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Design Synthesis and Optimization

Concept Study for a Mach 6 Transport Aircraft

(Extended Abstract)

J.M.A. Longo[1], R. Dittrich, D. Banutti, M. Sippel[*], J. Klevanski[*]

German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology, 38108 Braunschweig, Germany

[*]German Aerospace Center (DLR), Institute of Space Systems, 28359 Bremen, Germany

G. Carrier, Ph. Duveau

Office National d'Etudes et de Recherches Aérospatiales (ONERA), FR-92190 Meudon, France

A. Loubeau, F. Coulouvrat

Université Pierre et Marie Curie (UPMC), 4 place Jussieu 75252 Paris cedex 05, France

R. Jarlas, O. Hamnér

Swedis Defence Research Agency, (FOI), 164 90 Stockholm, Sweden

D. Perigo, J. Steelant

European Space Agency Technical Center, (ESA-ESTEC), 2200 AG Noordwijk ZH, the Netherland

A conceptual study is here presented and discussed on the possibility to transport 200 passengers over a distance of about 7000km in a nominal point-to-point mission through the Atlantic (either London-New York or London-Rio) at a cruise Mach number of 6 and an altitude about 30km. Because of the challenge the mission poses, its is being optimised with the major disciplines involved by means of Multi-Disciplinary Optimisation (MDO) tools as a way to realize an optimum integrated airframe/propulsion aircraft. The environmental impact is being analysed in terms of the resulting sonic boom. No experimental data is foreseen to be generated but CFD assessments of the configuration by means of independent results are made. The target of the study is not to maximize the efficiency of the mission but to identify if such a mission could succeed today. Preliminary results, available at the time of this draft indicate the potential to realize such airplane.

Nomenclature

(to be provided with the final manuscript)

I. Introduction

The rationale to develop a high-speed transport aircraft in line with very high ecologic and economic requirements is based on continued air travel growth since part of this growth also asks for reduced travel times. The potential to reduce overall travel times by reducing the ground service period is limited. Therefore, further significant reductions in travel time call for high-speed air transport. Reducing travelling time means raising the cruise speed associated with current subsonic aircraft to supersonic or even hypersonic velocities. The dramatic fall in lift to drag ratio at supersonic speed on the one hand but the increased propulsion efficiency on the other hand requires a design with an efficient propulsion-airframe integration to avoid high fuel consumption. Previous supersonic research in Europe was mainly focused on cruise Mach numbers similar to Concorde, around Ma=2. The challenges in designing a transport aircraft for a cruise Mach number of 6 largely exceed those recognised to achieve flight in the conventional supersonic regime. Between the seventies and the nineties, the SR-71, a military high altitude reconnaissance aircraft (i.e. a high altitude high cruise Mach number) was operating at Mach 3. On the other side, no operational Mach 6 aircraft has existed at all at any time. The only experimental Mach 6 vehicle to have flown is the X-15 but it was conceived to perform an acceleration climb by a non-airbreathing engine followed by an almost parabolic non-powered descent flight for a total duration of about 1 minute, i.e. a mission far a way from a high altitude high cruise Mach number. Indeed, still today there is no clear evidence if one can realize a high altitude Mach 6 aircraft. From the aerodynamic point of view it is clear that in order to realize cruise at high-speed, Mach

[1]Head Spacecraft Branch, Lilienthalplatz 7, 38108 Braunschweig, Jose.Longo@dlr.de

numbers (M > 5), high lift over drag (L/D) ratios must be achieved, but that is in opposition to sonic-boom mitigation guide-lines requirements. The concept of boom minimization is based on suppressing the coalescence of multiple secondary shock waves caused by the airplane in supersonic flight, so that the overpressure at ground level is reduced. This can be achieved through the manipulation of aircraft's design characteristics, resulting in an optimised wave pressure signature with significant sonic boom loudness attenuation. Advanced low-boom configurations can be achieved by a more uniform lift distribution stretched over a longer length, so that the sonic boom maintains its weaker mid-field features with a lower bow shock. However, in order, , to obtain adequate boom loudness suppression, the area distribution of an aircraft must be carefully determined aerodynamically. However, such advanced low-boom designs induce drag penalties. Because of the challenge any new high-speed aircraft development poses, its design needs to be highly optimised regarding all main disciplines involved, i.e. the development and application of a Multi-Disciplinary Optimisation (MDO) tools are in the end the only way to realize an optimum integrated airframe/propulsion aircraft.

Here a conceptual study is presented exploring the possibility to transport 200 passengers over a distance of about 7000km in a nominal point-to-point mission through the Atlantic (either London-New York or London-Rio) at a cruise Mach number of 6 and an altitude of about 30km. The target of the study is not to maximize the efficiency of the mission but to identify if such a mission could be successful today. Further, to minimize cost and time, the study departs from the most "close to the target" configuration [1] selected by the working team from a group of configurations identified in available literature. A multiple-point MDO process relying on high fidelity tools for flight phase models involving the disciplines of aerodynamics, structures and flight mechanics, is being developed during the study, to design a high-speed transport aircraft for a cruise Mach number of Ma=6, with sufficient capacity for transonic acceleration and landing. This MDO takes into account a specific propulsion system by using integral performance data and also takes into account a structural model. Further, trajectory assessment, internal layout and mass estimation are provided in the study. A second MDO process is being developed and applied for the design of the air-intake, to satisfy the demands of the propulsion system. The pre-optimized forebody will be integrated in a final multiple-point airframe MDO loop, allowing a reduction in the overall computational effort. The environmental impact of such a vehicle is focused onto specific analyses of the resulting sonic boom, accounting for atmospheric dispersion at high altitudes. Since no experimental data are planned for the present study, two evaluations of the configuration are scheduled at the early stage and at the end of the study by means of independent CFD results. This process uses a Navier-Stokes code previously validated with experimental data available for the base line configuration. The following chapters present an overview of the individual contributions of the working-team to the study, while the results of the MDO process will be available for the final paper.

II. Airplane Shape Definition by Multidisciplinary Multiple-Point Design Optimization

From the aerodynamic point of view it is clear that in order to realize cruise at high-speed Mach numbers (M > 5), high lift over drag (L/D) ratios must be achieved. In the past different approaches were used to come closer to this goal resulting in different designs like 'waverider' concepts or long slender fuselage designs with highly swept wing leading edges. Unfortunately most of them stayed in theoretical status due to the huge amount of physical and technical problems for high aerodynamic performance, feasible airframe structure design, efficient propulsion integration or light, robust material applications. Therefore the design should be approached by means of a multidisciplinary optimisation.

The principle work flow for the MDO tool developed by DLR-AS is arranged consisting of parameterised geometry generation, mass model for airframe components and centre of gravity computation, grid building, numerical aerodynamic flow solving, and thrust and trim capability determination (**Fig. 1**, left). Due to its complexity, the engine it self is treated as a 'black box' but the flow field in the intake and in the nozzle is fully computed. With this method three main parameters of the system can be defined; first, the resulting force coefficient in flight direction, second, the aerodynamic lift to drag ratio and third, the geometric point where all pitch moments equal to zero. Comparing this point to the centre of gravity gives trim capability of the configuration. The numerical flow solver code TAU [2] of DLR-AS is one of the main items of the multidisciplinary analysis tool. It is a three-dimensional Reynolds-averaged Navier-Stokes solver based on a finite volume method delivering flow properties in a wide range of Mach numbers from low subsonic up to super-orbital re-entry velocities. Both structured and unstructured grids are supported. To reduce computational effort for the flow solver, the Euler equations combined with a turbulent flat plate model for skin friction estimation is preferred instead of Navier-Stokes solutions. The MDO tool under development is fully integrated in a Python environment. Two main tasks can be identified for the

Python scripts. First, running and monitoring of all subprograms and software tools and second, input and output data handling including data formatting and transfer. Further on, Python is also chosen for the geometry generation module and output post processing for performing constraint checks and goal function update. A geometry tool which fulfils all requirements like easy handling and good batch possibilities based on NURBS (Non Uniform Rational B-Splines) provides a very effective and flexible way for handling all geometry relevant topics resulting in a parameterized geometry where all modifiable components can be handled by input files. An implemented mass model determines the centre of gravity depending on the geometric surface shape and given mass distributions. Point masses for nose and main gear as well as fuel masses are auxiliary added. The outer geometry is formatted and linked automatically to the commercial unstructured grid generator CENTAUR. For the optimisation the SubPlex option of the commercial software SYNAPS POINTER PRO [3] is used.

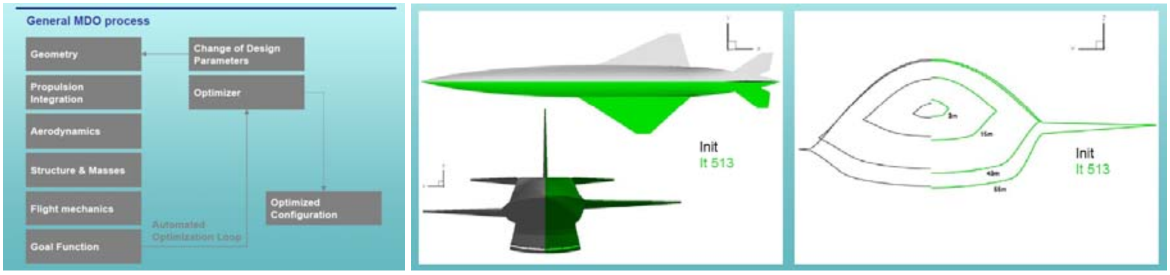

Fig. 1: MDO process for the airframe and first results using a single point multidisciplinary optimization. (DLR-AS)

Like the base line configuration the proposed concept here has a classical turbo-ram-jet integrated design with main components fuselage, wing and classical tail with horizontal and vertical components. All such geometrical parts as well as engine intake, nozzle and exhaust are generated followed by adding interior sections for passenger cabin, front and rear tanks. The fuselage is characterized by elliptic shaped cross sections added by a sharp leading edge for the outer forebody which merges to the wing leading edge. This forebody shape is derived from waverider principles offering high lift to drag ratios. Initially wing and elevator have double trapezium profiles. Further, except from take-off and landing, two flight points of mission profile are identified as critical and hence suitable for the optimisation: start of cruise at Mach 6 and transonic ascent at Mach 1.3. Both points are very important for the overall design and have different requirements. The cruise mode has to be characterized by a high lift to drag ratio, low fuel consumption and fulfilling the trim conditions. Due to the peak of wave drag at transonic Mach numbers the priority is set in the availability of sufficient thrust. Minimizing thrust in transonic flight means more fuel available for cruise. It has to be remarked that hypersonic vehicles can consume 40-50% of overall fuel mass during ascent up to cruise altitude. Both points have big impact on the maximum cruise distance which is defined here as goal function for the MDO. While results of a multiple-point MDO are expected for the final paper, a first test for a single-point MDO with 16 design parameters shows (Fig. 1 right) both the functionality of the multidisciplinary design tool and the capability of the initial Mach 6 configuration for raising cruise distance by fulfilling all constraints. To perform the computations, engine parameters obtained by DLR-SART have been used to provide the flow solver with the flow properties required at the entrance and exit of both turbo and ram-jet engine types (**Fig.2**).

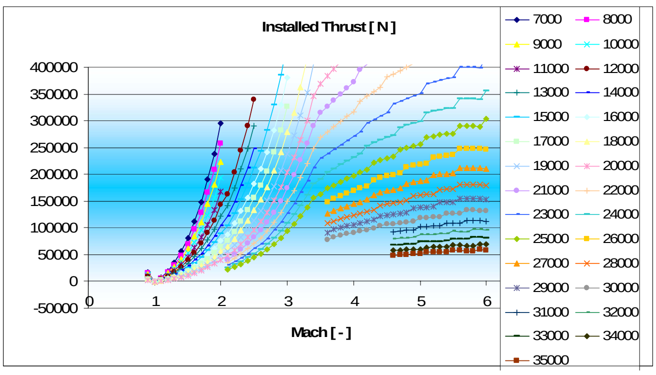

Fig. 2: Turbo-Ram-Jet Performances Data. (DLR-SART)

III. Propulsion Integration by Multidisciplinary Design Optimization

ONERA, as a contributor to the MDO, focuses on the forebody and inlet design as they are closely integrated. A 16 variables parameterization is chosen in order to define the most appropriate design space of research of the optimum for the given optimization problem. The new mesh corresponding to a set of design variables is generated using an advanced volume mesh deformation techniques such as free form [4]. Furthermore, a stochastic approach is used to search the design space. As sketched in **Fig. 3**, the optimization is performed using an automated process to ensure synchronised communication between the optimizer and the analyzer.

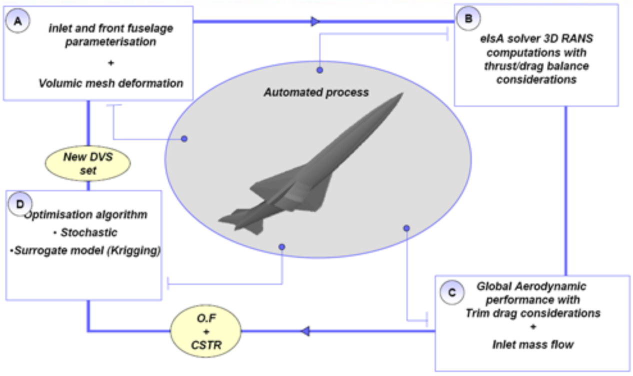

Fig. 3: MDO process for the propulsion integration. (ONERA)

The first stage of the design process consisted in defining preliminary air inlet geometry and performing a detailed aerodynamic analysis of the baseline design. The CFD RANS calculations are performed with the elsA [5] solver, using a structured mesh.

IV. Structure Model & Internal Layout

Preliminary structural design of the Mach 6 aircraft and the integrated propulsion system is one of the activities within the multidisciplinary optimization processes described above. FOI is responsible for the structural model and analysis of airframe and intake. The structural design requirements are, to put it simply, short load-paths and sufficient interior space so that structural members such as beams and frames can meet stiffness and strength-requirements without jeopardizing the weight budget. Stiffness requirements originate either from aircraft handling and aeroelastic considerations, including, for instance, flutter and control-surface authority, or from buckling constraints. Strength (stress) requirements depend on material selection, operating temperature and detail design. In the early design-phases it is important to find out what is driving the structural weight, for instance the slenderness of the fuselage or wing or the layout for principal load-paths. Further, an efficient interface to the aerodynamic surface-description has been created by FOI for the MDO-process, taking flexibility with respect to design changes into account. FOI is also providing input to the design process based on structural design considerations in general. Stress analysis and aeroelastic analysis (**Fig. 4**) are performed using the commercial finite element program NASTRAN.

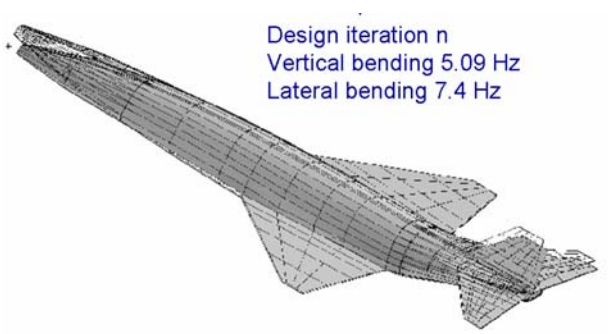

Fig. 4: Preliminary bending analysis of the aircraft' structure (FOI).

The internal layout of the vehicle is responsibility of DLR-SART. Here a design tool for multi-lobe tanks has been extended for preliminary design applications (**Fig. 5**) resulting in a fast, reliable and flexible tool due to its modularity.

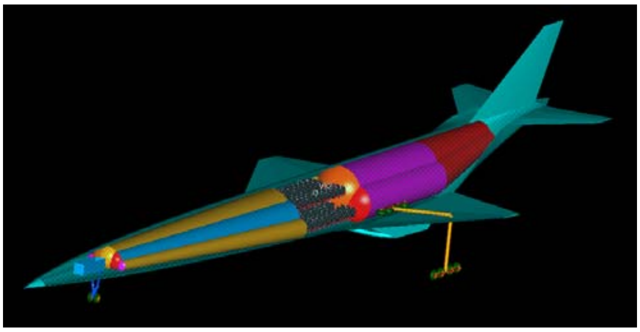

Fig. 5: A Multi-lobe Tank extension module is successfully used for fast design of the internal volume (DLR-SART).

V. Sonic Boom Assessment & Mitigation

The major technologically challenging problem in the design of environmentally compatible high-speed cruise vehicles is the management of the sonic boom and the resulting reflection of the shock system on the ground. The sonic boom is a footprint of the aircraft wake in the farfield. With the aircraft at high altitude the footprint is spread over a large area and energy considerations alone indicate that it should be a weak disturbance. However the human ear is very sensitive and pressure waves produced by supersonic aircraft like Concorde are too strong to allow supersonic overland flight. Here ONERA is applying a multi-layer sonic-boom evaluation approach to calculate the ground pressure resulting from the supersonic flight. The method [14] uses as input the CFD near-field pressure information computed by DLR-AS, taken on cylinders parallel to the freestream location and passing through the vehicle forebody, at a distance R/L = 0.15 (**Fig. 6**). An ONERA in-house developed multipoles matching method based on an azimuthal Fourier transform of the near-field pressures is employed to generate a locally axisymmetrical pressure signal that is then propagated to the ground through a standard atmosphere with the non-linear acoustic propagation code from UPCM.

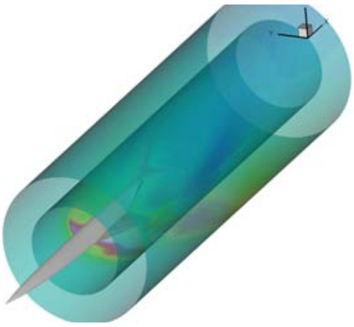

Fig. 6: CFD near field pressure footprint extraction from a DLR CFD solution (ONERA).

To perform the statistical analysis of the variability of sonic booms for the configuration [7], UPMC has extracted meteorological data from the ERA40 database of the European Centre for Medium-Range Weather Forecasts (ECMWF) for the year 1993, at two geographical points near Le Havre (France), which was the beginning of the Concorde's supersonic flight between Paris and New York, and near Edwards AFB (California, USA), where most of the recent sonic boom flight tests have been performed. The two points also are characterized by a very different humidity and temperature (and hence absorption) near the ground level, due to Le Havre being on the seashore while Edwards is in the Mojave desert. The sonic boom propagation predictions include ray tracing in a stratified atmosphere with horizontal winds, nonlinear distortion, atmospheric absorption due to classical thermoviscous effects and rotational relaxation, and atmospheric absorption due to molecular vibrational relaxation of nitrogen, oxygen, and carbon dioxide. The sonic boom emitted in the vertical plane at a 0° azimuth angle was computed every day for the Mach 6 configuration flying near a 28 km altitude and for two headings (West and East).

The width of the geometrical "carpet" has also been simulated systematically, along with lateral distributions calculated once per month. An example of such carpet computation is shown in **Fig. 7**. The ground track sonic boom reaches amplitude of approximately 65 Pa, comparable to that of existing aircraft, most of which are comprised between 50 and 100 Pa (this last value being typical for the Concorde). As expected, the rise time is somewhat larger at Edwards (mean value 1.7 ms) than at Le Havre (mean value 1.0 ms) and in both cases shows a strong variability, the minimum and maximum values being separated by almost one decade. The ICAO standard atmosphere tends to slightly overestimate the sonic boom at the ground level. The carpet width also shows a significant variability, with larger values and more scattering at Le Havre due to stronger winds. As a conclusion, the study estimated that the sonic boom from a Mach 6 configuration would induce at the ground a sonic boom level comparable to existing supersonic aircraft but covering a larger geographical area, due to a higher Mach and a higher altitude.

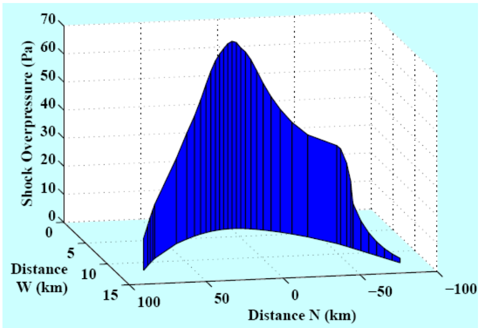

Fig. 7: example of delta pressure carpet prediction (UPMC).

Since, as consequence of those results, overland supersonic flight by such a hypersonic vehicle is likely to be considered unacceptable by a significant proportion of the population, the potential to apply aero-spikes, aero-jet-spikes and plasma-spikes to mitigate sonic-boom is here investigated by DLR-AS. The characteristic of the N wave can potentially be modified employing a spike system on high speed vehicles which could significantly weaken and disperse the strong shock system. Today, aero-spikes are in use on strategic war heads. Indeed, the effect of using either an aero-spike or an aero-jet-spike on a blunt-nosed body is well known. The present study demonstrates that aero-jet-spike behave similarly to physical spikes while in terms of reduction of overpressure the jet outperforms the physical spikes (**Fig. 8**). However, the aero-jet-spikes increases drag substantially and raise additional issues concerning system integration and propellant supply of the retro-rocket but it offers a flexible adaptation of flow manipulation in flight so as to adapt to different flight conditions.

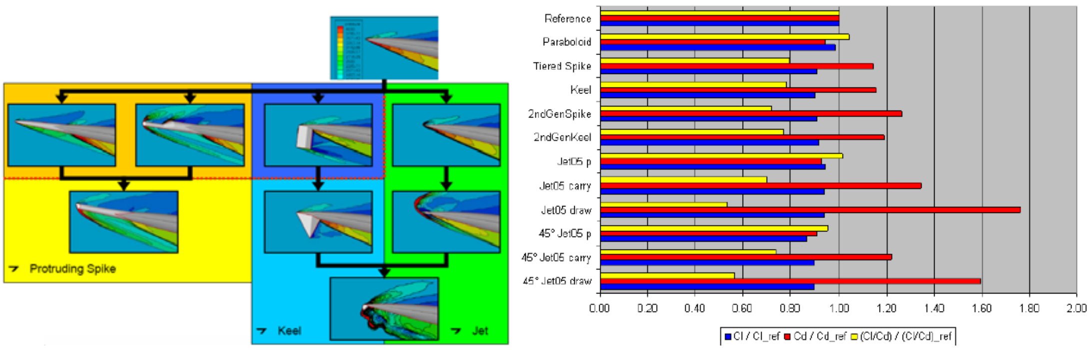

Fig. 8: Pedigree of spike design. Left: geometries, right: impact on aircraft performances. (DLR-AS)

Due to the still not well understood flow physics of such interaction phenomena, one objective is here to assess the potential of counter-flowing plasma jets as candidate technologies to significantly enhance sonic boom mitigation. The efficiency of the plasma flow control approach will be presented with the final paper, comparing the results with those obtained for classical aero-spike and aero-jet-spike applications.

VI. Design Verification

Since the final design of the airplane is based only on CFD results, an exhaustive assessment exercise with the CFD carrier code here employed is being done by ESA-ESTEC. Numerical solutions obtained with the CFD FASTRAN code of ESI GROUP for the base line configuration are compared with available experimental data from literature [8], as is shown in **Fig. 9**. The on-going test matrix includes more than 100 computations, covering longitudinal and lateral coefficients as well as the assessment of the viscous effects. A Cross validation (code-to-code) will be made with the DLR TAU code used in the MDO process in order to identify any major differences between the Euler methodology employed and the full viscous solutions

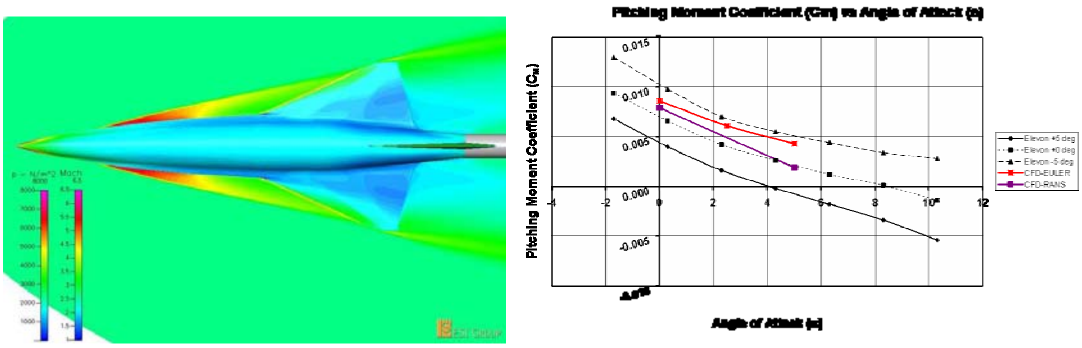

Fig. 9: Surface pressure distribution, left picture, and pitching moment coefficient vs. AoA.(ESA-ESTEC)

VII. Conclusions

The present paper summarises a conceptual study on the possibility to transport 200 passengers over a distance of about 7000km in a nominal point-to-point mission over the Atlantic (either London-New York or London-Rio) at a cruise Mach number of 6 and an altitude about 30km. Because of the challenge the mission poses, its is being highly optimised regarding the major disciplines involving aerodynamics, flight-mechanics, propulsion-integration and structure by means of Multi-Disciplinary Optimisation (MDO) tools. Two different MDO process, one for the airframe and one for the propulsion-integration are applied. The study includes a flexible structural model and provides engine parameters, internal layout (particularly tanks), mass distribution and trim considerations. The environmental impact is being analysed in terms of the resulting sonic boom, while mitigating devices are evaluated. No experimental data but CFD assessments of the configuration by means of independent results are given. Preliminary results, available at the time of this draft indicate the potential to realize such airplane.

VIII. Acknowledgment

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(other references will be added in the final version of the paper)