiple linear regression in developing the costing algorithms. Each step is described briefly in the following sections.

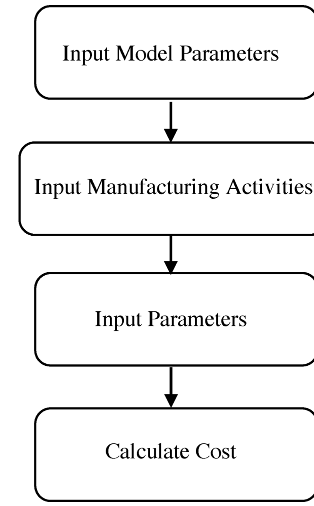
Specify Project Plan and Purpose

A clear understanding of any problem is the first step in its solution. The purpose of this exercise is to identify potential design improvements that will lead to a more cost-efficient design. This will be achieved by examining the effects of weight reduction on component performance with the primary method of manufacture being investment casting. The weight-reduction strategy is driven by simulated results for aerodynamic and structural performance.

Define Component Features

The main design features of a cascade box are the individual vanes, the transverse supports, and the surround (Fig. 10). Other features relevant to the task of costing the component are overall size, weight, etc.

Fig. 11 Steps required to develop cost model using SEER–DFM.



Divide Component Manufacturing Process into Separate Activities

The manufacturing process for any component can be modeled by the superposition of subprocesses using a rollup feature within SEER–DFM. This makes the cost estimate more transparent because the overall cost can be viewed as the sum of the individual subprocess costs. Costs are added at a rollup level allowing the designer to observe subsystem costs and their effects. The manufacturing processes that have been included in the cost model for the thrust reverser cascade include investment casting, rough shape machining, surface finish machining, and drilling.

Gather Data

To complete a cost estimate, the designer must input data relevant to the component and its manufacture. This includes the material, processing, and labor costs associated with the component features and manufacturing activities identified earlier. This needs to be as realistic and accurate as possible because, as is the case with any simulation method, the quality of the end result is only as good as the information used to obtain it. Consequently, this is one of the most difficult and important tasks associated with cost estimation using SEER–DFM.

Develop the Model

With the completion of the preliminary activities described in the preceding sections, the cost model can now be constructed using the steps outlined in Fig. 11.

Calibrate the Model

Calibration or validation is very important when using simulated data for any purpose. The cost for a component (or an activity used during its manufacture) determined using SEER–DFM can be calibrated using the cost of an existing component (or activity). The impact of any design changes can then be compared to this benchmark.

Evaluate and Review Estimate

The evaluation and review process is also important when using simulated data for decision making. Human input based on experience in a particular field and knowledge of project restraints is required for the identification of unrealistic data and unsuitable results. Engineering managers, cost estimators, and system experts must play their parts in this process.

Refine the Model

In the event that an estimate is unrealistic or unworkable, due to errors or the use of unrealistic data, the cost model has to be refined.

Cost Model for Thrust Reverser Cascade

For the purposes of this work, it has been assumed that the nacelle system has a total of nine identical cascade boxes extending to 342 deg around its circumference. In reality, the cascade vane configuration changes depending on where it is located on the nacelle for the reasons explained earlier. The final cascade design will be manufactured as part of a batch intended for use in a production run of 50 aircraft, which gives a total cascade box requirement of 900 units.

Cost estimates were obtained for the three cascade designs detailed in Fig. 4. Designs 2 and 3 have a comparable level of geometric complexity, and they will be more difficult to manufacture than the simpler design 1. All three designs have similar dimensional proportions, but their manufacturing and weight characteristics are different. Overall weight will influence material content, and manufacturability will affect tooling and labor costs.

Results

Aerodynamic Analysis

Mass Flow Rate Through Nacelle Section

Figure 12 shows a comparison of the mass flow rates obtained for the three cascade design configurations. The modifications to the cascade section in designs 2 and 3 have resulted in a minor reduction in the total mass flow through the system.

Static Pressure Distribution Through Nacelle Section

Figure 13 shows the static pressure distribution through the nacelle section and around the cascade vanes for designs 1 and 3. The higher pressures, indicated by the darker contours, occur to the right of the section where the airflow is physically blocked and redirected through the cascade. Note the area of low pressure associated with the separation of flow, on the original design (Fig. 13a).

Similar plots were obtained for designs 2 and 3 (Fig. 13b), using the same operational conditions; however, the exit pressures radially, outboard of the cascade, are lower than those obtained 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. The static pressure distributions for the separate design configurations were transferred and used in the structural models.

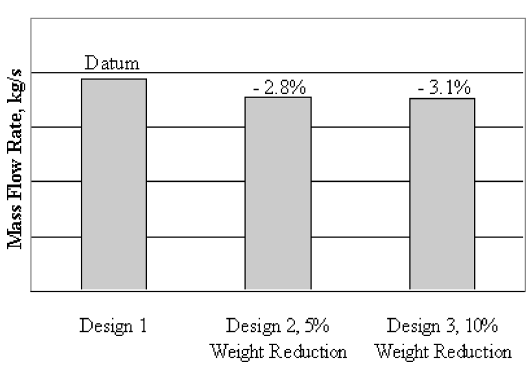


Fig. 12 Comparison of mass flow rate for three cascade configurations.

Total Reverse Thrust

Figure 14 shows how total reverse thrust dropped by only 0.28% when the deformed cascade geometry was used to reexamine 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 14 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 15 shows the effects of vane deformation on the static pressure distribution on vane 1 for design 1. Similar plots were obtained for the other vanes in the cascade where the pressures differed in magnitude.

Figure 15 shows that the pressure distribution around the vane is similar for the undeformed and deformed cases. This result, as well as the fact that the total degree of reverse thrust changed only by 0.28%, means that, for the conditions tested, there is no significant change in thrust reverser performance when the cascade vanes are deformed during reverse thrust.

Airspeed Through Nacelle Section

Figure 16 shows airspeed through the nacelle for cascade designs 1 and 3, with the thrust reverser engaged. Airspeeds above Mach 1 have been highlighted in Fig. 16a and this shows that supersonic speeds are reached within the nacelle during reverse thrust. The airspeeds shown are similar for the reduced-weight designs, but

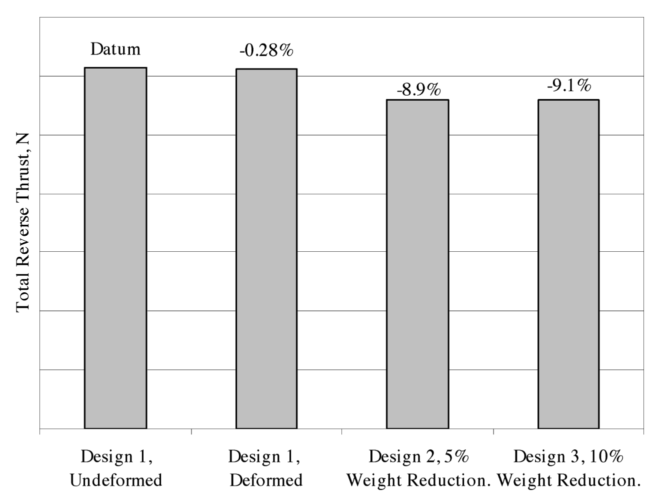
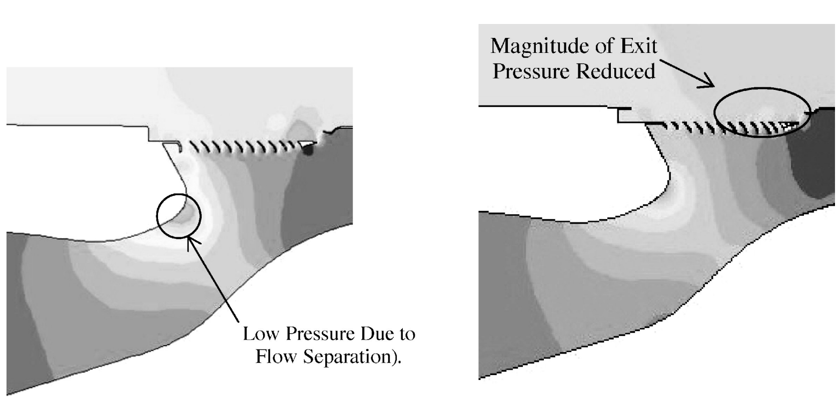


Fig. 14 Comparison of total reverse thrust for three cascade configurations.



a) Design 1, original **b) Design 3, 10% weight reduction**

Fig. 13 Static pressure distribution through nacelle section for designs 1 and 3.

the maximum airspeed through the nacelle section is subsonic for both designs 2 and 3 (Fig. 16b). This means that there is a reduced risk of the nacelle structure being subjected to the shock waves associated with the supersonic conditions predicted for design 1. The reduction in the upstream airspeed for the two new designs is due to the increase in the area ratio between the cascade and the throat of the nacelle, which causes the change in mass flow rate shown in Fig. 12.

Structural Analysis

Deformation

Figure 17 shows the deformations predicted for design 1 using the operational pressures shown in Fig. 13. The maximum displacements have been highlighted, and they 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, this outcome influenced the vane configurations used for designs 2 and 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 1–3 are in Fig. 18. The larger vane sections used for designs 2 and 3 have lead to significant reductions in the maximum vane displacement when compared to design 1.

Stress

Figure 19 shows the Von Mises stresses predicted for design 1 using the operational pressures shown in Fig. 13. The maximum midvane stresses have been highlighted, and they correspond to the areas of high pressure as predicted by the aerodynamic analysis. In all three cases, the maximum midvane stress occurs on vane 10, which has the smallest section of all of the cascade vanes. The maximum midvane stresses for designs 1–3 are in Fig. 20. Again, the larger vane sections used for designs 2 and 3 have lead to significant reductions in the maximum vane stress when compared to design 1.

Cost Modeling

It has not been possible to use the actual costings for the material, tooling, and labor used to manufacture the cascade boxes, on the grounds of confidentiality. The results presented in the following sections illustrate the percentage differences in between the various design scenarios, which allows the assessment of the relative merits of each configuration in terms of cost, so that each design can be ranked. Cost can, therefore, be considered alongside structural and aerodynamic performance when considering these early concepts.

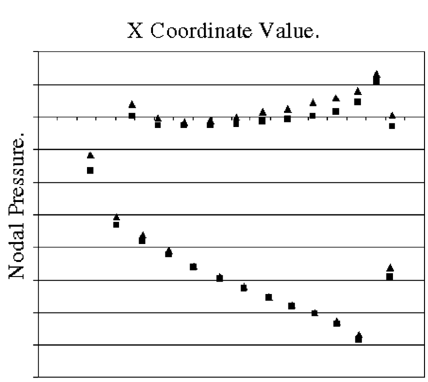


Fig. 15 Comparison of pressure distribution around vane 1 for undeformed and deformed cascade geometry: ■, undeformed and ▲, deformed.

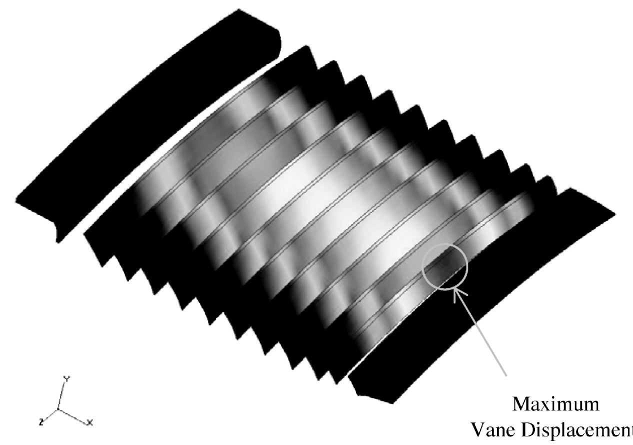


Fig. 17 Cascade box, design 1: displacement contours.

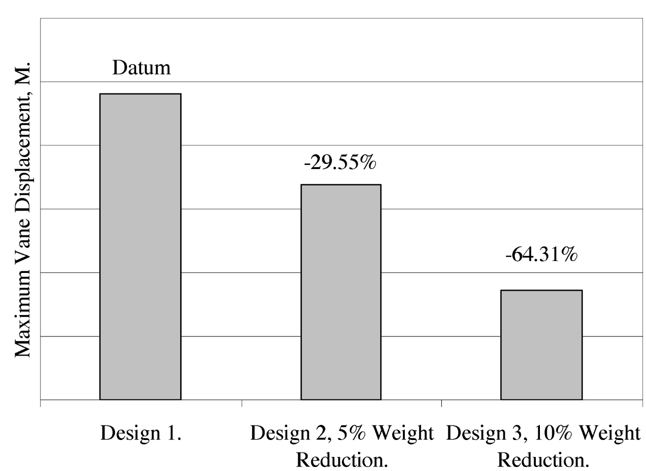
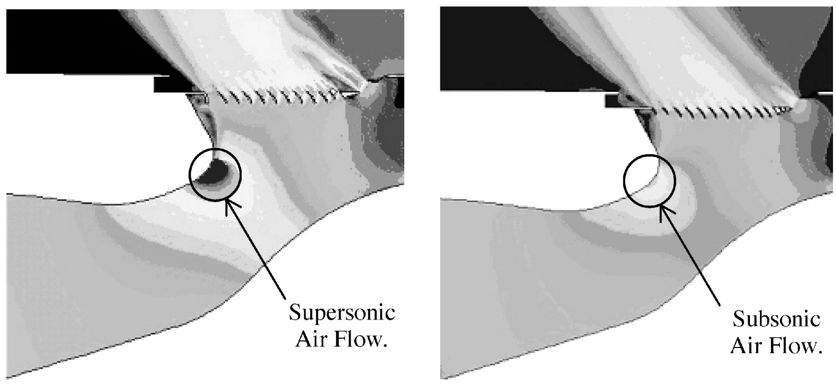


Fig. 18 Comparison of maximum vane displacement for three cascade configurations.



a) Design 1, original **b) Design 3, 10% weight reduction**

Fig. 16 Airspeed contours through nacelle section for designs 1 and 3.

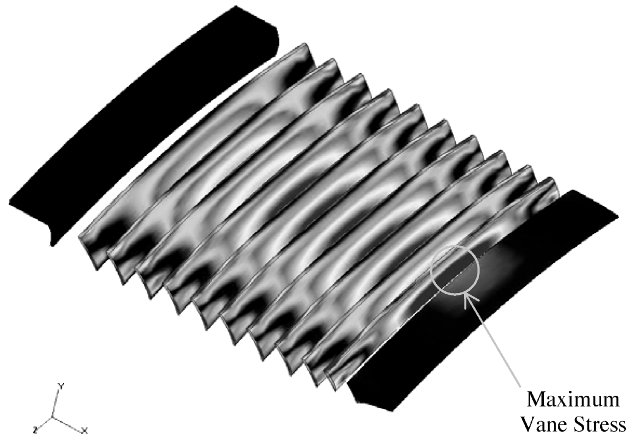


Fig. 19 Cascade box, design 1: Von Mises stress contours.

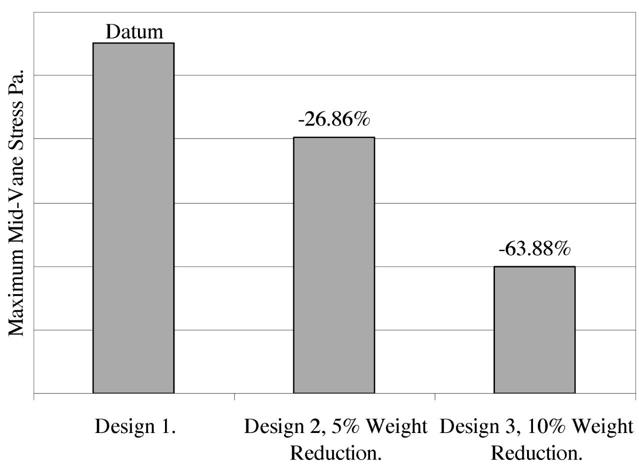


Fig. 20 Comparison of maximum midvane stresses for three cascade configurations.

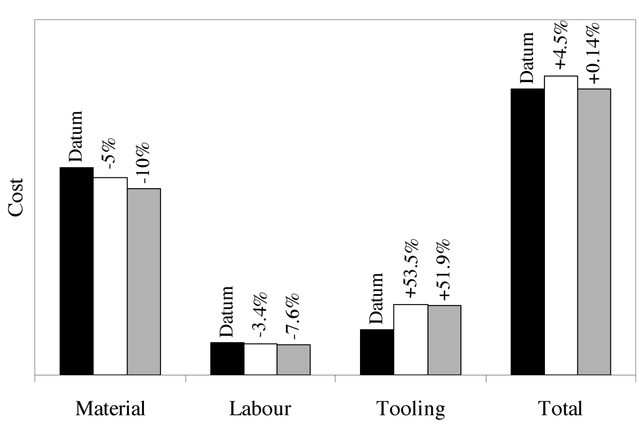


Fig. 21 Cost breakdown for three cascade configurations: ■, design 1; □, design 2; and ■, design 3.

Material Cost

As expected, the material costs for designs 2 and 3 are lowered in line with the percentage decrease in material content brought about by the change to the vane configuration (Fig. 21). The material cost for a single cascade box is reduced by 5% for design 2 and 10% for design 3.

Labor Cost

The labor costs for designs 2 and 3 are slightly lower than that for design 1 (Fig. 21). The labor cost for a single cascade box is reduced by 3.4% for design 2 and 7.6% for design 3. These reductions are a direct result of the weight reduction. Lighter components will take less time to pour because they are cast and cooling time is also lower. Weight reduction also makes transport and handling easier, and setup times are reduced.

Tooling Cost

The tooling costs for designs 2 and 3 are significantly higher than that for design 1 (Fig. 21). The addition of two slots through vane 11, the introduction of heavier vanes in high-pressure areas, and the use of lighter sectioned vanes in low-pressure areas make designs 2 and 3 more geometrically complex when compared to design 1. This added complexity significantly increases tooling cost. The tooling cost for a single cascade box is increased by 53.5% for design 2 and 51.9% for design 3. The slight difference between the tooling cost for designs 2 and 3 can be explained by the weight difference, which makes design 3 easier to handle thereby reducing setup time.

Total Unit Cost

With similar labor costs for all three designs, the difference in unit cost between each is a result of the tradeoff between lower material cost as weight is reduced and increased tooling cost as the cascade design becomes more complex. The cost of a cascade box increases by 4.5% for design 2 (Fig. 21), where the increase in tooling cost is not offset by the material saving. The cost of design 3 has also increased, but this time by only 0.14%.

Sources of Error

Aerodynamic Simulation

Experiments have been carried out on a 40% scale, 30-deg sector model of the Bombardier Aerospace, Shorts, thrust reverser design.[6] For the case where the thrust reverser was fully opened, the results showed that the resultant axial force (level of reverse thrust) on the transcowl was within 7.5% of the value predicted using the CFD simulation. This showed that the pressures extracted from the aerodynamic simulation for use in the structural model were reasonably accurate. One reason for the difference between the experimental and simulated results is the use of an axisymmetric CFD model to simulate a three-dimensional fan airflow, which would include swirl effects not included in the two-dimensional model parameters. 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 that 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 and 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.

Structural Simulation

Earlier work[5,7] has shown that the combined effects of various idealizations used on beam, shell, and solid element structural models result in predicted cascade vane displacements that are within a 4% results margin. For this work, three-dimensional solid elements were used for the structural models because of the ease with which displacement data could be extracted from the NASTRAN output files for reuse in the CFD model.

A benchmark test carried out on a simply supported beam model using identical material, geometry, and load data showed that the displacements predicted using beam, shell, and solid element types are within 0.3% of the value obtained using theoretical calculations. The use of beam, shell, or solid element types in themselves does not introduce significant errors to a structural analyses. This applies as long as the aspect ratio (length:width:height) of the structure is suited to representation by a particular element type, as was the case with the idealized solid element models representing the cascade vanes.

The maximum vane displacements predicted using the idealized, 6-point load distributions on the shell models differed by less than 5% when compared to the values obtained using the full 25-point load distribution.

Cost Modeling

Calibration or validation is very important when using simulated data for any purpose. Cost estimates generated as part of this work were compared to actual costing data provided by Bombardier Aerospace, Shorts. The cost predicted by SEER–DFM for a drilling operation was found to be within 3% of the actual cost of the same operation in a manufacturing environment, which is acceptable.

Discussion

The cost reductions achievable by using leaner designs for aerospace components are one of the practical motivations behind this work. Further benefits can be achieved by making the design process itself more efficient by using an integrated, multidisciplinary approach. Although the cascade within a jet engine thrust reverser has been chosen as the subject for this work, the methodologies developed are equally applicable to any complex component where structural performance is a key requirement and multidisciplinary 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, looking at the blocker configuration and nacelle throat section with a view to turning the reversed airflows more efficiently, or examining the use of alternative materials for thrust reverser components such as the vanes. In essence, the design methodologies in all of these cases would be the same in terms of the determination of structural and aerodynamic performance, as well as cost, but the geometry, material properties, and manufacturing methods would change.

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 behavior of the undeformed 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.

Previous work has shown how the structural and aerodynamic models representing a thrust reverser cascade could be linked so that its performance could be examined using deformed vane geometry.[5] Total reverse thrust decreased by 0.28% for the deformed case showing that aerodynamic performance was not significantly affected by the levels of displacement on the vanes for the conditions tested. With the deformation of the cascade vanes having minimal effect on thrust reverser performance, it was concluded that there was scope for changing the cascade design to reduce weight.

Two additional designs involving minor changes were devised, which used different vane configurations, to reduce the overall weight of the thrust reverser cascade. The pressure distribution predicted for the original design 1, influenced the new designs. Smaller vane sections were used in low-pressure areas, and larger vane sections were used in high-pressure areas. Aerodynamic simulations were carried out on the reduced-weight designs for the same operating conditions used for design 1. When the cascade weight was reduced by 5% and then 10% by modifying the vane configurations, it was found that total reverse thrust was reduced by around 9% for both designs 2 and 3. Despite this drop in overall performance, supersonic airspeeds were eliminated from the nacelle section during reverse thrust, for both of the reduced-weight designs. This means that the probability of any structural issues due to the occurrence of shock waves within the structure had been reduced.

Structural performance was significantly improved for both of the reduced-weight designs with reductions in both maximum vane displacement and midvane stress levels. 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%. With the knowledge 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 predicted for Design 1.

Good designs are worthless unless they can be manufactured efficiently, reliably, and within budget. Cost analysis has been used to determine the effect that design changes have on the final cost of the thrust reverser cascade. The results of the cost analyses show that labor costs are roughly equivalent for all three cascade designs.

As expected, the material cost per unit was lower for the more complex, reduced-weight designs. As expected, the 10% weight reduction in design 3 resulted in the greatest saving of 10% when compared to design 1.

The labor cost per unit for the reduced-weight designs was slightly lower than that for design 1 due reduced casting times and improved component handling characteristics. Design 3 resulted in the lowest labor cost per unit, with a 7.6% saving compared to design 1.

Increased component complexity with designs 2 and 3 has resulted in higher tooling costs. Design 2 was 53.5% more expensive per unit than design 1 and design 3 was 51.9% more expensive. Although the unit cost of design 3 is only slightly higher than that for design 1, the results show that to offset the higher tooling costs brought about by more complex design the material content needs to be reduced by more than 10% before the cost per unit starts to come down.

A decision on the final cascade design will involve a tradeoff between the improved physical performance and lower life cycle costs achievable with the reduced-weight designs and the higher degree of reverse thrust available with the heavier, original design that costs less to produce. In either case, the use of an integrated approach to the design process will allow the designer to make more informed design choices quickly, thereby reducing product development times.

Ideally, a reduced-weight, lower cost design would be preferred. Design 3 costs 0.14% more to manufacture than the original design. This will increase the manufacturing cost of the nacelle system (containing 18 cascade boxes) for single aircraft by $5.04. The financial saving per kilogram of weight reduction will vary according to aircraft type and mission but if it is assumed that a 1-kg saving in the weight of an aircraft will reduce operating costs by $100 per year,[8] then a 10% weight reduction in a single cascade box will result in an annual saving of $260. The thrust reverser only operates for a fraction of the operational lifetime of an aircraft; therefore, its operational efficiency tends not to be a major issue.[9] Current economic conditions mean that cost reductions remain a priority. Although total reverse thrust is reduced by 9% using design 3, its higher unit cost can be recovered in less than a year after the aircraft has gone into operation. This design also offers improve structural characteristics when compared to the original design.

It has already been stated that the number of configurations used to determine an integrated approach to the design of a thrust reverser cascade was not exhaustive. In this case, two additional vane configurations were examined with a view to reducing weight. The effect of these changes were then determined in terms of aerodynamic, structural, and cost performance. Although the new designs were lighter with improved structural properties, the aerodynamic performance of the cascade was reduced in terms of the level of reverse thrust. Another possible approach to cascade design would be to examine cost weight tradeoffs that maintain the level of reverse thrust as well as the level of fan bypass airflow while taking into account wider structural issues such as airframe requirements. The methodology presented in this paper would also be applicable to this approach.

Conclusions

Previous work has shown that having reduced the weight of an original cascade design (design 1) by 5% and then 10% by modifying the vane configurations reduces total reverse thrust by 9% (Ref. 4).

Levels of vane displacement and stress are significantly reduced for these reduced-weight designs.[4]

The material cost per unit for design 2 was 5% lower than the cost of the original configuration, design 1, and the material cost per unit for design 3 was 10% lower.

The labor cost per unit for the reduced-weight designs was slightly lower due reduced casting times and improved component handling characteristics. The unit labor cost for design 2 was 3.4% lower and the unit labour cost for design 3 was 7.6% lower than the cost of the original configuration, design 1.

Increased component complexity for the reduced-weight designs resulted in higher tooling costs. The unit tooling cost for design 2 was 53.5% higher and the unit labor cost for design 3 was 51.9% higher than the cost of the original configuration, design 1.

The total unit cost for design 2 was 4.5% higher than design 1, and design 3 was 0.14% more expensive. The increase in cost of two aircraft nacelle systems for a single aircraft (containing 18 cascade boxes) will, therefore, be $5.04. With a 1-kg weight saving resulting in a $100 per year reduction in operational cost,[6] increased expenditure on design 3 cascade boxes will be recovered in the first year of operation because the 10% weight reduction reduces operational cost by $260.

References

[1]Broede, J., "Saving Costs in Design, Manufacturing and Operation of Aero Engine Parts," *Aeronautical Journal*, Vol. 105, Nov. 1053, pp. 619–626.

[2]Sietzen, F., "Call to Arms for an Ailing Industry," *Aerospace America*, Vol. 41, No. 3, March 2003, pp. 30–34.

[3]Raju, J., "A Conceptual Design and Cost Optimisation Methodology," AIAA Paper 2003-1505, April 2003.

[4]Trapp, L. G., and Olivera, G. L., "Aircraft Thrust Reverser Cascade Configuration Evaluation Through CFD," AIAA Paper 2003-0723, Jan. 2003.

[5]Butterfield, J., Yao, H., Price, M., Armstrong, C. G., Raghunathan, S., Riordan, D., and Cathers, G., "Methodologies for Structural Optimisation of a Thrust Reverser Cascade Using a Multidisciplinary Approach," AIAA Paper 2003-0107, Jan. 2003.

[6]Yao, H., Benard, E., Cooper, R. K., and Raghunathan, S., "Aerodynamics of Natural Blockage Thrust Reverser," *Proceedings of the 9th Aerodynamics Symposium*, Canadian Aeronautics and Space Institute, Montreal, April 2003.

[7]Butterfield, J., Yao, H., Benard, E., Price, M., Cooper, R., Monaghan, D., Armstrong, C. G., and Raghunathan, S., "Investigation of Weight Reduction in a Thrust Reverser Cascade Using Aerodynamic and Structural Integration," AIAA Paper 2003-1576, April 2003.

[8]"International Review of Aircraft Interior Design and Fitting Out," *Aircraft Interiors International*, March 2000.

[9]Chuck, C., and McCarthy, D. R., "Computer Simulation of Thrust Reversers Reduces Testing, Enhances Performance and Reliability," FLUENT Article No. JA134, Fluent, Inc., Lebanon, New Hampshire.