Proceedings of COBEM 2005
18th International Congress of Mechanical Engineering
November 6-11, 2005, Ouro Preto, MG

OVERVIEW ON NACELLE DESIGN

Jesuíno Takachi Tomita, Cleverson Bringhenti, Daniel Pozzani, João Roberto Barbosa
Gas Turbine Group - CTA/ITA/IEM - CEP 12.228-900 - FAX: +55-12-3947-5967, São José dos Campos – SP – Brazil.
jtakachi@mec.ita.br

Antonio Batista de Jesus, Odenir de Almeida, Guillherme Lara Oliveira
EMBRAER -Empresa Brasileira de Aeronáutica S.A., São José dos Campos – SP – Brazil.
antonio.jesus@embraer.com.br

Abstract. *Nacelles are responsible for good engine performance and considerable percentage of total aircraft drag, thus fuel consumption. Energy conservation and cost of fuel, among others, require good nacelle design. Optimized nacelle design would require CFD calculations of the flow around it, since high drag-generating phenomena, like shock waves and wake, may appear during flight. A literature review was carried out aiming at familiarization with nacelle types and basic rules for nacelle design. A methodology was established to determine main nacelle dimensions. A case study is presented and design optimization is proposed.*

Keywords*: Nacelle, Nacelle design, CFD, Gas Turbine.*

1. Introduction

The problem of drag reduction caused by engines and their nacelles is not new, since it has been a reported concern since the 1920s. In 1926 the Bureau of Aeronautics and in 1927 the industry requested NACA the support to understand the effects of cowling on the performance and cooling of radial engines. The first NACA attempts were experimental. Without backing theory they were unable to completely solve that problem and an impasse was established. To move beyond the paralyzing confusion of this experimental impasse, NACA's Langley cowling research group hired the work of Theodore Theodorsen, general head of the laboratory's small Physical Research Division to develop the analytical studies to support the experiments. The work lasted from 1926 to 1936 and demonstrated another important general point about research: no matter how practical or otherwise advantageous any one method may be, it always has some disadvantages; the experiments have arrived to a dead end and required a backing theoretical support.

Gas turbines are designed to provide thrust at many operating points over the flight envelope. For this reason, it is seen as a main component of an aircraft. Different amounts of air mass flow at each flight condition are necessary to attain all possible required thrust, therefore the importance of a well designed nacelle. Nacelle has an important role on the overall aircraft performance due to its interaction with the aircraft flow field. The nacelle must also protect the engine from foreign objects and impacts (FOI).

An extensive literature review, carried out to evaluate what has been done to improve design methodologies, revealed that most of the published papers refer only superficially to design methods. At the same time, contacts have been made with experienced engineers that have worked on engine-aircraft integration to share their expertise. From the available literature, the ESDU reports 81024 and 80037 are the few that disclose the needed information for the design and performance assessment. They will serve as the basis for the present study. Indications for the improvement of the procedures here reported will be made at the appropriate time.

Nacelle is the cowling that covers the gas turbine to protect it against Foreign Object Ingestion (FOI), which may cause damage to the engine and decrease the engine drag while keeping its good performance all over the flight envelope. It is a multi-functional unit designed with the purpose of: (i) delivering air to the fan both efficiently and with the minimum amount of distortion, and (ii) expanding the gases through an exhaust system with the maximum amount of efficiency.

Figure 1 shows the 3 major parts into which a nacelle may be divided: the forebody, the centerbody and the afterbody. An insertion shows also details of the forebody lip.

For the validation of a complex CFD program under development, several test cases were defined. This work concerns part of one of such cases, where a long-duct nacelle is used. A design procedure for a long-duct nacelle, defined after a thorough literature search and best practice reported in the literature, has been defined. A test nacelle has been designed and analyzed using commercially available CFD code as far as flow patterns are concerned. In this part of the study an axisymmetric nacelle was chosen because of simplicity and the possibility of spotting unwanted aerodynamic phenomena, like shock waves and boundary layer separation at the upper surface.

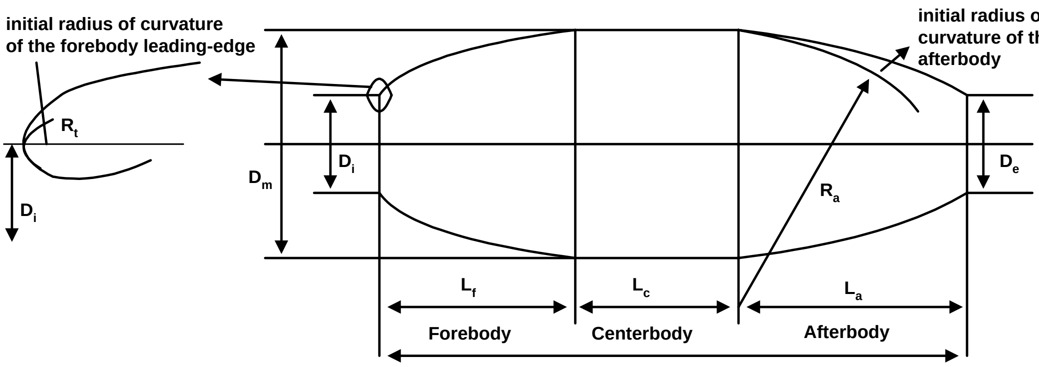

Figure 1. Long Duct Nacelle showing its three main parts

The air intake is the most important part of the nacelle. It requires careful design because it must deliver the air required by the engine, from free stream conditions to the conditions required at the fan or compressor inlet with minimum total pressure loss and distortion, in a high speed environment where Mach number may exceed 0.7. Also, as the installed engine performance depends on the intake installation losses (additive drag, forebody or cowl drag, bypass air, boundary layer, bleed air, etc.), the intake design should minimize these losses. The aircraft angle of attack may vary during the takeoff rotation and landing phases of flight, which will change the angle of the air flow with respect to the engine centerline. Inlets may operate with high angles of flow incidence that may cause flow separation; this flow separation causes large regions of low total pressure. The magnitude of the inlet flow distortion is a function of the intake geometry, mass flow rate, flight Mach number and flow incidence angle. The effect of high distortion is to shift the fan or compressor surge line to values of higher mass flow. Crosswind may also cause flow separation in the internal forebody surface causing fan stall. This effect can be reduced by making the leading edges on the side of the inlet thicker to minimize flow separation with crosswinds. The internal diffuser curvature and length are based mainly on maintaining the flow attached to the inside walls of the inlet and matching the inlet diameter of the engine.

The size of the nacelle forebody is a design compromise between the requirement of low cruise drag and avoiding catastrophes when one or more engines are out. The nacelle forebody size that gives minimum drag at cruise may not give a good engine-out drag. The minimum drag for a nacelle does not necessarily occur when the inlet is designed for minimum inlet drag because the influence of the afterbody drag, interference drag and aircraft trim drag need to be included in the integration and design of an engine nacelle. Another important analysis is the engine location on the wing that provides the best integration of engine and airframe. This integration depends on the nacelle design, wing design and resulting interference drag. Thus, considerable analytical and experimental work is needed, not only for the nacelle design but also for the design of each installation.

The afterbody needs also much attention during design. It must collect the exhaust gases leaving the propelling nozzle and merge it with the surrounding air stream. For large values of thrust the kinetic energy of the exhaust gas must be high, which implies a high exhaust velocity. The pressure ratio across the nozzle controls the expansion process and the maximum thrust for a given engine is obtained when the exit pressure equals the ambient pressure. The two basic types of nozzles used in jet engines are the convergent and convergent-divergent nozzle. Both nozzle and nacelle afterbody must be designed to minimize drag and noise generated by the out coming jet as well as to maintaining the maximum thrust during the aircraft operation (Mattingly et al, 1987)

2. Literature review

Major research concerns implied by the available literature were:

- Development of computer analysis capability for calculation of streamlines and pressure distributions around two-dimensional (planar and axysimmetric) isolated nacelles at transonic speeds and for predicting nacelle/inlet flowfields (Keith and Ferguson, 1973; Vadiak and Atta ,1983);
- 3-D flowfield for flow-through nacelle, examining both inviscid and viscous-inviscid interactions solution (Compton, 1985);
- Influence of different Mach numbers and angles of attack to determine if nacelle/pylon/wing integration affects the achievements of natural laminar flow and to determine the longitudinal aerodynamics effects of installing flow-through, mixed-flow engine nacelles (Lamb *et al.*, 1985; Abeyounis and Peterson, 1990); the effect of propeller solidity and thrust axis inclination on the propeller normal-face coefficient (Garl *et al.,* 1991); inlet test methods and determine the impact of the fan on inlet separation when operating at large angles of attack (Larkin and Sehweiger, 1992);
- Effects of the way different parts of the aircraft are joined together (wing/pylon/engine) (Hoheisel, 1997; Tillman and Hwang, 1999; Eleshaky and Baysal, 1998; Smith and Grossley, 2000; Brodersen, 2002; Runsey *et al.,* 2004; Riedel, 1998);

- Effects of flowfield around ducted-nacelles (Mack, 1998) to determine exterior and interior mass-flow characteristics and to measure flowfield overpressures as well as a numerical investigation of the flowfield associated with a generic isolated long duct nacelle (Humphries and Raghunathan., 1997); wave drag characteristics of an over-the-wing nacelle configuration (Fujino and Kawamura, 2003); two possible nacelle configurations, under-wing and over-wing, for higher bypass ratio turbofan for subsonic transport (Kinney *et al.,* 1997); wing-nacelle interference effects of flow-through nacelles simulating superfan engines (Odies *et al.,* 1992; Pendergraft *et al.,* 1992) were studied to give better insight into the flow behavior around nacelles;
- Importance of a CFD-based design system for the engine nacelle integration in HSCT - High Speed Commercial Transport - (Kano and Nakahashi, 1997); the aerodynamic design of the future STA - Supersonic Transport Aircraft - propulsion system (Prat *et al.*, 1997); flowfield around a supersonic transport aircraft with integrated engine nacelles (Kanazaki *et al.*, 2003); experimental investigation to determine the effect of diverter wedge half-angle and nacelle lip height on the drag characteristics of an assembly consisting of nacelle fore cowl from a typical high-speed civil transport and diverter mounted on a flat plate(Flamm and Wilcox, 1995);
- Aircraft/propulsion system integration of a fuselage-mounted turbofan engine using CFD analysis of the complete fuselage/wing/nacelle configuration (Yates *et al.*, 1998); interactions existing between the airframe and the propulsion system and the engine installation effects (Jie *et al.*, 2000); iterative design of engine nacelles and wings being part of complex aircraft configuration (Wilhelm, 2004), show the need of interactive nacelle/fuselage design;
- Hailstone impacts (Anghileri *et al.*, 2004); flow transition detection when flight testing engine nacelles (Riedel and Sitzmann, 2002); improvements to nacelle acoustic treatment for noise reduction (Powell and Preisser, 2000); influence of suppression effects in thrust determination of the short-ducted turbofan engine (Almeida *et al.*, 2002); isolated nacelle with a supersonic cruise nozzle (Deere and Pandya, 2002); CFD applied to the investigation of the effect of excrescences due to manufacturing tolerances, seen as aerodynamic defects, on the surface of an isolated engine nacelle (Humphries *et al.*, 1999); flow visualization to examine shock and boundary layer flow interaction for a nacelle in close proximity to the lower surface of a simulated wing (Biber and Ellis, 1993); parametric investigation of the aeroelastic flutter stability behavior of a semi-rigid 3-D wing-with-engine nacelle model in subsonic flow (Försching and Knnack, 1993) are other concerns during nacelle design and integration to the aircraft;
- Nacelle design methods and inverse design methods (Kiock and Hoheisel, 1993; Brodt *et al*., 2002; Wilhelm, 2002; Naik *et al*., 1995); criteria for the design of a nacelle to take account of a certain number of requirements related to engine and the aircraft (Kiock and Hoheisel, 1993) indicates that inverse solution is being sought already;

Nacelle design and integration to the aircraft is a key point in the overall aircraft design (Brodt et al., 2002). Usually it starts from the axisymmetric assumption. Three major steps are envisaged: location of points appropriate for the enclosure of the engine and its accessories; aerodynamic profile design and the CFD analysis. An inverse design, based on an iterative residual-correction-type approach to generate a geometry that satisfies a user-prescribed target pressure distribution may be used instead (Wilhelm, 2002), starting, say, from a tentative geometry, which is gridded for the CFD analysis (Naik *et al*., 1995).

3. The design procedure

A nacelle is designed for a specific engine; therefore the starting point is to draw the engine sketch with the relevant dimensions, followed by the location of the guidance points to indicate the minimum limits of the nacelle external surfaces. Allowances for nacelle cooling air, hardware structures, engine accessories and the nacelle own structure must be given at this stage. Figure 2 shows an engine cutaway view and the chosen anchor points for the nacelle surfaces. The design may then be started with the determination of the flight conditions at which the nacelle swallowing capacity is the most demanding (usually at end-of-climb, where the engine is at high power and density is lowest) – ambient and flight conditions, engine mass flow and rotational speed.

The following steps are adopted for the design:

a) forebody
   - determination the fan inlet area and fan inlet Mach number;
   - determination the throat area for the chosen throat Mach number;
   - design the internal intake diffuser that efficiently drives the air smoothly to the fan, taking care of the throat dimensions in order not to allow high Mach number, to accommodate future increase in engine mass flow. Since the diffuser requires small divergence angle, the forebody length may be excessively long if the throat Mach number is too high;
   - design the forebody lip to accommodate angles of attack that occur during take-off and cross winds;
   - design the upper cowl surface taking care of the drag rise Mach number. The NACA 1-series profile may be used. This means that special care must be taken to avoid excessive flow acceleration that

would cause shock waves. Check for the spillages at engine low rotational speeds that will cause excessive drag.

b) centerbody

Usually the centerbody is of cylindrical shape, requiring that care must be taken only with the transitions of the surfaces of the fore- and afterbody. When thrust-reverser is to be located on the centerbody, a check for possible adverse pylon and airframe flow interference has to be done.

c) afterbody

The afterbody comprises two subsections, as shown in Fig. 1: a conical surface with cone angle whose exit section coincides with the engine exhaust duct, and a circular section joining the cone to the centerbody. Care must be taken to ensure that: i) the boat tail radius R_a, shown in Fig. 1, is sufficiently large to avoid premature drag-rise in the flow suction at the initial expansion around afterbody shoulder; ii) the radii ratio (inlet to outlet radius ratio) is adequate to compromise the afterbody length with the excessive boundary layer growth and separation that cause high drag.

A trade-off exercise may be required to choose the cone angle that would result acceptable drag.

In addition to the recommendations already listed, there are other related to the specific part of the nacelle that is being designed.

3.1. Forebody design recommendations

The forebody is the engine intake region that is made of a lip, a throat, a diffuser and an external surface. It must be capable to work at all the operational envelope of the aircraft. Its duty is to deliver good quality air to the fan and to diverse non-required air around the nacelle at minimal drag penalty.

Sizing the throat requires compatibility of the intake lip to the internal diffuser; minimization of the diffuser losses and very good air quality delivered to the engine at any point over the aircraft envelope, that is, at take-off, climb, cruise, descent, landing and maneuvers.

The intake maximum throat Mach numbers is chosen in the range 0.7 to 0.75 to operate choked-free, whereas lip contraction ratio (highlight/throat area ratios, A_H/A_{max}) is chosen in the range 1.2 to 1.35. The higher the throat Mach number the highest the internal diffusion angle and the drag rise Mach number.

The intake may not be axially symmetric and the contraction ratio may vary around the circumference of the intake to permit:

- maximum lip thickness biased towards the bottom of the intake in order to achieve good high incidence, therefore high internal performance;
- intermediate thicknesses at the sides of the intake to achieve good crosswind tolerance;
- minimum thickness at the top to achieve good external-cowl performance at and circa the crown of the nacelle.

The cowl external lines may not be axisymetric in order to accommodate the engine gearbox and accessories, located, say, in the region of the keel of the nacelle. The design method that provide general guidelines for determining the leading dimensions of the nacelle forebody are:

- cowl thickness, expressed in terms of the ratio D_H/D_{max} or its inverse, where: D_H is the highlight diameter and D_{max} is the nacelle maximum diameter;
- cowl length, expressed as the ratio L_F/D_{max} and cowl lines between the highlight plane and the maximum cross-sectional area, A_{max} of the forebody, where L_F is the nacelle forebody length.

These ratios are chosen to avoid the onset of significant spillage drag, wave drag at cruising conditions, by ensuring that the operating mass flow ratio range of the intake is greater than a critical value and that the free-stream Mach number for drag rise is greater than the aircraft operating Mach numbers.

3.2. Centerbody design recommendations

Usually the centerbody has a cylindrical shape, so that care must be taken only with the transitions of the surfaces of the fore- and afterbody. The centerbody length may be of minute dimensions, or even not exist, providing the fore- and the afterbody are sufficient to cover the engine and its peripherals. Conical shape may also do in cases where the forebody has larger diameter than the afterbody.

3.3. Afterbody design recommendations

The aerodynamic design of the nacelle afterbody, again assumed to be axisymmetric, involves fairing the boat tail between the nacelle maximum cross-section and the final nozzle, taking into account any centerbody, thrust-reversal or other design requirements; for example, the need to minimize adverse pylon/pod and airframe/pod flow interference effects. Typical geometrical parameters are as sketched in Fig. 1.

Premature drag rise in the flow-suction region of the initial-expansion around the shoulder of the afterbody is avoided by ensuring that the radius, R_A, is sufficiently large.

The free stream drag-rise Mach number, which must be compatible with the drag-rise Mach number of the nacelle forebody, and the drag-rise requirements of the aircraft as a whole, can be related to the afterbody length to diameter ratio. Too small a ratio may cause the excessive boundary layer growth and flow separation on the afterbody in the flow recompression region at the rear of the boat tail and high skin-friction drag.

The radius used for the circular-arc section of the afterbody terminates at the nozzle-exit plane or fair into a conical section. In either case, the final boat tail angle, β, must be chosen to limit boundary-layer growth and to avoid flow separation, allowing for the adverse static-pressure gradient imposed on the external flow over the final boat tail by the jet exhaust of the engine. This requires a deflection of the external flow.

In civil turbofan engines the jet flows are not significantly under-expanded. The boundary-layer management requirements can be met fairly readily as the flow turning is minimal. In the case of afterbodies for military engines equipped with convergent nozzles, operating at high flight speeds, the flow is highly under-expanded. The jet plume causes extra turning of the flow at the boattail, causing flow separation.

The flow over the afterbody may well be affected significantly by the proximity of the nacelle to the adjacent wing and/or fuselage of the aircraft. The suction and recompression regions of the flow on the afterbody are sensitive to the nature of the flow, particularly the diffusion in the gulley between the nacelle and the airframe. The nacelle design must take these flow-interference considerations into account.

4. Case study

The end-of-climb condition (EOC) was chosen for the nacelle design. Table 1 shows the relevant data. An engine deck developed at ITA, capable of engine simulation at steady and transient operations, has been used to calculate all the engine-related parameters used in this study.

Table 1. Data from engine running at EOC

Altitude (H)	10668 m
Ambient Stagnation Temperature (T_t)	242.85 K
Ambient Stagnation Pressure (P_t)	34323 Pa
Flight Mach number (M)	0.74

Relevant engine dimensions and parameters, such as mass flow, fan diameters (hub and tip) and exhaust area should be known.

Figure 2 shows an axisymmetric nacelle designed following the recommendations mentioned before. Indicated by the red lines are the limits of an actual engine. For this study the engine external accessories were removed for the sake of axial symmetry. Blue lines indicate the calculated surfaces.

LONG-DUCT NACELLE

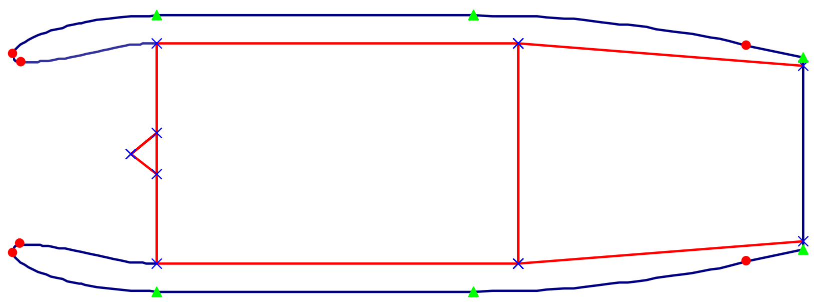

Figure 2. Final shape of the designed nacelle.

Dimensions were intentionally removed to avoid disclosure of proprietary data. 2D and 3D-views of the designed nacelle are shown in Fig. 3.

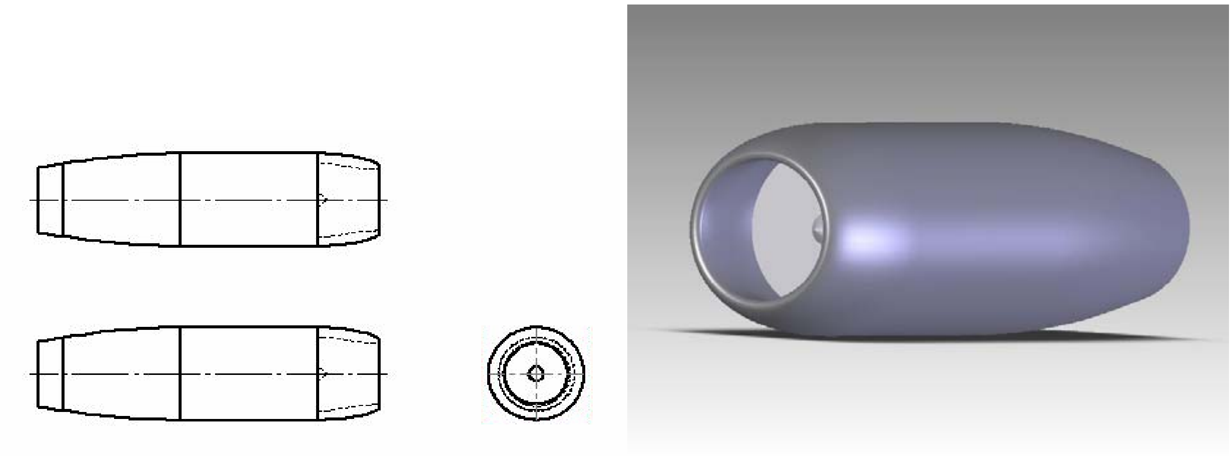

Figure 3. 2D and 3D-views of the designed nacelle.

This nacelle designed was simulated at an altitude of 11278 m and zero angle of attack to obtain the preliminary flow pressure, temperature and velocity distributions and to study the critical zones at which excessive Mach number and boundary layer separation may occur.

Figures 4 to 9 present the calculated pressure, temperature and Mach number contours.

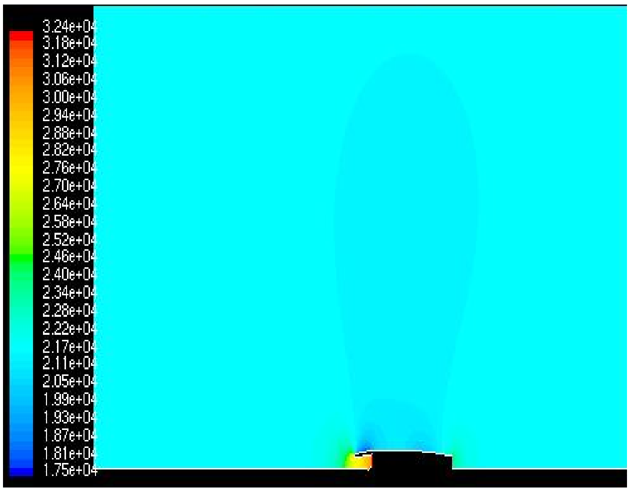

Figure 4. Static pressure contours (Pa).

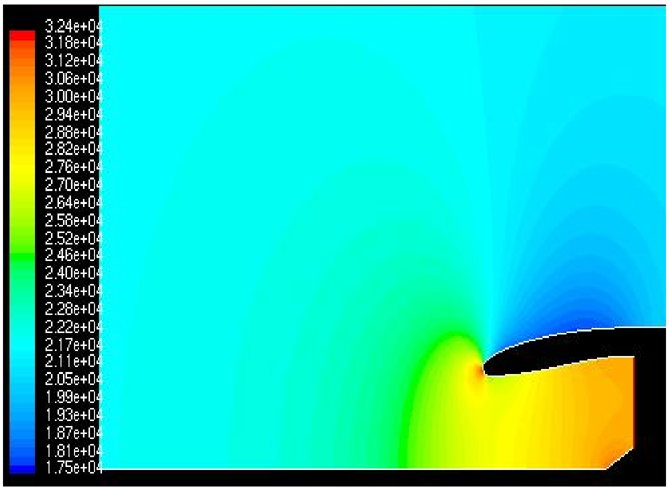

Figure 5. Detail of the static pressure contour at forebody (Pa).

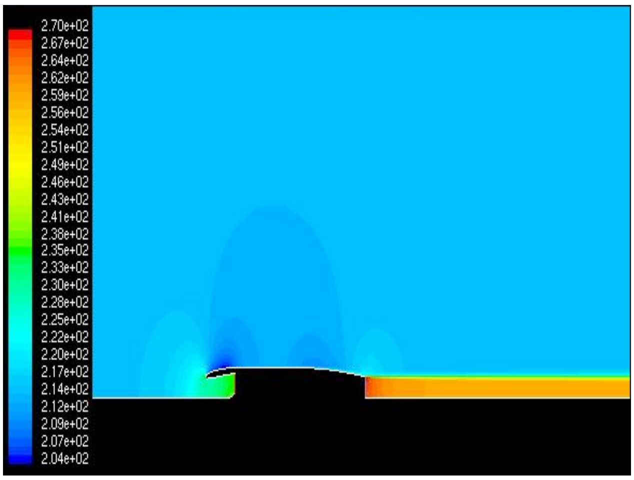

Figure 6. Static temperature contours (K).

Figure 7. Mach number contours (K).

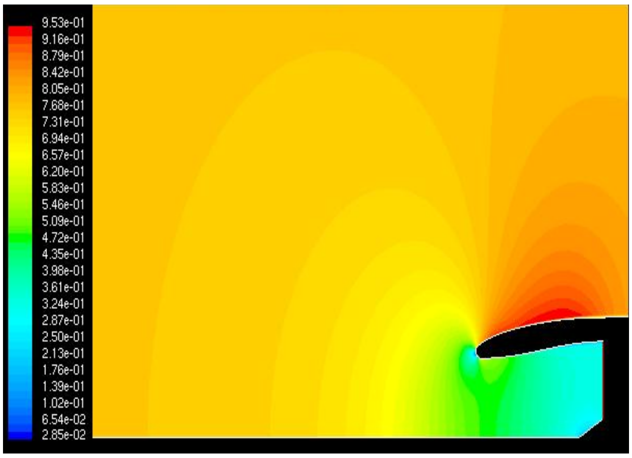

Figure 8. Detail of the Mach number contours at forebody.

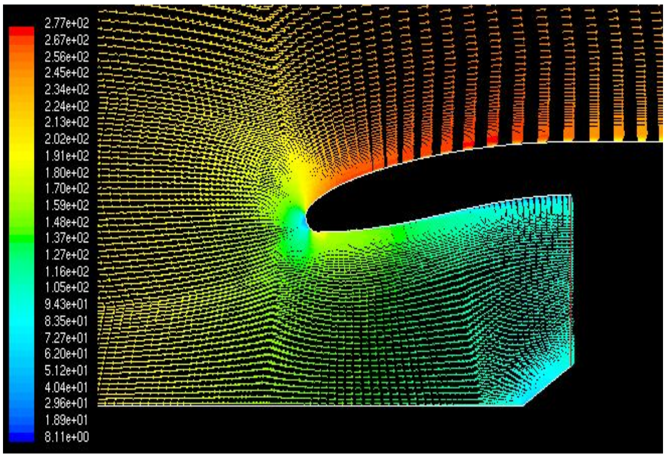

Figure 9. Velocity vectors at forebody (m/s).

5. Conclusion

The nacelle design procedure presented, having in mind both the analytical and the CFD calculations, is adequate to start the nacelle design. The flow quality inside and around the nacelle seems too be adequate. Others flight conditions should be simulated including different angles of attack relevant to other flight conditions.

6. Acknowledgements

The authors thank EMBRAER - Empresa Brasileira de Aeronáutica S.A., ANEEL and El Paso - Center for Reference on Gas Turbine - for the support to this work.

7. References

Abeyounis, W. K., Pattersen, J. C., 1990, “Effect of Location of Aft-Mounted Nacelles on Longitudinal Aerodynamic Characteristics of a High-Wing Transport Airplane”, NASA Technical Paper 3047.

Almeida, O., Oliveira, G. L.; Trapp, L. G., 2002, “CFD Analysis of Suppression Effects in a Commercial Aircraft’s Turbofan Engine”, ENCIT CIT02-0591.

Anghileri, M., Castelletti, L. M. L., Invernizzi, F., and Mascheroni, M., 2004, “A Survey of Numerical Models for Hail Impact Analysis Using Explicit Finite Element Codes”, International Journal of Impact Engineering, ELSEVIER.

Biber, K., and Ellis, D. R., 1993, “Supersonic Flow Visualization of a Nacelle in Close Proximity to a Simulated Wing”, NIAR Report 93-18.

Brodersen, O., 2002, “Drag Prediction of Engine-Airframe Interference Effects Using Unstructured Navier-Stokes Calculations”, Journal of Aircraft, Vol. 39, No. 6, November-December.

Brodt, C. S., Oliveira, G. L., and Barbosa, J. R., 2002, “Nacelle Design for Aeronautical Engines”, ENCIT 2002, IX Congresso Brasileiro de Engenharia e Ciências Térmicas, paper CIT02-0759.

Compton, W. Bernard, 1985, “On the Solution of the Three-Dimensional Flowfield about a Flow-Through Nacelle”, NASA-TM-87448.

Deere, K. A., and Pandya, M. J., 2002, “Propulsion Simulations with the Unstructured-Grid CFD Tool TetrUSS”, American Institute of Aeronautics and Astronautics.

Eleshaky, M. E., and Baysal, O., 1998, “Shape Optimizing Nacelle near Flat-Plate Wing Using Multiblock Sensitivity Analysis”, Journal of Aircraft, Vol. 35, No. 1, January-February.

ESDU 80037, “Pressure Recovery of Axisymmetric Intakes at Subsonic Speeds”.

ESDU 81024, “Drag of Axisymmetric Cowls at Zero Incidence for Subsonic Mach Numbers”.

Flamm, J. D., and Wilcox, Jr., F. J., 1995, “Drag Measurements of an Axisymmetric Nacelle Mounted on a Flat Plate at Supersonic Speeds”, NASA Technical Memorandum 4660.

Försching, H., and Knaack, J., M., 1993, “Parametric Study of the Flutter Stability of a Semi-Rigid 3-D Wing-With-Engine Nacelle Model in Subsonic Flow”, Journal of fluids and Structures 7, 567-593.

Fujino, M., Kawamura, Y., 2003, “Wave-Drag Characteristics of an Over-the-Wing Nacelle Business-Jet Configuration”, Journal of Aircraft, Vol. 40, No. 6, November-December.

Garl, L., Gentry, Jr., Dunham, D. M., and Takallu, M. A., 1991, “Effect of Solidity and Inclination on Propeller-Nacelle Force Coefficients”, Technical Memorandum NASA, NASA TM-4316.

Hoheisel, H., 1997, “Aerodynamic Aspects of Engine-Aircraft Integration of Transport Aircraft”, Aerospace Science and Technology, 1997, No. 7, 475-487.

Humphries, P., Gillan, M., and Raghunathan, S., 1997, “A Study of Isolated Nacelle Flows at Subsonic and Transonic Speed”, American Institute of Aeronautics and Astronautics, Inc., AIAA-98-0946.

Humphries, P.; Kundu, A.; Cooper, R.; and Raghunathan, S., 1999, “CFD Investigation of Excrescence Effects on an Engine Nacelle External Flow”, AIAA 99-0884.

Jie, L.; Fengwei, L., Quin, E., 2000, “Numerical Simulation of Transonic Flow over Wing-Mounted Twin-Engine Transport Aircraft”, Journal of Aircraft, Vol. 37, No. 3.

Kanazaki, M., Obayashi, S., and Nakahashi, K., 2003, “Numerical Simulation: Supersonic Flow Around Wing-Body Configuration with Integrated Engine Nacelle”, AIAA Journal, Vol. 41, No. 2, February.

Kano, S., Nakahashi, K., 1997, “CFD Based Design System for Engine Nacelle Integration on HSTC”, AIAA-97-1886.

Kieth, J. S., Ferguson, C. L., 1973, “Analytical method for predicting the pressure distribution about a nacelle at transonic speeds”, NASA CR-2217.

Kinney, D. J.; Ham, A. S. and gelhausen, P. A., 1997, “Comparison of Low and High Nacelle Subsonic Transport Configurations”, AIAA-97-2318, A97-31775.

Kiock, R. and Hoheisel, H., 1993, “Design of the Axi-asymmetric Nacelle for the Counter Rotating Ultra-High-Bypass Fan Simulator”, DLR-FB 93-52.

Lamb, M., Abeyounis, W. K., and, Patterson Jr., J. C., 1985, “Nacelle/Pylon/Wing Integration on a Transport Model With a Natural Laminar Flow”, NASA TP-2439.

Larkin, M. J., and Sehweiger, P. S., 1992, “ULTRA HIGH BYPASS AERODYNAMICS”, NASA Contractor Report CR-189149.

Mack, R. J., 1998, “Experimental and Theoretical Study of Flow Fields Around Ducted-Nacelle Models”, NASA/TM-1998-207683.

Mattingly, J., D., Heiser, W., H., and Daley, D. H., 1987, “Aircraft Engine Design”, AIAA Education Series, ISBN 0-930403-23-1.

Naik, D. A.; Krist, S. E.; Buning, P. G.; and Gea, L. M.; 1995, “Inverse design of nacelles using Multi-Block Navier-Stokes codes”, American Institute of Aeronautics and Atronautics

Odis, C. Pendergraft, Anthony, M. Ingraldi, Richard, J. Re and Timmy, T. Kariya, 1992, “Installation Effects of Wing-Muonted Turbofan Nacelle-Pylons on a 1/17-Scale, Twin-Engine, Low-Wing Transport Model”, NASA TP-3168, March 1992.

Pendergraft Jr., O. C., Ingraldi, A. M., Re, J.R., Kariya, T. T., 1992, “Installation Effects of Wing-Mounted Turbofan Nacelle-Pylons on a 1/17-Scale, Twin-Engine, Low-Wing Transport Model”, NASA Technical Paper 3168.

Powell, C. A., and Preisser, J. S., 2000, “NASA’S Subsonic Jet Transport Noise Reduction Research”, NASA Langley Research Center.

Prat, D., Surply, T., and Gisquet, D., 1997, “Application of CFD Methods to Propulsion System Integration in the Future Supersonic Transport Aircraft”, Americam Institute of Aeronautics and Astronautics, AIAA-97-2212

Riedel, H., 1998, “Analysis of the Static Pressure Distribution on a Laminar Flow Nacelle Based on Euler Calculations and Flight Measurements”, Aerospace Science and Technology, No. 2, 129-143.

Riedel, H., and Sitzmann, M., 2002, “Aspects of Flow Transition Detection When Flight Testing Engine Nacelles”, Journal of Aircraft, Vol. 39, No. 6, November-December.

Rodriguez, D. L., 2000, “A Multidisciplinary optimization method for designing inlets using complex variables”, Symposium on Multidisciplinary Analysis and Optimization, AIAA 2000-4875.

Rumsey, C. L., Rivers, S. M., and Morrison, J., H., 2004, “Study of CFD Variation on Transport Configurations from the Second Drag-Prediction Workshop”, Computers & Fluids, ELSEVIER.

Smith, C. F., Crossley, W. A., 2000, “Investigating response surface approaches for drag optimization of a subsonic turbofan nacelle”, Symposium on Multidisciplinary Analysis and Optimization, AIAA 2000-4797.

Tillman, T., G., Hwang, D. P., 1999, “Drag Reduction on a Large-Scale Nacelle Using a Micro-Blowing Technique”, AIAA-99-0130.

Vadyak, J. and Atta, Essan H., 1983, “A Computer Program for the Calculation of Three-Dimensional Transonic Nacelle/Inlet Flowfields”, NASA Contractor Report 166528.

Wilhelm, R., 2002, “Inverse Design Method for Designing Isolated and Wing-Mounted Engine Nacelles”, Journal of Aircraft, Vol. 39, No.6, November-December.

Wilhelm, R., 2004, “An inverse design method for engine nacelles and wings”, Aerospace Science and Technology, aescte133, ELSEVIER.

Yates, D. E., Blodgett, K., and Kafyeke, F., 1998, “High Speed Aerodynamic Integration of a Fuselage-Mounted Turbofan Engine”, American Institute of Aeronautics and Astronautics, AIAA-98-3421.

6. Responsibility notice

The authors are the only responsible for the printed material included in this paper.