THE ULTRA-GREEN AIRCRAFT - SOME ASPECTS FROM THE AEROELASTIC POINT OF VIEW

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1 Summary

This article describes selected aspects of multidisciplinary aircraft design in general, and aeroelasticity in particular, on the example of a new class of civil transport aeroplanes: the "ultra-green" aircraft. It is to be expected that this new class will demand for novel design solutions, probably up to a degree which can be described as an entirely new configuration.

The article reflects the personal opinion of the author and is intended to serve as a stimulus for an open and fruitful discussion at the UCLA/Univ. of Tokyo/Kyushu Univ./JAXA workshop "Lectures and Workshop International - Recent Advances in Multidisciplinary Technology and Modeling", to be held from May 23rd to May 25th at Tokyo, Japan.

2 Introduction

The early days of air travel were exciting times - not only for the passenger, but also for the aircraft designer and engineer. Fundamentally new ideas, concepts and technologies were evolving every year, many manufacturers and their sometimes very individual products were competing on the developing market, and the general progress could be seen by everybody at the first glance. Figure 1 is intended to capture that rapid development in a sequence of transport aircraft. It is covering a period of 25 years, ranging from the times of propeller-driven biplanes to the first commercial jet airliner, the de Havilland Comet. And less than five years later, the famous Dash 80 took off for its maiden flight - the prototype of the Boeing 707 which proved to be the "blueprint" of the modern jetliner.

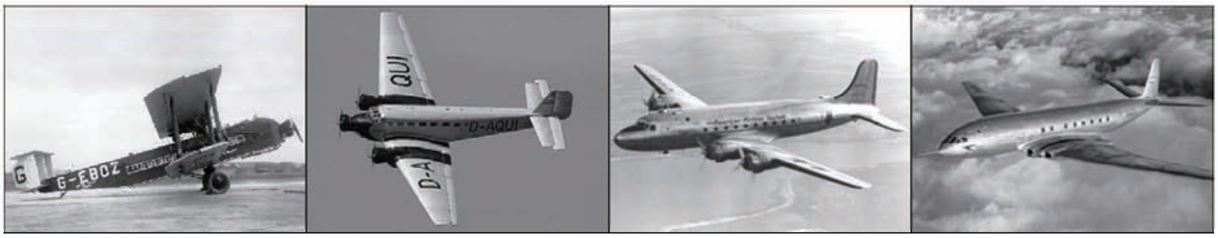


Figure 1 *Sequence of transport aircraft over a period of 25 years (maiden flight): Armstrong Whitworth A.W. 154 Argosy (1926), Junkers Ju-53/3m (1932), Douglas DC-4/C-54 (1942), de Havilland DH 106 Comet (1949)*

More than twice that time has passed since then. Figure 2 shows a comparison of the Boeing 707, and an artist's view of the Boeing 787 which is currently under development and supposed to have its first flight in less than a year. From the overall picture, not much fundamental difference can be detected between the design of 1954 and that of 2007; the technological progress is hidden in the detail, and the path since the 1950s has been an evolutionary rather than a revolutionary one.

Figure 2 *The "classical" jet airliner configuration: Boeing 707 (1954) and Boeing 787 (~2007)*[1]

One of the reasons is that the basic requirements have not changed: the business case is still to transport the passenger safely, quickly and with a certain amount of comfort over a distance of several thousand miles - and to be able to make money on it. But with the impressive growth in air travel over the last five decades and the prospect of comparable future development, a new class of design requirements arise. At a time when flights between European capitals or major US cities are offered for less than 50 $, the primary public interest is no longer to further enhance mobility, but to minimise the impact of that mobility on the citizen’s everyday life - in particular, to reduce aircraft noise in the vicinity of airports, and to tackle the global issue of climate change. The environmentally friendly, hence "ultra-green" aircraft is not the only, but one of the most important factors in meeting that public demand.

3 The Ultra-Green Aircraft

3.1 The Background

With growing political pressure, increasingly stringent regulations on emissions and noise, and supported by a continuously rising fuel price, environmental friendliness is becoming a hard, **market-driven requirement** in aircraft design.

This is amplified by a growing, and not always rational, public awareness of environmental issues: future growth of air travel depends on the public image. A first impression of this impact could be seen in early 2007 in Germany, when the United Nation’s report *Climate Change 2007*, [1], led to an emotional public debate, culminating in public incitements of German politicians to avoid travelling by air.

In 2000, European Community Commissioner Philippe Busquin assembled a group of high-ranking experts, the "Group of Personalities", in order to develop a vision for aviation in the year 2020, entitled *European Aeronautics: A Vision for 2020,* [2]. This report aims to find a balanced perspective between societal and political demands, technological feasibility and economical reasonability. Its findings have been transformed into a roadmap for European research in ACARE’s *Strategic Research Agendas SRA 1* and *SRA 2*, [3].

1. Artist’s view (© Boeing, picture is licensed under Creative Commons Attribution ShareAlike 2.0 Germany License)

Vision 2020 put forward quantified goals against which future aeronautical products will be measured. The environmental goals for air transport are:

- to reduce fuel consumption and CO_2 emissions by 50%,
- to reduce perceived external noise by 50%,
- to reduce NO_x by 80%, and
- to make substantial progress in reducing the environmental impact of the manufacture, maintenance and disposal of aircraft and related products.

These goals are by no way mandatory for aeronautical products, but they may serve as a reasonable benchmark of what the market will demand from the next generation of civil transport aircraft. Extrapolating the achievements in emissions and noise reduction of the last 30 years reveals that evolutionary improvements along the current trend line will not result in the 2020 targets being met. To achieve the step change in performance required to meet the environmental challenge demands for the incorporation of breakthrough technologies. It is probable that this breakthrough will lead to aircraft configurations which are different to that we grew accustomed to since the B 707 made its first transatlantic crossing, like the concept depicted in Figure 3.

Figure 3 *Concept of an ultra-green transport aircraft, presented by D. Schmitt, VP R&T and Future Projects, Airbus (France) at ICAS 2004 Congress, [4]*

3.2 "Ultra-Green" and Aeroelasticity

A major driver towards the ultra-green aircraft design is weight reduction. Reducing structural weight directly translates to increased flexibility of the airframe - a "wake-up call" for aeroelasticians:

- *New aircraft configurations are "terra incognita".*
  There is little empirical knowledge to rely on, analysis tools may not suit the particular needs of that design, modelling techniques will have to be adapted or improved, decision makers and authorities may be reluctant to go ahead, etc. This "climate of uncertainty" also raises the bar for aeroelastic analysis and certification.

- *Increased structural flexibility of the airframe, although in certain ways a disadvantage, may also be exploited.*
  Concepts like aeroelastic tailoring or actively controlled aerodynamic measures may reduce fatigue, gust or manoeuvre loads. The flexibility may also be used to adapt to off-design conditions and thus increase the actual cruise performance.

- *Low-drag wings will be a challenge for the aeroelastic design.*
  The future low-drag wing is expected to have: high-aspect-ratio, little or even negative

sweep, laminar flow and complex flap/slat systems. Local flow separation and shock waves will make high demands on CFD analysis and wind tunnel experiments. Large high-bypass-ratio engines, if attached to the wing, will add additional complexity. For laminar flows, little is known so far of the effects of oscillations of the transition point on aeroelastic stability.

- *A higher level of integration usually results in an increased probability of aeroelastic interactions.*
  Even for new, unacquainted configurations there is one experience the designer or engineer can rely on - pushing the limits in terms of performance and efficiency often leads to unforeseen, and sometimes critical aeroelastic interactions, such as wing-store-LCO, wing-tail-buffet or engine oscillations.
- *The benefits of new technologies have to materialise for the flying aircraft.*
  Local improvements by new technologies may result in adverse effects for the actual aircraft, e.g. because of unfavourable structural deflections or increased trim drag. Designers and engineers must be able to evaluate the eventual gain of a new technology for the overall aircraft.

Designing an ultra-green aircraft design raises high demands on researchers, designers and engineers. This also holds for the discipline of aeroelasticity.

3.3 Activities at the DLR Institute of Aeroelasticity

The *DLR Institute of Aeroelasticity* prepares for this challenge by focusing its strategic research on two key aspects: to further advance its capabilities for detailed investigation of local and global aeroelastic mechanisms, and to embed its methods and tools in an integrated aircraft design environment.

The DLR project *High Performance Flexible Aircraft* (HighPerFLEX, 2004-2006) has paved the way towards these goals. The successor *Integrated Green Aircraft* (iGREEN, 2007-2010) continues the research of HighPerFLEX, concentrating on questions which are of particular interest for aircraft concepts which are designed to achieve a technology leap in respect of environmental sustainability, but will also be beneficial if the trend of the last three decades of evolutionary "small steps" prevails.

The work of HighPerFLEX and iGREEN, as well as that of other projects, has lead to some observations which are connected with aeroelasticity (the only established aeronautical discipline which, by definition, addresses multidisciplinary design), or with the somewhat wider frame of multidisciplinary design and optimisation. These observations will follow in the next section. The reader should keep in mind that these aspects are a personal view and intended to initiate an open discussion at a workshop on *Multidisciplinary Technology and Modeling*, and do not necessarily represent the opinion of all researchers, scientists or engineers at the Institute of Aeroelasticity, or DLR in general.

4 Some Aspects of Multidisciplinary Design on the Example of the Ultra-Green Aircraft

▶ In times of supercomputing and high-fidelity CAx, low- and medium-fidelity methods are important as ever.

Computer power is getting very cheap these days. A combination of off-the-shelf PCs, like Beowulf-Clusters, are matching the performance of the most advanced supercomputers of the 1980ies, but are affordable for the budget of rather small units like institutes and departments.

It is a sweet temptation to use sheer computer power to run parameter variations and optimisations of large high-fidelity models, in the hope to receive the optimal, high-fidelity solution.

But unfortunately, in the real world it is often not that easy:

- Although high-fidelity jobs can nowadays be executed comparatively fast, they still take their time. This limits the number of variations which can be examined. It often pays off to investigate a large design space with analyses of moderate complexity, than to limit the design space to a first, hopefully good guess and then explore it in high-fidelity.
- Performing a medium-fidelity analysis which captures all relevant physical effects, but is still relatively cheap to compute, is a job for an experienced engineer. But inexperienced users are not necessarily achieving better results when applying high-fidelity methods.
- If a good, feasible and robust design has been found by not-so-high fidelity methods, the results can still be crosschecked, "verified" and adjusted by high-fidelity analysis.
- Generating complex models which represent reality down to the tiny detail is more an art than a routine job. Automatically adapting complex models to design changes, e.g. as required in optimisation loops, may lead to very detailed results - but if these results still reflect reality is questionable.
- Last but not least, low- and medium fidelity methods prove to still deliver relevant results, even for complex problems.

An illustrative example which may underline this plea for medium-fidelity analysis derives from the HighPerFLEX/CTARP project WIONA (wing with oscillating nacelle), a joint DLR/ONERA experiment. The objective of this experiment was to investigate an nacelle-pylon-wing interference effect which can cause violent nacelle/engine oscillations, [6]. This potential aeroelastic instability was caused by unsteady shock wave/boundary layer interactions, Figure 4.

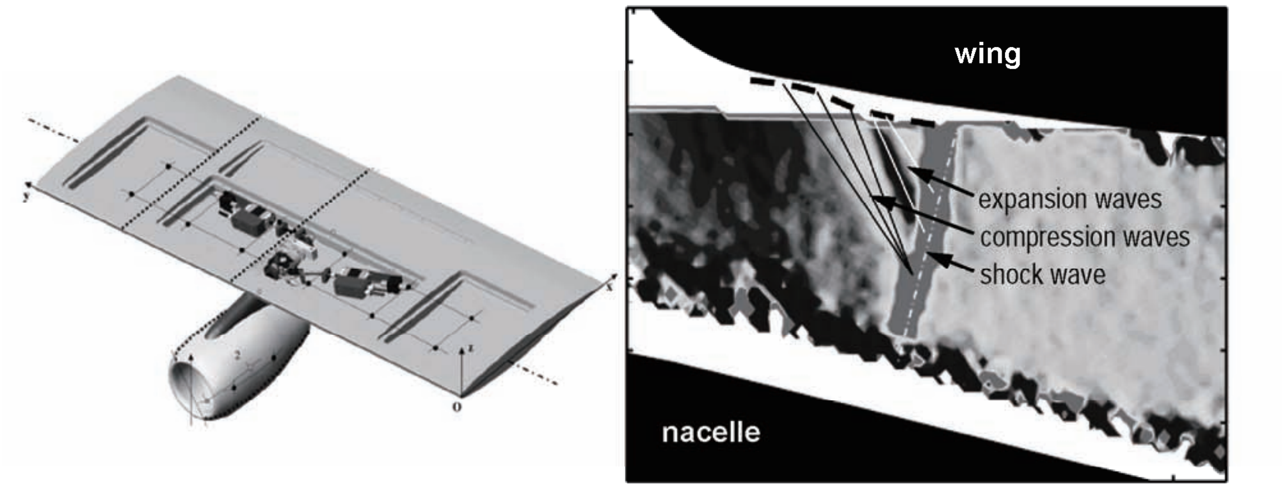


Figure 4 *Research project WIONA: sketch of the model with excitation system (left) and PIV-evaluated, streamwise development of mechanical energy for the maximum downstream shock location*

Engine-wing interference scenarios, including the WIONA experiments, were also simulated, using the low-/medium-fidelity method TDLM (transonic doublet lattice method) and steady and unsteady RANS computations with the DLR-code TAU and the ONERA-code elsA, [7-9]. The results revealed that even for complex problems like this, the unpretentious but fast TDLM gave a fair representation of the real-world behaviour, Figure 5. The take-away of these tests: for verifying a clearly defined setting, the RANS solvers performed superbly and cannot be substituted, but for most design purposes, a cost/benefit-comparison would have clearly favoured a conceptual/preliminary, multidisciplinary lay-out using methods like TDLM, and few RANS verification jobs to receive supporting points or investigate equivocal results.

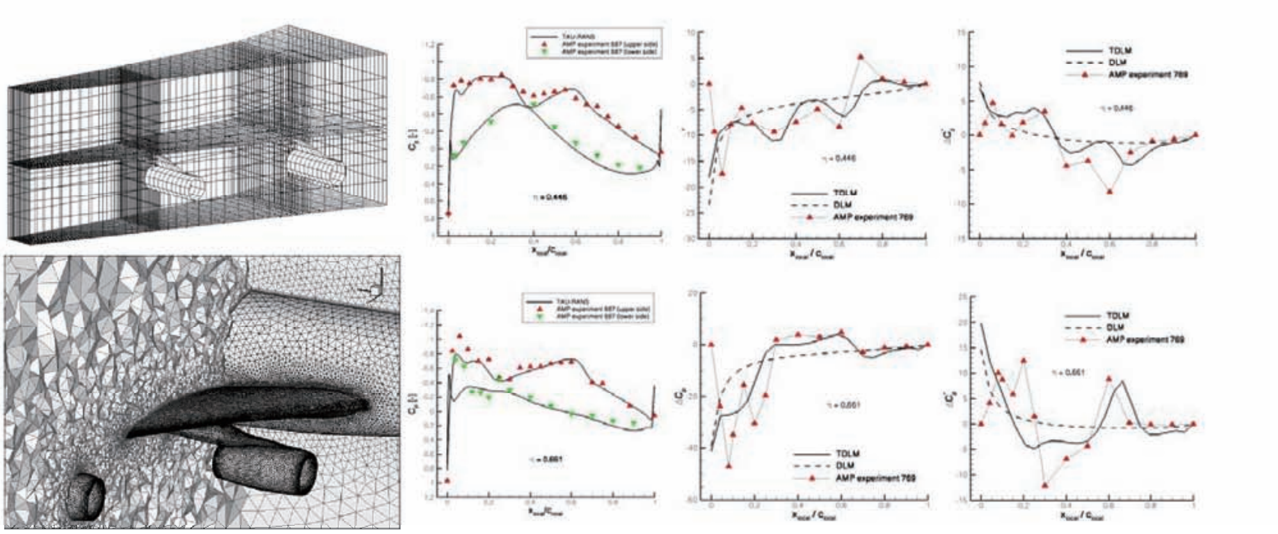


Figure 5 *Unsteady C_p distribution (real and imaginary components) for AMP WBPN model comparing TDLM and steady RANS results with experimental data (pure pitching motion, ω*=0.369, Ma=0.820, α=1.80°, Re=3.57*10^6)*

▶ Surrogate modelling by RSM, Kriging or splines is not the answer to everything

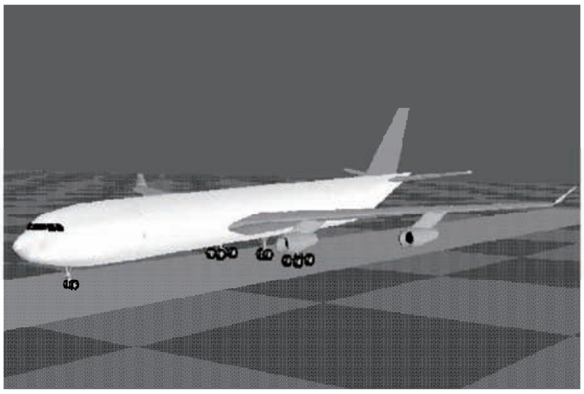
Especially on conceptual and preliminary design level and for multidisciplinary and/or multi-level optimisation, surrogate modelling techniques are used to take the place of expensive disciplinary analyses. These surrogate models are basically approximation methods to interpolate between supporting points. Methods like response surface methods (RSM), Kriging, n^{th}-order splines and, to some extent, neural networks are simple to use and (with some restrictions in respect to Kriging) robust in optimisation. Supporting points are often defined using design of experiment (DOE) methods, allowing to cover a wide parameter field with a minimum of points, and to run all necessary computations automatically.

The number of supporting points, each of which requires its own high-fidelity analysis, may grow with $O(c^n)$ in respect to the number of (independent) design variables, respectively the number of those which are picked as explanatory variables, depending on the DOE method used. This may prove to be quite costly for time-consuming jobs like CFD. Additionally, the problem of having to adapt the high-fidelity model to cover the design space does also exist here. The most important point, however, is that during complex optimisations, when a design variable which is not an explanatory variable is modified, the surrogate model has to be re-generated for the DOE parameter set.

An alternative is the use of physically reduced models. The idea of this class of models is to extract the important physical properties of a disciplinary model, e.g. using linearisation or Taylor series, or, sometimes, "engineering intuition" to condense on the important characteristics of the high-fidelity model, respectively reality. Well-known, established physically reduced models can be found in structural mechanics, such as the beam models of *Euler-Bernoulli* and *Timoshenko* for long, slender ("one-dimensional") elements, or the *Ritz approach* to use eigen- and/or static modes to represent a more complex flexible structure.

With setting up a number of well-defined boundary conditions, like the Kirchhoff assumptions of the Euler-Bernoulli beam, the strengths and limitations of the model reduction can be assessed more reliably, and the region of trust is usually larger than that of surrogate models. Alterations of global design variables may also necessitate a re-computation to modify the reduced model, but those are usually cheap compared to the effort necessary to generate an entirely new surrogate model for a large set of explanatory variables.

An example of adapted model reduction is the multibody simulation of a landing aircraft, which was used in an integrated design exercise to harmonise the work share between airframer and landing gear manufacturer. The simulation brings together the disciplines of mechanical dynamics, structural mechanics, aerodynamics and control. Controlled elements are included by co-simulation or code-export, structural flexibility is represented by a set of linearised base functions, and the aerodynamic effects of structural deformation are coupled directly in the equation of motion, [10]. The result is a fast-performing analysis of a complex scenario with a very reasonable level of fidelity.



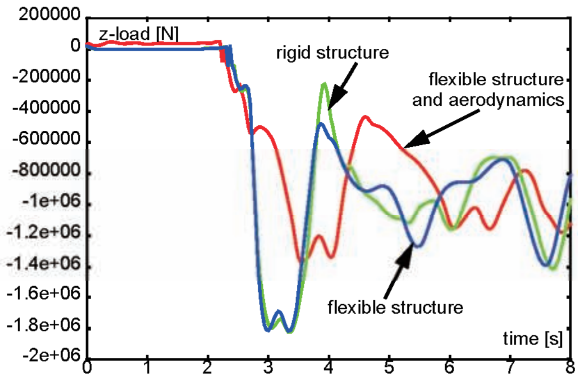


Figure 6 *Multibody simulation of the touch-down of a large transport aircraft (left), vertical load on the main landing gear leg attachment (right) comparing: certification requirement (rigid airframe), industry standard (flexible airframe) and including aerodynamic effects of airframe deformation (flexible and aerodynamics)*

▶ The optimal solution to a local problem is not the solution to the optimal aircraft

Today's aircraft are highly integrated systems, and it is safe to assume that an ultra-green commercial transport aircraft will have an even higher degree of internal interrelations. The consequences are well explained by a quote from Curtis Johnson of Sierra Engineering, Inc., a provider of liquid propulsion systems, (2006):

"Lately our program for doing optimization of this upper stage rocket engine (the USET program) has been showing much success. We now can routinely run overnight optimizations that show a much higher degree of fidelity than anything we have seen before. The system optimizations are pretty interesting too. For example the results are showing that overall engine weight can be minimized by de-tuning some components (and making them heavier) so that other components can be made smaller and lighter. This was something that was not previously done in this field where everything is made to push performance."

The application of multidisciplinary optimisation (MDO) in industry has, for the most part, started in the detail design phase and is now moving upstream into the preliminary design stages. MDO has also been introduced at the conceptual design level, where low complexity models are handled by a manageable number of software tools. Applications there are now moving in the opposite direction further downstream, but it will still take its time until both lines of attack merge in preliminary design. The ultimate goal, however, is to achieve a highly integrated but flexible, physics-based multidisciplinary optimisation. Figure 7 is a depiction of Boeing's systematic progress toward full aircraft MDO, [11].

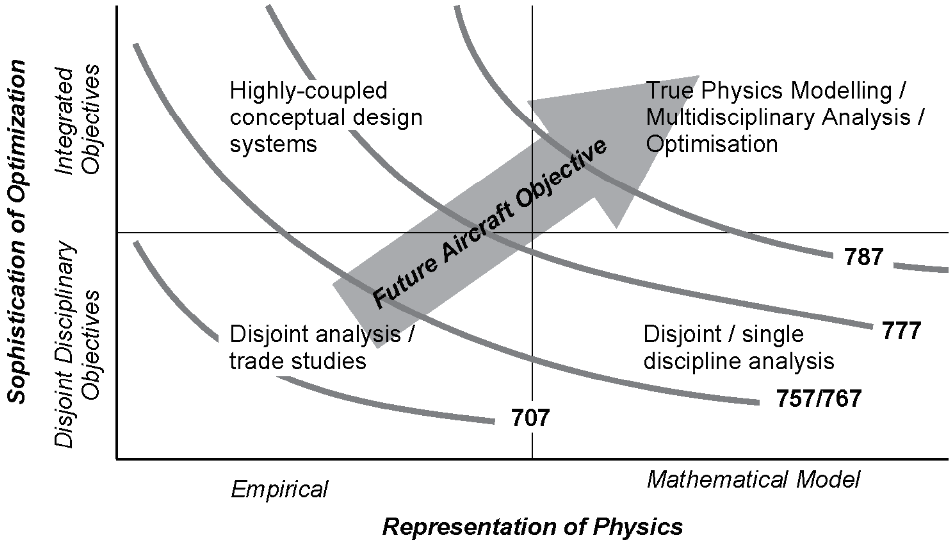


Figure 7 *Development of MDO in aircraft design across the successive jet airliner families of Boeing*

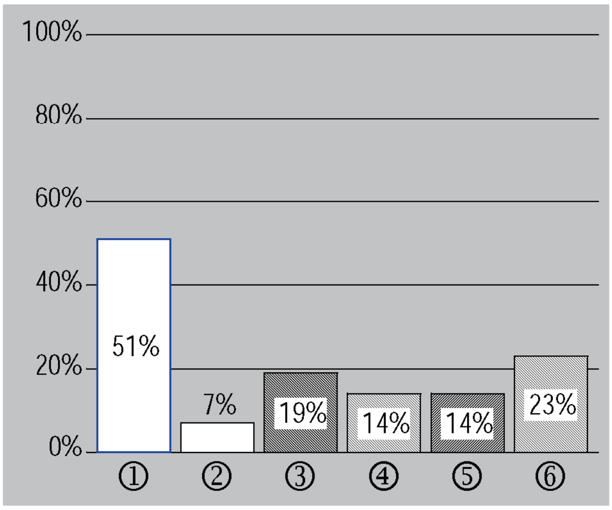
DLR is devoting considerable effort to enhance its R&D activities on system, i.e. the overall aircraft, and to even look beyond the single aeroplane and to investigate the air transport system in a holistic approach. iGREEN is the institute's strategic approach to closely connect aeroelasticity with the systems level:

- Being part of the integrated design platform will boost the efficiency, especially for generating or modifying models, and to feed back the results into "the system".
- Highly flexible novel configurations require the aeroelastician to be part of the entire design cycle, from conceptual design until roll-out and certification.

▶ Multidisciplinary design is communication - not only between software tools, but between people

R. Belie, [12], distinguishes between four layers which have to be connected in multidisciplinary problems: the disciplinary layer, the data layer, the human layer and the organisational layer. When challenged by a multidisciplinary problem, aircraft designers, engineers, managers and especially IT specialists are often enthusiastic about tackling the disciplinary and data layer. The human layer is about people-to-people communication, mostly team members. The negative effects of too little, wrong and also too much communication as well as the manifold pitfalls of misunderstanding are known. Overcoming these shortcomings is possible, albeit in no way easy - an entire consulting branch is living quite well from it. Most critical, and also most political, is the organisational layer. People may recognise the need for multidisciplinary work, but in the end of the day the salary of an employee and the budget of a department depends on how the very own work was done - in most cases, providing help to other entities to do a better job and to build a better product, e.g. by preparing and exchanging data, is not being rewarded.

A survey, [13], taken in 2006 among American aerospace companies on the current strength and weaknesses of multidisciplinary design revealed that although hardware, simulation software and MDO software limitations exist, a majority of managers and engineers saw organisational barriers as the major obstacle to multidisciplinary design, respectively MDO, Figure 8.



The most important barriers that prevent MDO approaches at your company are...

① organisational barriers
② hardware limitations
③ simulation software limitations
④ data handling issues
⑤ MDO software limitations
⑥ other

Figure 8 *Barriers for the employment of MDO (multiple answers possible)*

Also illustrative is the success of the Aerospace Systems Design Laboratory (ASDL) of the Georgia Institute of Technology, [14], which brings together designers, engineers and decision makers - not to exchange results generated at their respective working places and return with the intention to work in a multidisciplinary way, but to offer them the possibility to work interactively towards a common goal while at ASDL and then return to further detail the achieved results.

5 Conclusions

Lessons-learned of the last aircraft development programs, in Europe, in the USA and elsewhere, have shown that integration is a critical issue: it offers most potential for improving the product's performance and competitiveness, but getting it wrong can be very costly, and sometimes even dangerous. It is very important to have deep insight into the various disciplinary technologies, but excellent aerodynamics, the ultimate lightweight structure and the best engine alone do not necessarily add up to the best aircraft - harmonising the disciplinary excellence is crucial, too.

This plea for not forgetting the big picture may be concluded by the words of Edgar Allan Poe's narrative character C. Auguste Dupin, [15]:

"He erred continually by the very intensity of his investigations. He impaired his vision by holding the object too close. He might see, perhaps, one or two points with unusual clearness, but in so doing he, necessarily, lost sight of the matter as a whole. Thus there is such a thing as being too profound. Truth is not always in a well."

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