11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
E. Oñate, J. Oliver and A. Huerta (Eds)

AN AUTOMATIC AERODYNAMIC DESIGN PROCESS IN AN INDUSTRIAL MULTI-DISCIPLINARY CONTEXT

DAVIDE DI PASQUALE*, CARREN HOLDEN†, TIMOLEON KIPOUROS* AND MARK SAVILL*

* Cranfield University, School of Engineering
College Road, Cranfield, MK43 0AL, UK
e-mail: {d.dipasquale, t.kipouros, mark.savill}@cranfield.ac.uk, www.cranfield.ac.uk

† Airbus Operations Limited, Flight Physics UK
Pegasus House Aerospace Avenue, Filton, Bristol, BS99 7AR, UK
e-mail: Carren.Holden@airbus.com, www.airbus.com

Key Words: *Multi-Disciplinary Design Capability (MDDC), Aerodynamic Process, Computational Fluid Dynamics (CFD), Automation, Integration.*

Abstract. In the aircraft industry, aggressive weight targets, shortened development time scale and reduced costs require different approaches for the design process to be competitive in today's global market. A challenge for the scientific community is to adapt to and exploit the trend towards multi-disciplinary consideration of many objectives and design criteria. Such a multi-disciplinary approach is essential in the design process of real world applications. In particular the step change in performance required by the ACARE 2050 vision for commercial transport aircraft will be dependent on the successful integration of Multi-Disciplinary (MD) design capabilities at the preliminary design stage. A preliminary MD approach would allow aircraft architects to study more design alternatives in greater detail. An automated, integrated aerodynamics process is a pre-requisite for such a capability, and so must be developed if this opportunity is to be addressed. The present work is concerned with the development and enhancement of an automatic industrial aerodynamics process that will enable MD trade studies for the preliminary design of aircraft.

1 INTRODUCTION

The design of a large commercial aircraft is a daunting task. It represents the synthesis of a staggering array of technologies, concepts, material and subsystems into a functioning machine. A complete commercial aircraft is one of the most complex systems in operation today. It is not only an engineering system which performs a set of specified functions, but it is also a value-creating mechanism for the manufacturer, and furthermore, it generates revenue to the operator, the airline. For an aircraft industry, in order to be competitive in today's global market, where aggressive weight targets, shortened development time scale and

reduced costs are the primary objectives and constraints, a different approach for the design process is necessary [1].
The field of technical aircraft design is a very well-established and thoroughly documented one. The problem of meeting a set of technical requirements with a system design has been performed hundreds of times by engineers developing new aircraft. Recently, there have been advances in performing these design tasks from a multi-disciplinary standpoint, where several different types of analysis are combined into an optimisation simulation process. In the design of complex engineering systems, such as a large transport aircraft, it is critical that the interactions between the subsystems of the problem are accounted for. Only by considering the fully coupled system can an optimal design emerge [2, 3, 4]. Several examples of such multidisciplinary analysis and optimisation techniques may be found in the published literature, see for instance the work of Baker [5], Perez [6], and Peoples [7].

2 DESIGN IN AEROSPACE INDUSTRY

In current industrial practice, the design process can generally be divided into three phases: conceptual design, preliminary design, and final detailed design, as illustrated in Figure 1.

Figure 1: Higher level view of a design process

The conceptual design stage defines the mission in the light of anticipated market requirements, and determines a general preliminary configuration, together with first estimates of size, weight and performance. In the preliminary design stage the aerodynamic shape and structural skeleton progress to the point where detailed performance estimates can be made and guaranteed to potential customers. While the costs are still fairly moderate, decisions made at this stage essentially determine both the final performance and the development costs. In the final design stage the structure must be defined in complete detail, together with complete systems, including control systems, avionics, electrical and hydraulic systems, landing gear, and cabin layout for commercial aircraft. Major costs are incurred at this stage, during which it is also necessary to prepare a detailed manufacturing plan.

2.1 The role of CFD in the design process

In the development of commercial aircraft, aerodynamic design plays a leading role during the preliminary design stage, in the course of which the definition of the external aerodynamic shape is typically finalized. The aerodynamic design process starting point is an initial CAD definition resulting from the conceptual design. The entire design technology is driven by the increased industrial demand for reduction of design cycle time and minimisation of the need for the costly a posteriori design modification. In general, the development of computational design methods aim to support man-in-the- loop activities, by increasing the level of automation during the design process. Although automation can reduce the design processing time, its success depends heavily on the reliability and accuracy of the computational methods and the definition of the goals. The actual use of CFD by aerospace companies is a consequence of the trade-off between perceived benefits and costs. The need for rapid turnaround, including the setup time, is also crucial. In order to realise these advantages it is essential to move beyond the flow simulation to a capability for aerodynamic shape optimisation and ultimately multidisciplinary system optimisation.

2.1.1 Complexity of fluid flow

The complexity of fluid flow is well illustrated in Van Dyke's Album of Fluid Motion [8]. Many critical phenomena of fluid flow, such as shock waves and turbulence, are essentially non-linear and the disparity of scales can be extreme. The flows of interest for industrial applications are almost invariantly turbulent. The length scale of the smallest persisting eddies in a turbulent flow can be estimated as of order of $1/Re^{3/4}$ in comparison with the macroscopic length scale. In order to resolve such scales in all three spatial dimensions, a computational grid with the order of $Re^{9/4}$ cells would be required. Considering that Reynolds numbers of interest for airplanes are in the range of 10 to 100 million, the number of cells can easily overwhelm any foreseeable supercomputer. Consequently mathematical models with varying degrees of simplification have to be introduced in order to make computational simulation of flow feasible and hence produce viable and cost-effective methods in the real world. Figure 2 indicates a hierarchy of models at different levels of simplification which have proved useful in practice. Inviscid calculations with boundary layer corrections can provide quite accurate predictions of lift and drag when the flow remains attached. Procedures for solving the full Reynolds Average Navier-Stokes (RANS) equations are necessary for the simulation of complex separated flows.

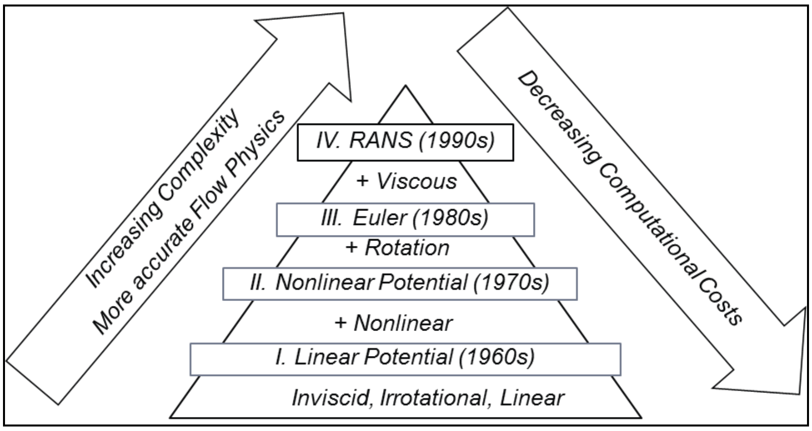

Figure 2: Hierarchy of models for industrial flow simulations

In external aerodynamics most of the flows are steady, at least at the macroscopic scale. Computational costs vary drastically with the choice of mathematical model.

3 MD PROJECT AND AERO PROCESS OVERVIEW

The step change in performance required by the ACARE 2050 [9] vision for commercial transport aircraft is, in part, dependent on the successful integration of Multi-Disciplinary

Design Capabilities (MDDC) at the preliminary design stage. Conceptual design capabilities are now extensively developed and routinely used at conceptual project level. However, the challenge for today is to transition smoothly from conceptual to preliminary design whilst maintaining a true Multi-Disciplinary (MD) approach, as sketched in Figure 3.

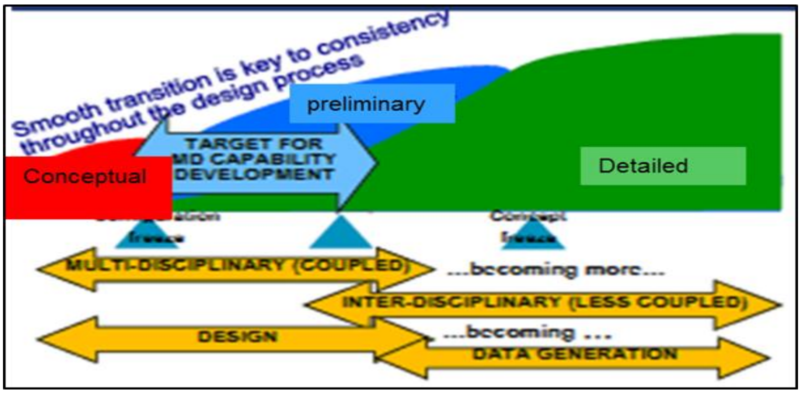

Figure 3: Sketch of target for MDDC development

The design space must be progressively constrained, whilst at the same time increasing the level of modelling fidelity and keeping as many design options open for as long as possible, as illustrated in Figure 4, where the Levels represent MD toolsets which are appropriate for the various stages of overall aircraft design.

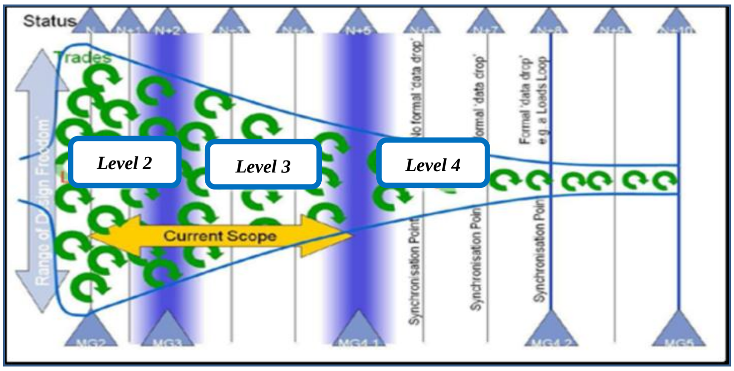

Figure 4: Aircraft design concept convergence process

A preliminary multi-disciplinary Level 3 design capability should use methods with higher level of fidelity than is possible with current Level 2 that is realised by the Conceptual Design team. At the same time the MD Level 3 has to be less consuming than methods available at Level 4 that are employed within engineering centres of competency during the detailed design phase, with specialist high fidelity methods used to mature designs to production. Such methods are typically complex and require long run times. Level 3 represents an opportunity to enhance the overall design process by introducing MD processes, which use methods pitched between Level 2 and 4 in terms of both fidelity and rapidity.

A design iteration, from geometry to cost, should be performed within a week, and for this reason a higher degree of automation and deployment of appropriate methods is necessary.

The main benefit expected from a preliminary MDDC is the enabling of robust aircraft architectures, where no bad features will be revealed in later detailed design phases which could involve more engineers for expensive rework and which may not deliver the committed aircraft performance. A Level 3 MD design capability will ultimately strengthen industry competitive position by reducing development time and costs, and delivering aircraft with reduced environmental, purchase and operating costs. An automated, integrated Level 3 MD aerodynamics process is a pre-requisite for such a capability, so must be developed if the MD opportunity is to be addressed. The preliminary design process high level target as previously stated is to go from geometry to cost in a week time frame. As with the other domains, the MD aerodynamics process within the design project must be compatible with these requirements, which means that the time per aero design iteration should be no more than 24 hours, to fit with a week-long overall process.

3.1 Aero process

The adopted process should have increased fidelity over methods available at Level 2 such as semi- empirical and Panel methods, whilst at the same time to be less time-consuming than methods available at Level 4 such as RANS CFD. An Euler coupled with a boundary layer method has been chosen as flow solver kernel. Figure 5 shows how the MD Aerodynamics Process should be integrated into the overall multi-disciplinary process. The inputs required are the datum aircraft geometry and flight envelope definitions, which typically include Mach number, incidence ranges, Reynolds number and air temperature, which are common to all domains.

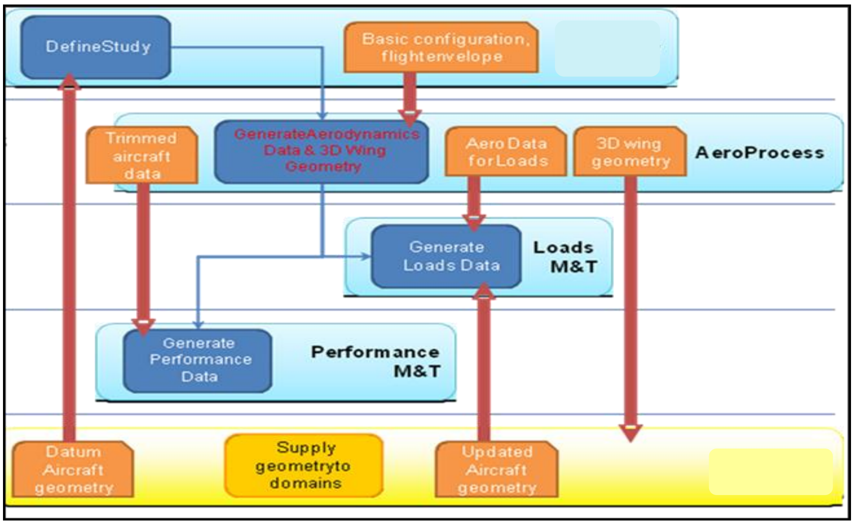

Figure 5: Aerodynamics process vision within multidisciplinary context

The MD aerodynamics process produces aerodynamic data. The data is passed downstream to the Performance domain and, via Aerodynamic Data for Loads methods, to the Loads domain. A generalised MD aerodynamics process architecture is illustrated in Figure 6.

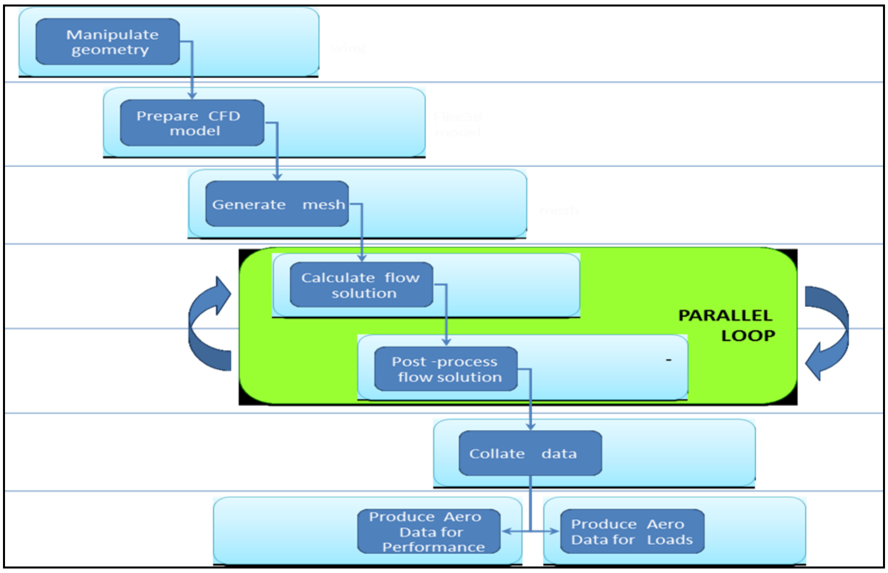

Figure 6: Schematic of MD Aerodynamics Process

In the present case the aero process has been developed and integrated using the commercial software 'ModelCenter', which is an integration/process building environments. It allows any program to be 'wrapped' in a generic, re-usable way to produce a 'component'. A Wrapper is a set of instructions that describe inputs, outputs, and how to execute the analysis. Components can be connected by linking their output and input variables, forming a 'workflow'. The finished workflow can be run automatically from start to finish and saved as a ModelCenter model. All the components have been wrapped using Python language scripts. A screenshot of the aero process implemented in ModelCenter, in its contracted form, is shown in Figure 7.

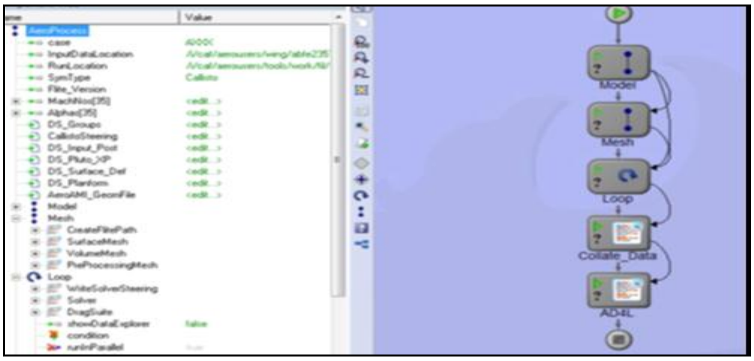

Figure 7: MD Aerodynamics Process implementation in Model Center

The first step is to import the new CAD description of the wing geometry from a database using a data management tool. In order to prepare the geometry for the start of the automatic aero process, the geometry needs to be converted from Catia to IGES format using Catia and then from IGES to an *icms file format readable by the pre-processor using an IGES to *icms converter. Once the *icms file is generated, it will be the input for the automatic aero process.

The overall process is divided into several components. The first one is “Model” containing, in turn, another four components, as shown in Figure 8. These four components manipulate the geometry and prepare the CFD model. The purpose of it is to generate a model that will be used as input afterwards for the meshing process.

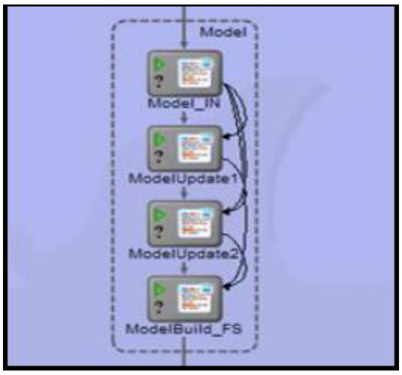

Figure 8: “Model” collapsed showing its four components

The first component loads the pre-existing model and the new wing description (ICMS file) into ModelCenter. The second takes the new wing and splits this into two entities at the trailing edge crank. The third one replaces the two new WING entities in the Model. The last one, “ModelBuild”, creates valid model with correct edges and intersections, adding the viscous mesh and the sources needed for the mesh generation. See Figure 9.

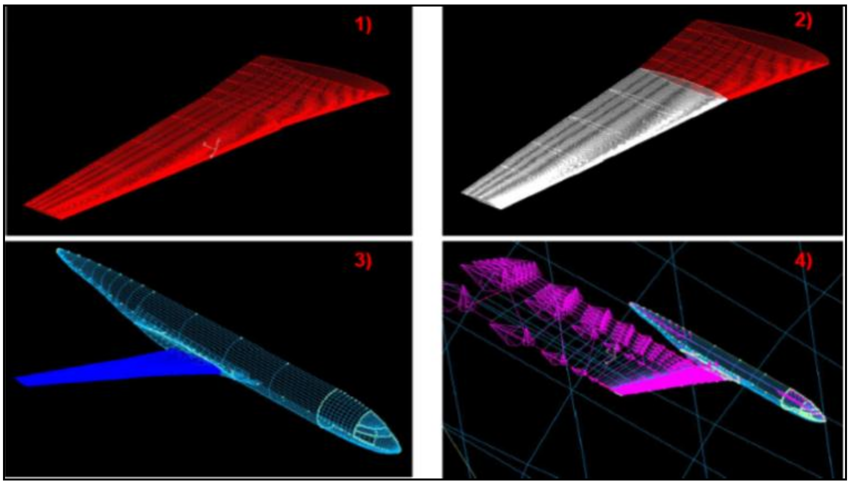

Figure 9: Visualization of the four components output

In addition, the fourth component has the capability to transform the wing from jig to flight shape, before running the meshing process. The baseline wing panels are defined with only the design sections. These sections are translated using dx, dy, dz translations and rotations defined in an external text file. The transformed wing panels are re-sampled in a spanwise direction to give a fine distribution of points aiding surface grid generation. Figure 10 compares the starting geometry and the flight shape.

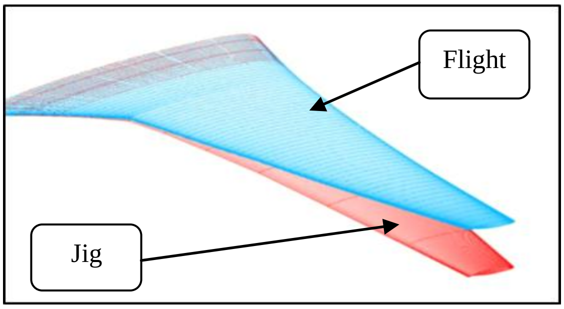

Figure 10: Jig to flight shape transformation

After the model is completed, the next step is the generation of the mesh.
The loop module is the flow solver loop shown in Figure 11.

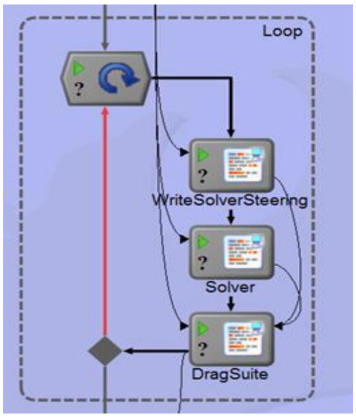

Figure 11: "Loop" collapsed showing its three components

In its original version the loop could only run in serial mode, which means that around 70 hours were necessary to generate aerodynamics data for an flight envelope, comprising a minimum of 35 operating points (7 incidences at each 5 Mach numbers) as required for the calculation of loads. This time to generate the aero data for loads is not compatible with optimisation requirements, and so led the authors to work on the looping capability in liaison with the Model Center developers in order to address this issue; testing and reporting all the problems encountered to them. After a long iterative process, loop parallelization has been successfully implemented which now allows the running of data points simultaneously via grid computing resources. This capability has drastically reduced the wall-clock time and consequentially met the requirements of the Aero Process in the Multi-disciplinary context. In the first component "WriteSolverSteering" the input of the simulation are set, such as number of iterations, Mach numbers and angle of incidence range. The second component is the Euler flow solver coupled with a boundary layer method. Following flow solution the Drag suite component performs the necessary post-processing to generate the output file containing the overall forces and drag breakdown, span loading and other diagnostics. The last two components of the process assemble the CFD data into a polar and extracts the polar data. Specifically, the last tool is used to supply linearised aerodynamic data for loads calculation, producing aerodynamic data in a suitable format for load methods.

4 VALIDATION

In order to check the accuracy of the flow solver, pressure profile results have been compared with RANS data results. The RANS results are for a complete wing-body configuration, including engine, flap track fairings and winglet as in Figure 13 (left), although the Model Center geometry is a clean wing (right). The “Model Build” component has not yet the automatic capability, at least at the moment, to handle winglet. The winglet was added manually for a more fair comparison with the RANS data. In this paper some selected results are shown, specifically the chordwise pressure distribution at only four spanwise sections (shown in figure 13) for only the cruise Mach number (M=0.8) and at two different angles of attack, see Figures 14 and 15.

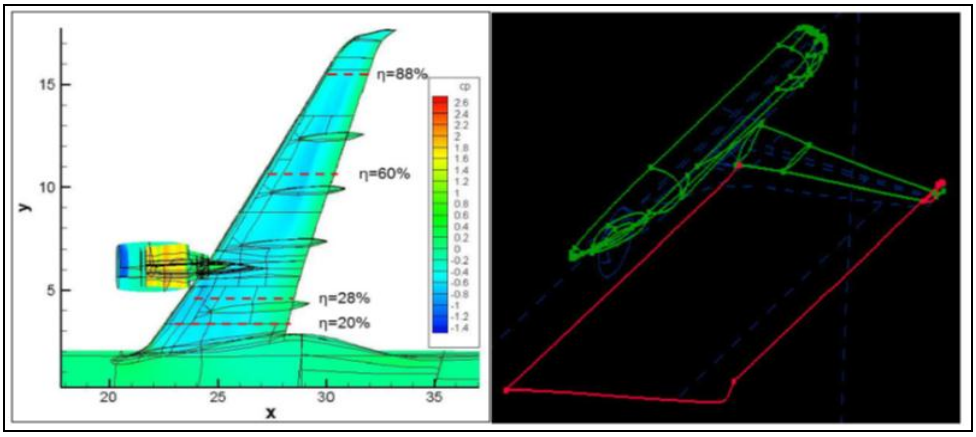

Figure 13: RANS model (left) and Euler model (right)

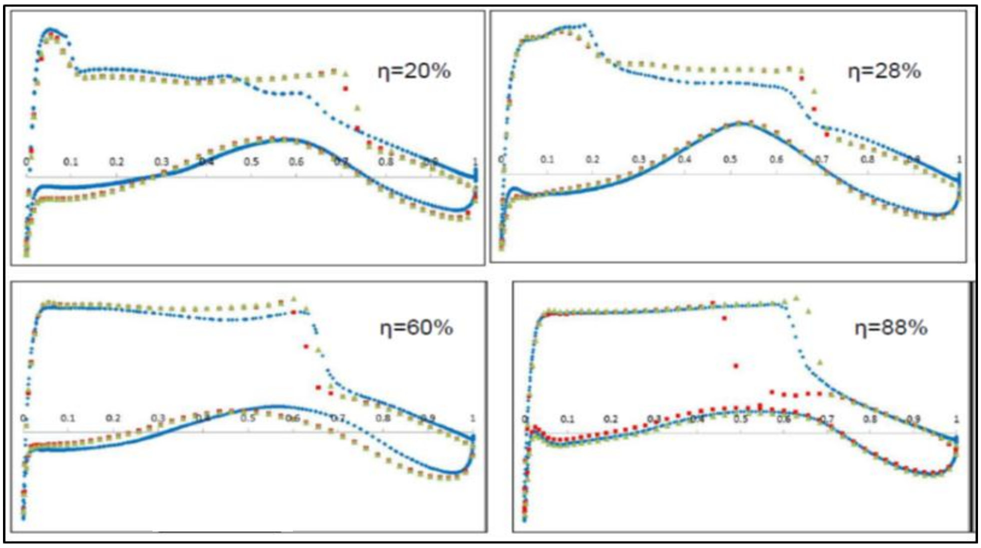

Figure 14: Cp distribution at alpha=3

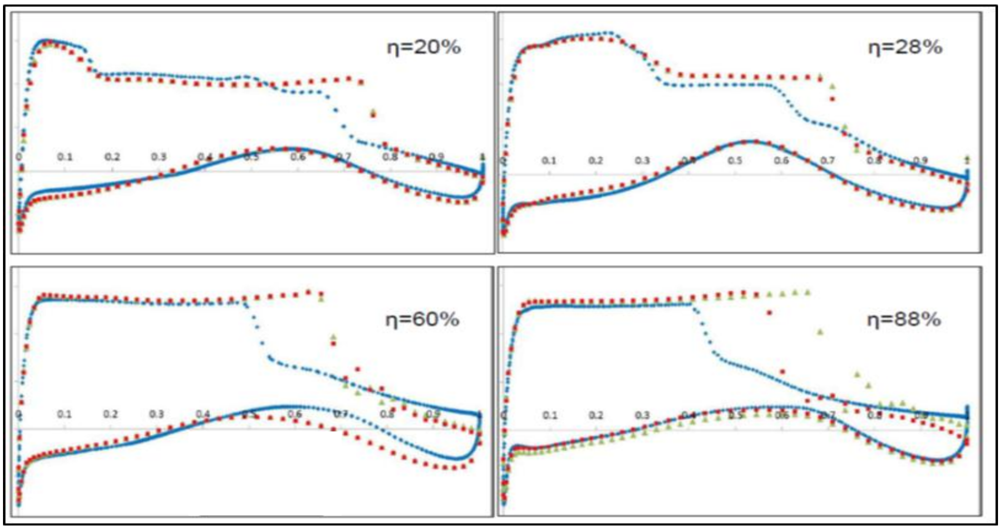

Figure 15: Cp distribution at alpha=5

The blue diamond symbols represent the RANS data, the red circles represent the Euler Coupled solver results for a clean wing configuration model without winglet and the green triangle symbols represent the Euler Coupled results for a clean wing configuration including the winglet. Looking at all the plots in the above figures is clear that the winglet has not affected the inboard sections but an effect is visible at the outboard section. For an angle of attack, alpha of three degrees (figure 14) the results computed for the winglet case, within the aero process are in good agreement with the RANS data. (As previously stated, the RANS simulation includes engine and flap track fairings that of course perturb the flow field, compared to the clean wing case). At the highest angle of attack (figure 15) the results are not in good agreement with the RANS data. This is due to a limitation of the Euler flow solver in that it does not predict correctly the flow separation that occurs at such high angles of attack, hence the solution fails to predict the lift loss due to the separation; leading in general to an over-estimation of the loads. For the cruise condition at smaller angles of attack, the Euler coupled solver predicts quite well the flow physics and at much lower computational cost compared to RANS simulations.

5 RESULTS

The developed aero process runs automatically from start to end, calculating 35 points (7 angles of attack for each of 5 different Mach numbers) in about three hours using 35 different CPUs. Figure 16 shows lift coefficient and pitching moment coefficient along the span for some of the simulations performed.

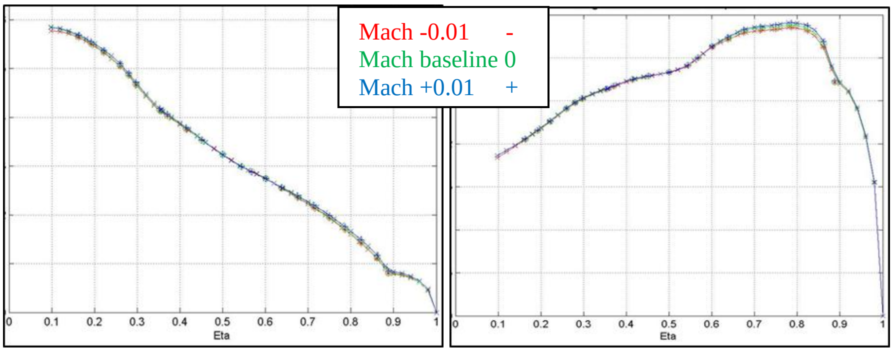

Figure 16: Wing Local pitching moment (left) and Lift coefficient (right) at Alpha=0 along the span passed to the load domain for three different Mach numbers

6 CONCLUSION AND FUTURE WORK

The Aero solution chain has been implemented as a high speed aerodynamic evaluation capability. However there is not yet an automated complementary Aerodynamic design process. It is possible only to perform this manually at present, and the module to generate the Aero Data for performance has not yet been implemented in the work flow. Hence, further developments are necessary to cover these two aspects, as highlighted in Figure 17.

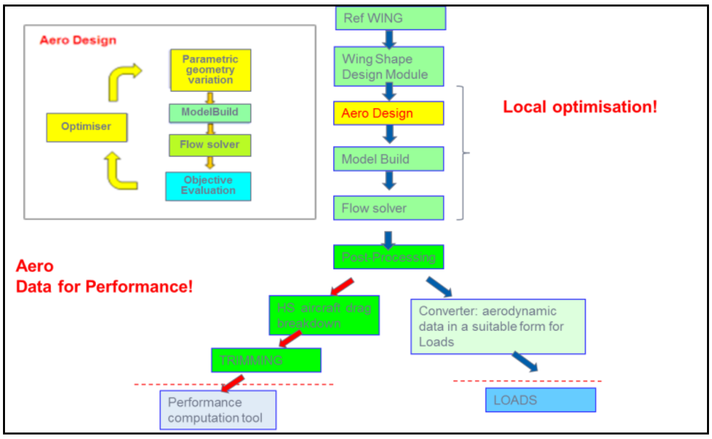

Figure 17: Further advances needed on the automatic aero process workflow

Some further modifications will also have to be made to the “ModelBuild” software to allow it to handle winglets. In conclusion, the automatic and integrated aero process developed thus far enables generation of aero data for loads for the cruise phase, in a time frame which is compatible with the requirements of an overall multi-disciplinary preliminary design process at this level. The scheme has already been tested for different aircraft configurations, from single aisle to long range aircraft, and has been demonstrated to be seamless and robust. Once the further developments discussed are added into the current aero process, it will be ready to be integrated into the overall preliminary multi-disciplinary design process. Such a preliminary multi-disciplinary design approach, should lead to a faster, more efficient design process resulting in both a step change increase in aircraft performance and a considerable reduction in time to market.

REFERENCES

[1] Sehra, A.K. and Whitlow, W.J. Propulsion and Power for 21st Century Aviation. *Progress in Aerospace Science*, Vol. 40 pp. 199-235, 2004.

[2] Price A. R., Keane A. J., Holden C. On the coordination of Multidisciplinary Design Optimisation Using Expert Systems. *AIAA Journal*, Vol. 49, No 8, 2011.

[3] Ghisu T., Parks G. T., Jarrett J. P. and Clarkson P. G., An Integrated System for the Aerodynamic Design of Compression Systems—Part I: Development. *Journal of Turbomachinery* Vol. 133, Issue 1, January 2011.

[4] Ghisu T., Parks G. T., Jarrett J. P. and Clarkson P. G., An Integrated System for the Aerodynamic Design of Compression Systems—Part II: Application. *Journal of Turbomachinery* Vol. 133, Issue 1, January 2011.

[5] Baker A. P., Mavris D. N. Assessing the Simultaneous Impact of Requirements, Vehicle Characteristics, and Technologies During Aircraft Design. *AIAA paper* 2001-0533, Jan, 2001.

[6] Perez Ruben E., Liu Hugh H. T. Flight Dynamics and Control Multidisciplinary Integration in Aircraft Conceptual Design Optimization. *10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference* Albany, New York, AIAA 2004-4435, 30 Aug. - 1 Sep, 2004.

[7] Peoples R., and Willcox K., Value-Based Multi-Disciplinary Optimization approach for Commercial Aircraft Design and Business Risk Assessment. *Journal of aircraft* Vol. 43 No.4, July-August, 2006.

[8] Van Dyke M., An album of fluid motion, Parabolic Press, 1982.

[9] European Commission, ACARE Flightpath 2050 Europe's Vision for Aviation, 2011.