OVERVIEW ON THRUST REVERSER DESIGN

Santin, Marco Aurélio; Barbosa, João Roberto; Bontempo, Luciano Porto; Silva, Franco Jefferds dos Santos
Grupo de Turbinas - CTA/ITA/IEM - CEP 12.228-900 - FAX: +55-12-3947-5967
marcoabs@ita.br

Jesus, Antonio Batista; Trapp, Luis Gustavo; Oliveira, Guilherme Lara
EMBRAER -Empresa Brasileira de Aeronáutica S.A.
antonio.jesus@embraer.com.br

Abstract. *Aircraft landing speed is usually high. Efficient braking system is essential. The braking system is improved with the use of thrust reversers. The higher the landing speed the higher thrust reverser efficiency is required. In adverse conditions, like wet and icy runways, when deceleration of the aircraft with the wheel brakes becomes poor, thrust reverser utilization is a must. In order to acquaint with the thrust reverser technology and design, a literature review was carried out aiming at the cascade-type thrust reverser. A design methodology was defined that is adequate for a cascade module design. To account for the total needed thrust reverser drag (braking force), several cascade modules may be assembled, directing the outflow to different directions, avoiding re-ingestion and contact with the aircraft surfaces.*
Example of thrust reverser cascade calculation and total braking force is presented.

Keywords: *Reverser, thrust, cascade, CFD, boundary condition.*

1. Introduction

The study of thrust reversers reported here is within the scope of design and grid generation for thrust reverser CFD analysis developed at ITA. This paper deals with the proposition of a procedure for the aerothermodynamic design of a module of a cascade thrust reverser.

2. Literature review

As early as the 1950's, a research program was inaugurated at the NACA Lewis Laboratory to isolate the more promising concepts of thrust reversers and to investigate its performance characteristics, as presented by Povolny, Steffen and McArdle (1957). Dietrich (1975) published some papers showing experimental tests that evaluated the influence of several thrust reverser installations parameters. A research on airline industry was made to find out the advantages and disadvantages of the use of thrust reverser on commercial transport airplanes by Yetter (1995). Johns (2000) showed the solution of an engine inlet compatibility problem in a C-17 aircraft by CFD analysis. Recently the NASA Innovative Thrust Reverser Program released a report of six innovative thrust reverser concepts for very high bypass ratio engines, used in subsonic transport aircrafts as presented by Asbury and Yetter (2000). Chuck (2001), Trapp and Oliveira (2003) made simulations of external flow on commercial aircraft. Butterfield *et al*. (2004) studied the improvement of thrust reverser design by using computational tools.

3. Cascade thrust reverser

Thrust reverser is a device installed in the aircrafts to provide reverse thrust to decelerate the aircraft during landing. The cowl-mounted cascade thrust reverser is a pre-exit device composed of an internal blocker and a cascade located on the cowl. The flow is deviated by the blocker to the cascade that guides it forward producing reverse thrust.

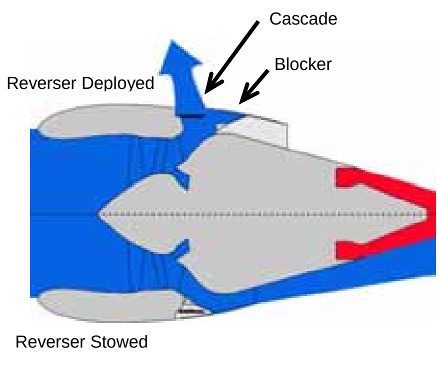

Figure 1. Cowl-mounted cascade thrust reverser

4. Thrust reverser design

The thrust reversers design comprises three main stages: the choice of the type of thrust reverser, the geometry design and drive mechanism design. The geometry design involves the definition of the aerodynamic and geometric parameters and its evaluation using performance parameters.

Up to 80% of the component total cost is associated with the design; thus, the development of tools capable of shorten this phase is of great importance. In this way, Finite Elements Analysis (FEA) and Computational Fluid Dynamics (CFD) have been successfully applied to thrust reverser design (Butterfield *et al*. 2004).

The thrust reverser design must attain the following requirements:

When stowed, it must:

- avoid extra drag and
- not affect engine performance.

When deployed, it must:

- not affect the engine operation limits;
- avoid re-ingestion of the reverted jets;
- avoid foreign object damage (FOD);
- avoid impingement of the reverted jets on the fuselage;
- avoid buoyancy on the nose;
- avoid controllability problems;
- allow the cutoff speed to be as low as possible and
- result in maximum reverse thrust.

It is an iterative process involving the following steps:

1. Definition of design requirements and initial values;
2. engine performance prediction and cascade calculation;
3. improvement of channel losses and flow angles estimates, based on axisymmetric flow calculations;
4. repetition of steps 2 and 3 until the results in 3 agree with 1;
5. adjustment of cascades angles based on 3-D external flow calculation and
6. repetition of steps 2, 3, 4 and 5 until the results in 5 agree with 1.

5. Performance parameters

The thrust reverser efficiency η_r is defined in Eq. 1 as the ratio of the reverse thrust F_r under static condition (null free stream velocity) and the engine forward thrust F_f at the same power conditions. According to Asbury and Yetter (2000), for a cascade thrust reverser its value is of the order of 0.3:

$$\eta_r = \frac{F_r}{F_f} \qquad (1)$$

The area match parameter β is defined as function of the ratio of the thrust reverser effective area A_r to the fan nozzle effective area A_{fan} operating at forward thrust mode.

$$\beta = \frac{A_r}{A_{fan}} \qquad (2)$$

6. Geometric configuration of the cascade thrust reverser

The channel geometry, when the thrust reverser is deployed, is dependent on the bypass channel and blocker geometries and on the axial placement of the cascades. It defines the cascade inlet aerodynamic characteristics. The azimuthal location, number and dimensions of the cascade sectors (modules) influence the area match and the thrust reverser performance on lateral wind conditions. A sketch of the modules located around the nacelle is shown in Fig. 2.

7. Fan exit design conditions

A generic engine deck developed at ITA (Barbosa and Bringhenti, 1999; and Bringhenti, 1999 and 2003) was used for the definition of the initial parameters at fan exit. Numerical values are obtained for:

- Stagnation temperature at fan exit;
- stagnation pressure at fan exit and
- mass flow at fan exit.

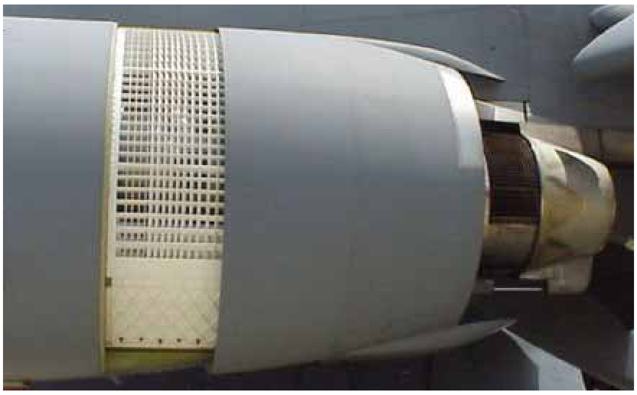

Figure 2. Example of modules placement around the nacelle and some modules

8. Cascade design

For the sake of the thrust reverser performance prediction, preliminary geometry estimation for the standard cascade module is carried out, beginning with assumptions on the streamlines and cascade inlet flow angles, assuming 1-D and null incidence. The flow is considered compressible but the other properties are assumed constant.

8.1. Cascade inlet definitions

From Fig. 3 and additional dimensional data, the average inlet flow angle α_1 is evaluated. This angle may be estimated as starting guess from the geometry of the channel assuming streamlines distributed along the straight lines A and B shown in Fig. 3. Bidimensional CFD calculation will be used later to improve the initial guess.

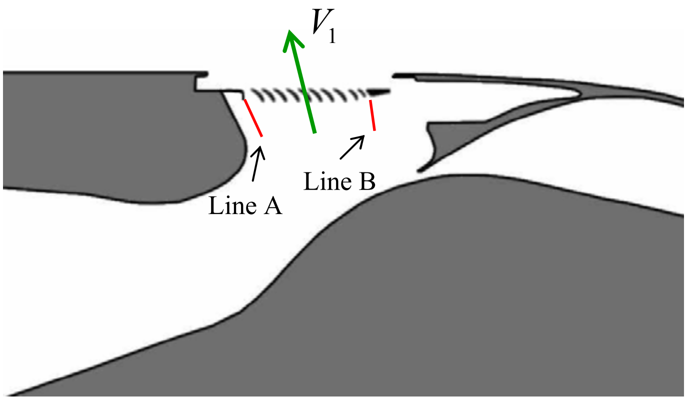

Figure 3. Engine section containing the relevant parts of the channel formed by the thrust reverser deployment.

The channel between fan exit and module inlet is considered as simple duct and the losses calculated using Idel'cik (1986) recommendations. As a result, numerical values are obtained for the cascade inlet:

- Stagnation temperature = stagnation temperature at exit of fan.
- Stagnation pressure = stagnation pressure at exit of fan - calculated losses.
- Mass flow = mass flow at the exit of the fan – leakage

The leakage will be evaluated later, taking into account the geometry of the exhaustion system.

8.2. Cascade geometry and losses

The cascade exit angle α_2 is a key parameter to accomplish the design requirements. The cascade pressure loss is defined using Eq. 3 where P_{01} and P_{02} are inlet and outlet stagnation pressures and P_2 is the outlet static pressure. Both are established at this point and will be checked later. The velocities, temperatures and pressures are obtained from continuity, energy, and isentropic relations.

$$Y = \frac{P_{01} - P_{02}}{P_{01} - P_2} \qquad (3)$$

The choice for the aspect ratio h/c involves manufacture, weight, aerodynamic and structural considerations. At this point, it will be made using the designer experience.

Cohen et al. (2001) consider profile loss as function of inlet and outlet flow angles, s/c and t/c, where t is blade maximum thickness. Therefore an optimum value for s/c can be obtained as a function of α_1 and α_2.

Null incidence is initially fixed. The deviation δ, difference between the blade exit angle α_2' and α_2, is calculated using Carter's correlation (Horlock, 1966)

$$\delta = m_c \theta \frac{s}{c} \tag{4}$$

where $\mathrm{m_c}$ is a function of outlet flow angle and θ is the camber angle.

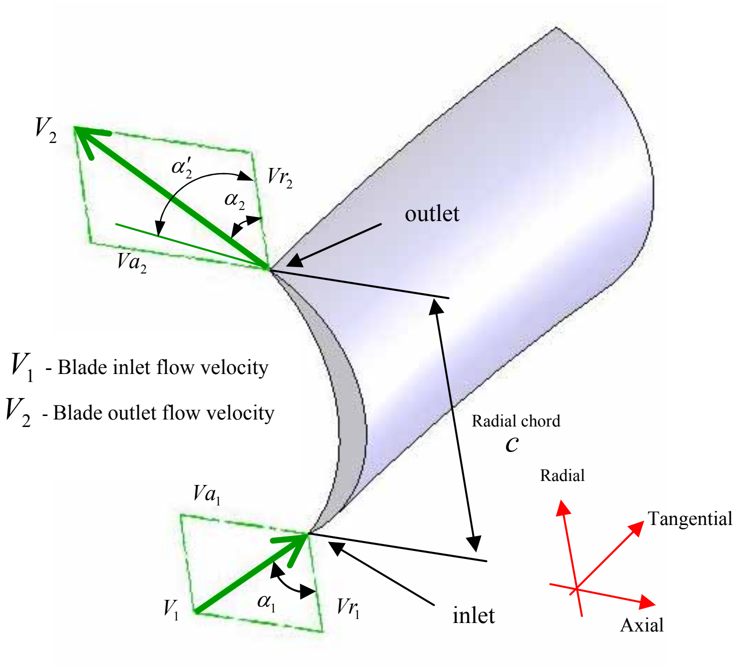

Figure 4. Blade section with indication of velocities, dimension and angles

Airfoil sections for the thrust reverser blades were selected to guarantee low losses, therefore greatest exit fluid velocity and reverse thrust. However, Povolny (1957) suggests that the blades may also be manufactured from rolled plates, incurring in a loss of efficiency of about 5% in the reversion.

MCA airfoils of 3 arcs (see Fig.5) were selected for this study and eventually 5 arcs would be used instead.

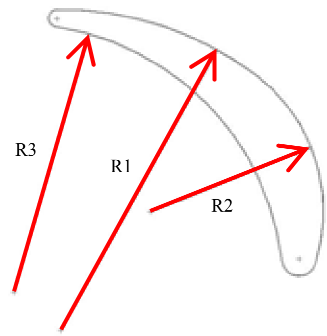

Figure 5. MCA 3 arcs airfoil

The losses are calculated by the Soderberg's correlation (Horlock, 1966) for an accelerating cascade, where Y' is a function of the flow deflection and the Reynolds number at outlet, Re_D, calculated using the throat hydraulic diameter.

$$Y = \left(\frac{10^5}{\mathrm{Re}_D} \right)^{1/4} \left[(1 + Y')\left(0.975 + 0.075 \frac{c}{h} \right) - 1 \right] \qquad (5)$$

The calculated pressure loss is used to confirm the initial guess made for Eq. 3.

8.3. Module mass flow

Figure 6 illustrates a module of thrust reverser, with the cascade blades assembled at an angle ψ with the tangential direction. The evaluation of the engine installation on the aircraft will indicate the best distribution of the N modules around it, as well as the expected orientation of the thrust reverser flow. The angles $\psi_i, i = 1,\ldots,N$ will be established based on designer experience and checked using 3D simulations, to comply with the requirements indicated in Section 4.

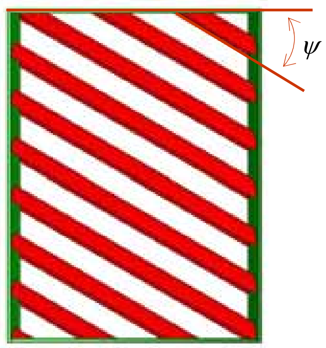

Figure 6. Module skew

The calculation of the mass flow, $\dot{m}_P$, in a standard module (in which $\psi = 0$) is made by guessing the module area ($a \cdot l$), checked using Eq. 7.

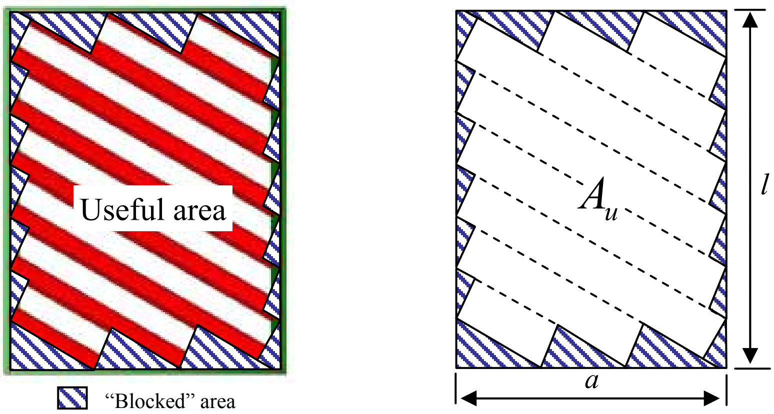

Figure 7. Module areas

A blockage coefficient, K_B, was defined based on the shaded area shown in Fig. 7.

$$K_{B_i} = \frac{A_{u_i}}{a \cdot l} \qquad (6)$$

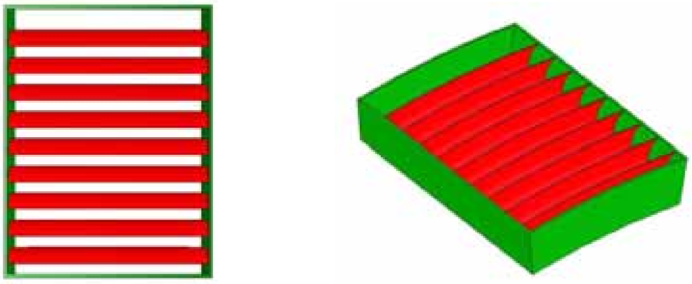

Figure 8. Standard module ($\psi = 0$)

The total mass flow passing through all modules must be checked using Eq. 7, where $\%\dot{m}_{leak}$ is the fraction of blocker leakage and $\dot{m}_{BP}$ is the mass flow from the bypass. If necessary, the module area must be corrected.

$$\sum_{i=1}^{N} K_{B_i}\dot{m}_{T_i} = (1-\%\dot{m}_{leak})\dot{m}_{BP} \qquad (7)$$

8.4. Reverse thrust

The reverser total thrust in the direction of the engine axis is given by Eq. 8, where F_i is the standard module thrust:

$$F_R = \sum_{i=1}^{M} F_i sen(\alpha_{2_i})\cos(\psi_i) \qquad (8)$$

Analysis of these calculations may require revision of the initial assumptions. An interactive process may be established so that a set of parameters may be made available to proceed with the studies using 2D and 3D models.

9. Improvement to the cascade inlet boundary condition using axisymmetric simulation

A standard module, formed by the blades placed transversally to the engine flow as shown in Fig. 8, is dimensioned.

The initial assumptions concerning the cascade flow inlet angle may be improved using the results of axisymmetric simulation of the channel flow leaving the fan and entering the cascade. The standard module design is iterative, use being made of the engine deck for the engine performance simulation and the cascade 2D calculations.

Although there is no flow axial symmetry, it will be admitted in order to better identify the parameters initially adopted: inlet flow angle, losses in the duct preceding the cascade, deviation, incidence, etc. This approach would give qualitative information used for the identification of regions with undesirable flow properties (high velocities, high losses, etc.) and adequacy of the cascades geometry. An interactive process would then be established to improve the quality of the results obtained during the preliminary design phase.

The internal flow was modeled using 2D computational domain by Butterfield *et al.* (2004) for a conventional cascade thrust reverser and by Marconi and Tindel (1997) for a blockerless cascade thrust reverser. A structured grid is shown in Fig. 9.

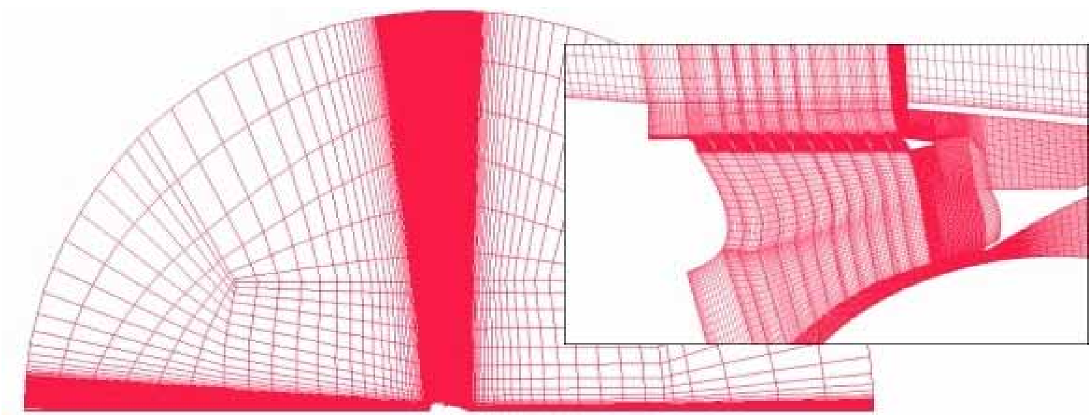

Figure 9. 2D grid for axisymmetric simulation

10. Engine-aircraft integration using 3D simulation

This study must be carried out in order to confirm the adequacy of the thrust reverser integration to the engine and of the engine to the aircraft. One would be looking for jet flows colliding with surfaces, re-ingestion of exhaust gases, ingestion of ground debris, in additional to the total reverse force in the direction of the engine axis.

These verifications are made through a 3D simulation of the flow around of the nacelle and neighborhood. Thrust reverser CFD simulation is made at the cancellation speed. It is a critical condition because at this speed the reverted jets are getting more intense than the free stream, allowing FOD, re-ingestion and buoyancy.

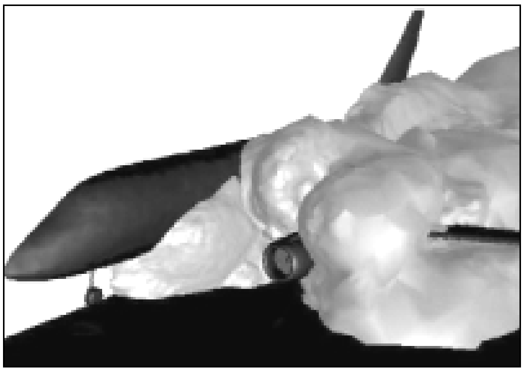

Figure 10. CFD application on thrust reverser

For the study without lateral wind only half airplane is modeled. The aircraft can be studied with complete landing configuration, including landing gear, flaps, slats, spoilers and thrust reversers deployed. A mesh with tetrahedral elements can be employed due to its adequacy for complex geometries and due to its good performance for flows without a characteristic direction containing regions of great scale differences. The simulation uses Reynolds Averaged Navier Stokes, k-ε turbulence model, finite volume formulation, upwind scheme, second order spatial interpolation and a coupled implicit solver. Figure 10 shows the isosurface of total temperature indicating the development of the thrust reverser plume (Trapp and Oliveira, 2003).

11. Case study

ISA sea level
Forward thrust at 85% of fan design speed – 131581 N
Flight Mach number – 0.0
Stagnation temperature at reverser duct inlet – 324.1 K
Stagnation pressure at reverser duct inlet – 145.9 kPa
Fraction of fan exit mass flow – 0.1
Number of modules – 12
Range of modules skew angles – 0 to 22 deg
Range of modules exit angles – 40 to 52 deg

Results:
Reverse thrust - 39187 N
Thrust reverser efficiency – 29.8 %

Figure 11. Standard module geometry

11. Conclusion

Recent studies indicate that safety is the motivation for the airlines to require thrust reversers, despite of its increased costs.

The aircraft manufacturer companies are developing the CFD as a design tool for thrust reversers, since it produces quick and inexpensive results, good visualization of the plumes and predict flow field properties with acceptable accuracy.

The requirements and parameters of the thrust reversed design are listed and a procedure for cascade thrust reverser design is presented. It comprises a one-dimensional cascade calculation, axisymmetric calculations for the internal flow analysis and 3D simulations for the external flow analysis. As this procedure requires an iterative calculation, the experience on adopting the first guesses is of fundamental importance for quick results.

An axisymmetric CFD simulation is employed to verify the losses in the bypass duct and the cascade inlet flow angle. The external 3D flow is simulated to better adjust the choices of exit flow angles and thrust reverser positioning.

Finally, a case study was proposed using a generic engine similar to those installed on commercial aircrafts. A standard module geometry, reverse thrust and efficiency are presented.

12. Acknowledgements

The authors thank EMBRAER and El Paso - Center for Reference on Gas Turbines - for the support to this research.

13. References

Asbury, S. C. and Yetter, J. A., 2000. “Static Performance of Six Innovative Thrust Reverser Concepts for Subsonic Transport Applications - Summary of the NASA Langley Innovative Thrust Reverser Test Program”. NASA Langley Research Center. NASA/TM-2000-210300.

Barbosa, J. R. and Bringhenti, C. Simulação numérica do desempenho de turbinas a gás. In: COBEM Proceedings. 1999.

Bringhenti, C. Analysis of Steady State Gas Turbine Performance. Dissertação (M. Sc.) — Instituto Tecnológico de Aeronáutica, São José dos Campos, 1999.

Bringhenti, C. Variable Geometry Gas Turbine Performance Analysis. Tese (Ph. D.) — Instituto Tecnológico de Aeronáutica, São José dos Campos, 2003.

Butterfield, J et al., 2004. “Integration of Aerodynamic, Structural, Cost and Manufacturing Considerations During the Conceptual Design of a Thrust Reverser Cascade”. AIAA 2004-282

Chuck, C. 2001. “Computational Procedures for Complex Tree-Dimensional Geometries Including Thrust Reverser Effluxes and APUs”. 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. 8-11. AIAA 2001-3747.

Cohen, H., Rogers, G. F. C., Saravanamuttoo, H. I. H., 2001. “Gas turbine theory”, Longman, UK, 4th edition.

Dietrich, D. A., 1975. “Effect on fan flow characteristics of length and axial location of a cascade thrust reverser”. NASA Center for Aerospace Information (CASI). NASA-TM-X-3247; E-8223, 19750601.

Horlock, J.H., 1966. “Axial flow turbines fluid Mechanics and thermodynamics”, Butterworths, Londres.

Idel'cik, I.E. , 1986. “Memento des pertes de charge”, Ed. Eyrolles, Paris

Johns, C. J., 2000. “Solution of an engine inlet compatibility problem during C-17 low cost N/EAT nacelle thrust reverser development”. AIAA-2000-5579. 2000 World Aviation Conference, San Diego, CA, Oct. 10-12.

Marconi, B. G. F. and Tindel, R., 1997. “Computational fluid dynamics support of the development of a blockerless engine thrust reverser concept”, 33rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. Seattle.

Povolny, J. H., Steffen, F. W. and McArdle, J. G., 1957. “Summary of scale-model thrust-reverser investigation”. NACA Report 1314.

Trapp, L. And Oliveira, G., 2003. “Aircraft Thrust Reverser Cascade Configuration Evaluation Through CFD”. AIAA-2003-723. 41st Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 6-9.

Yetter, J. A., 1995. “Why do airlines want and use thrust reversers? A compilation of airline industry responses to a survey regarding the use of thrust reversers on commercial transport airplanes”. NASA-TM-109158; NAS 1.15:109158 , 19950101.

14. Responsibility notice