Chair:
Prof. Sergio Ricci

DOCTORAL PROGRAM IN AEROSPACE ENGINEERING

The aim of the course is the acquisition of the high level competence required to carry out innovative research and/or state of the art advanced applications in industries, public or private research centers, Universities or public and service companies in the area of aerospace engineering, including all the fields associated to it. The level of the course allows the graduates to compete in a European and international environment.

The course is three years long, requiring 180 credit points (ECTS), including possible study-abroad periods and internships in private or public institutions. The programmes and credits are divided in three main educational areas:

1. Main courses (40 credits), during the first year: courses examining fundamental subjects (problems, theories and methods) of the scientific research in the disciplinary areas involved;
2. Elective courses and training on specific themes (20 credits), gained in the second year: specific and personalised educational programs aimed at a more deep overall knowledge and to master the techniques adequate for the subsequent development of the doctoral thesis, plus seminars focused on specific and advanced methods;
3. Development of the Doctoral Thesis (120 credits): the thesis is developed within the Department or, in some cases, in other institutions, in close contact with the Department. The thesis is started immediately (20 credits in the first year), and developed in the second (40 credits) and third year (60 credits) of the doctoral program.

If the candidate has a background curriculum lacking some introductory knowledge required for the Doctorate, the Faculty will ask to recover such knowledge, with the assistance of the tutor. The same Faculty will verify afterward the overcoming of whatever was lacking during the annual meeting of admission to the second year of the course.
The course program related to point 1 does not follow a rigid scheme. So, besides widening the basic scientific culture of the candidate, it will take into consideration also the objectives and the core topics of the candidate's thesis. Again the program outlined at points 2 and 3 will try to consider general cultural requirements as well as what is deemed to be more specifically related to thesis subject, as agreed between the candidate and the Faculty. For the activities of type 2 and 3 a study period in a foreign country is allowed, even strongly suggested perhaps. Its duration should range from a few weeks up to one and a half years. The related activities should be carried out in well known and qualified scientific institutions (universities, research centres, etc.), and well contribute to the cultural and scientific achievements of the research.

Due to the amplitude and interdisciplinarity of the aerospace sector, the professional skills achievable will span a wide area and not cover just a specific topic. The educational goals will create high level specialists in the domains of: helicopters and rotary winged vehicles, fixed winged vehicles and space vehicles.
In this context, a more specific competence can be gained either in a single or in the integration of special subjects such as: dynamics and control, fluid mechanics, systems and equipment, flight mechanics, passive structural safety, intelligent and automated systems, structures and materials.
In this respect, some examples of professional skills achieved in the course of the passed 22 years of doctoral program are here reported:

- expert in computational and/or experimental fluid mechanics, with capabilities to develop methods and models for both aerospace applications and generic vehicles;
- expert in active and passive control of the dynamics of aerospace structures, integrating global and subsystem design;
- expert in active and passive structural safety of vehicles, both aerospace and non-aerospace;
- expert in vibration and noise control, including modelling analysis, system design and implementation of specific subsystems;
- expert in the dynamics and control of aerospace vehicles and related operational missions;
- expert in integrated design of complex aerospace systems.

Since its foundation, 23 years ago, the doctoral course on Aerospace Engineering graduated more than 60 PhDs.

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INNOVATIVE FUEL FORMULATIONS FOR HYBRID ROCKET ENGINES

Mechanical and Ballistic Characterization

Matteo Boiocchi

This research project, performed at the Aerospace Engineering Department of Politecnico di Milano from 2009 to 2011, is focused on the development of innovative solid fuels for hybrid rocket propulsion (fuel in solid state, oxidizer in liquid or gaseous state). Heterogeneous combustion processes in hybrid rocket motors involve a complex fluid-dynamic flow-field, characterized by a turbulent reactive boundary layer, with a blowing effect due to the pyrolysis of the solid fuel, turbulence, chemical kinetics, heat transfer, radiation, especially when the solid fuel grains are added with metal powders, two-phase flows. Inside the boundary layer a macroscopically diffusive flame develops, thus allowing the heat feedback to the fuel grain surface, which is responsible for the solid fuel pyrolysis. The final result of such an extremely complex physico-chemical picture is a low regression rate of the fuel grain. Aim of this work is to investigate the possibility to improve the performance of hybrid rocket solid fuels in terms of fuel regression rate and mechanical properties. Different strategies were followed and investigated in this work. The first one involves the filling of traditional fuels, such as HTPB (Hydroxyl Terminated Poly Butadiene) with metal powders, nano-sized (i.e. nano-Al), or metal hydrides (i.e. Magnesium hydride (MgH_2) or Lithium Aluminum hydride ($LiAlH_4$)). The second one is based on the investigation of fuels characterized by a low melting temperature, such as paraffin-based solid fuels. The regression rate increases due to the entrainment effect, represented by the mechanical removal of the liquid layer formed on the fuel surface by the oxidizer flux. The entrainment mass transfer from the liquid fuel film into the gas stream originates a spray, whose combustion entails that the regression rates of paraffin-based fuels increase three-four times compared with those of traditional HTPB fuels. Further increases can be obtained by adding to the paraffin matrix energetic powders, such as metal hydrides powders, as shown in Figure 1.

Nomenclature. H: HTPB-based fuel family. P: paraffin-based fuel family. P_{Gu}: gel wax fuels. P_{Wu}: solid wax fuels. V20, X10, K10: liquid paraffin (20%), hexane (10%), kerosene (10%). MGH3: Magnesium Hydride, MgH_2 (3% mass fraction). LAH3, LAH6, LAH10: Lithium Aluminum Hydride, $LiAlH_4$ (3, 6, 10 % mass fraction). L3AH3 (Trilithium Aluminum Exahydride, Li_3AlH_6 (3% mass fraction).

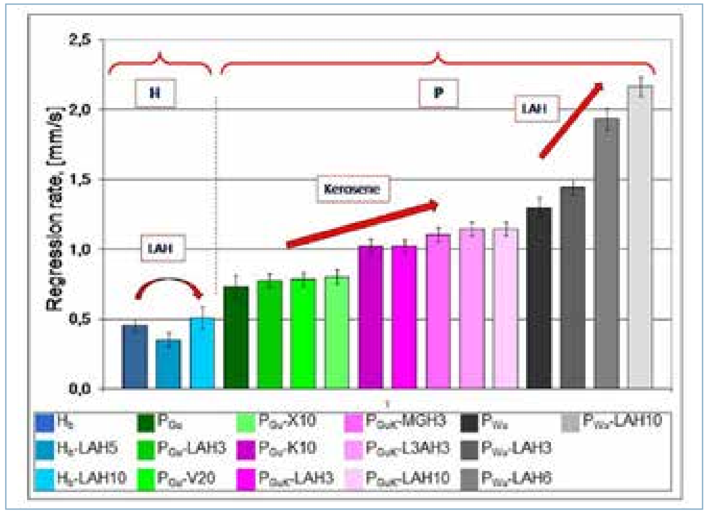
However, this family of fuels suffers of poor mechanical properties, especially when temperature approaches the melting degree. Two different techniques are originally proposed in this thesis to deal with the reinforcement of these fuels. The first concerns the use of a poly-urethane foam, the second of polymeric materials. The third strategy, the more innovative one, involves the use of epoxy resins. Several tests, thermal (gasification, DSC and pyrolysis tests), optical (high speed video recording of pyrolysis process) and ballistic (regression rate measurement) were carried out in order to plug the gap about this new family of fuels. It is shown that an epoxide group is much more reactive with Lithium Aluminum Hydride than with a hydroxyl group; the gasification process of an epoxy-based fuel (Ep1-LAH10) is much faster than that of a HTPB-based fuel (Hb-LAH10). DSC tests allow a quantitative estimation: a HTPB/LAH mixture reaction heat is up to ten times lower than that of a similar epoxy resin/LAH mixture. High speed visualization of the pyrolysis process shows a pyrolysis surface regression rate of 10 mm/s for the fuel named Ep2-LAH5-cur; this value is more than seven times higher than that of a pure HTPB fuel, as shown in Figure 2.

Nomenclature. H_b: HTPB-based fuel family. E_{p2}: epoxy-based fuel family. LAH3, LAH5: Lithium Aluminum Hydride, $LiAlH_4$ (3, 5 %, mass fraction).

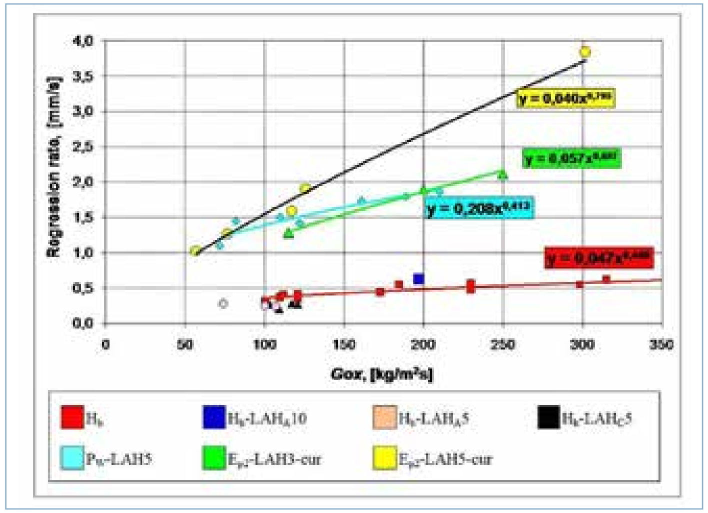
Significant increases of the regression rates can be obtained, according to this approach, especially when metal hydrides are used to fill the compositions. A ballistic, rheological and mechanical characterization of the fuels is proposed.

The last chapter of the thesis summarizes the activity performed at Safran-Sme (France); it concerns the ignition problem and the techniques implemented to measure the regression rate. Several techniques are investigated to perform the motor ignition; electro-explosive, through-bulkhead, high-current, spark torch, laser, catalytic and hypergolic devices are examined to ignite the fuel grain and to raise its temperature to a self-sustaining combustion. This analysis is performed taking into account the need to re-ignite the solid fuel grain, which is one of the most important prerogatives for the achievement of hybrid propulsion systems. A theoretical approach to HTPB ignition is presented to support the performed analysis. The development and evaluation of new hybrid rocket motors also require an accurate characterization of the propellant surface regression as a key operational parameter. These characteristics establish the propellant flow rate and are prime design drivers affecting the propulsion system geometry, size, and overall performance. Different techniques, such as ultrasound, microwave, X-ray, resistive and fiber optic methods are discussed, pointing out both advantages and disadvantages.

Aim of this research project is to investigate, develop, manufacture and characterize innovative solid fuel formulations for hybrid rockets of the next generation. Different paths are proposed to perform this specific task. A first direction is to consider the filling of traditional binders (HTPB), or innovative binders (paraffins), with energetic powders, such as nano-Aluminum powders or sim-ple or metal hydrides. The second direction is to investigate very original formulations, based on epoxy resins mixtures, added with metal hydrides, in particular with Lithium Aluminum hydride ($LiAlH_4$). Solid fuels for hybrid propulsion applications need also good mechanical properties, because of stresses charged to the fuel grain. The measurement of the main rheological and mechanical properties show the way to follow in the near future for a mature achievement of this new class of solid fuels.



1. Regression rates of paraffin-based fuels added with different metal hydrides investigated in this study. Oxygen mass flux: Gox = 120 kg/m² s.



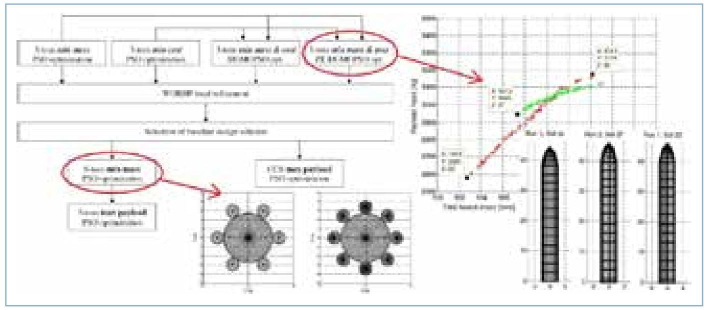
2. Regression rate of two epoxy-based fuels investigated in this study, compared with the best performance of the paraffin-based fuel (light blue) and the performance of the reference HTPB fuel (red curve).

MULTIDISCIPLINARY DESIGN OPTIMIZATION FOR EXPENDABLE LAUNCH VEHICLES

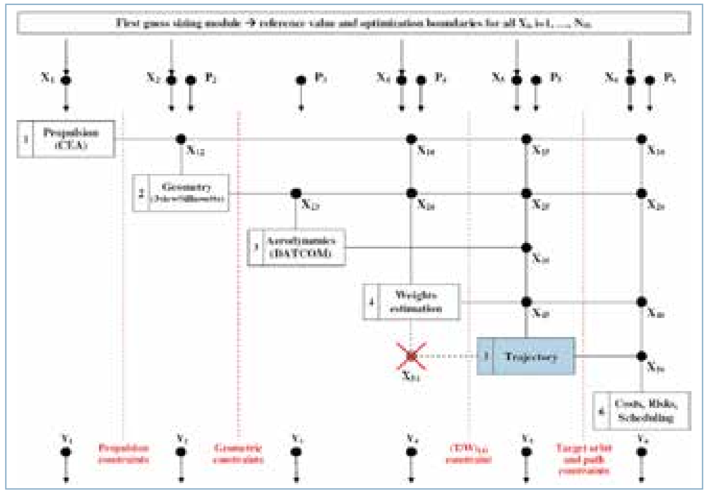
Francesco Castellini

Since the dawn of the space age, development, production and operations of launch vehicles and other Space Transportation Systems (STS) have required huge investments. After the Moon landings, drastically reduced budgets forced engineers to start including in the design cost and programmatic aspects. In the current international context, which shows several attempts to reduce the cost for the access to space, the quality of the design process in general and of the initial design decisions in particular assume a key role, being the major drivers of the total life cycle cost (LCC) of launch systems. Specifically, it has been shown that about 80% of the LCC is determined in conceptual design, while optimization efforts in later design phases only result in minor improvements. For these reasons, Multidisciplinary Design Optimization (MDO) was chosen as the main topic of this doctoral research, in light of its potential benefits on both the efficiency of the design process (i.e. required time and effort) and the quality of the design solutions. In the European scenario, ESA's Future Launchers Preparatory Programme (FLPP) and other national projects are paving the way - through technology demonstrators and system studies - for the transition in the 2025 timeframe from the current fleet of launchers (Ariane 5, Soyuz and Vega) to a more flexible and cost effective, modular family of Expendable Launch Vehicles (ELV). Hence, through collaboration with ESA, the primary application of the present research was identified in ELVs, although the developed environment was kept as flexible as possible to allow for easy extendibility to other STSs, such as re-entry vehicles, crewed and reusable systems. An example of design study for FLPP's launcher family is reported in **Figure 1**, showing how a complex design process usually requiring months of work from several engineers could become a one man-month effort with the assistance of MDO methodology.
The main objective of the research was therefore identified in the development and quantitative assessment of a MDO environment capable of tackling the early design phases of ELVs. The focus was primarily on the engineering modelling aspects, whereas the necessary global and local optimization infrastructure was only considered as a mathematical tool enabling MDO, in light of the criticality of the models definition for the applicability of MDO methodology to real-world design. In fact, in spite of the rather impressive list of achievements promised by MDO and of a growing interest in the research community, successful industrial applications are still extremely rare. This is in part due to a certain resistance of design offices, motivated by the large required initial investments, to the introduction of MDO against the traditional fixed-point iterations process. But the largest obstacle is certainly constituted by the fact that MDO's industrial applicability is subject to the assessment of the confidence which can be placed in the achieved design solutions. In particular, the definition and calibration of the multidisciplinary models are particularly challenging, the main obstacle being the identification of a reasonable compromise between simplicity and accuracy.

With this problem in mind, a quantitative assessment of the engineering models was carried out, including a detailed analysis of the accuracy of all developed analysis codes, both in terms of disciplinary errors and of system level sensitivities and results. Although a rather significant number of developments documented in recent years have been focused on the application of MDO to the design of different types of STS, the evaluation of accuracy and reliability of such models to the extent described in the present research represents an innovative and necessary endeavour, to the author's knowledge.
The main question proposed for the research - whether it is possible to develop relatively simple models permitting fast design cycles while still ensuring sufficient accuracy to place confidence in the achieved design solutions – does not hold a straightforward answer. The computational effort required with the implemented models, whose Design Structure Matrix is shown in **Figure 2**, surely matches the original target (i.e. <2 s for a complete multidisciplinary analysis), but it is not nearly as easy to measure the accuracy requirement. It can however be said that the decided two-steps development process proved to be of key importance for the incremental improvement of the models, which ensured a sensible enhancement in accuracy at a manageable price in computational effort from Version 1 to Version 2. As a result, the final models are characterized by accuracies on the global performance which should be sufficient in most of the cases to fairly compare two significantly different design solutions through MDO.



1. Example of study flow and resulting outcomes for an FLPP MDO application.



2. DSM for conceptual ELVs design: analysis proceeds sequentially from left to right along the diagonal, with terms above/below diagonal representing feed-forward/backward information flows.

Throughout lengthy details on the modelling and validation as well as on few relevant applicative cases, the PhD dissertation highlights how the development and tuning of a reliable MDO environments is a very complex task, requiring large efforts in most engineering areas, besides computer science and mathematics. However, reasonable accuracies and physically sound design modifications can be obtained through the MDO approach, even when exploiting only fast engineering level models to avoid resorting to high performance computing. With today's computational resources, which allow conceiving the introduction of high fidelity in the design cycle, MDO guided by human expertise is therefore a powerful approach for the initial design phases of launchers and other STS. Although the huge initial investment in terms of development and personnel training is a major obstacle to widespread industrial application, it is the opinion of the author that the resulting benefit in terms of design quality and efficiency is well worth the effort, with the potential of contributing to the long term goal of achieving low cost access to space.

AN INTERPOLATION-FREE TWO-DIMENSIONAL CONSERVATIVE ALE SCHEME OVER ADAPTIVE UNSTRUCTURED GRIDS FOR ROTORCRAFT AERODYNAMICS

Dario Isola

A novel method for compressible gasdynamics is presented to solve the arbitrary Lagrangian-Eulerian formulation of the Euler equations is solved within the finite-volume framework over adaptive grids. Thanks to the interpetation of the grid topology modifications as of continuous deformation of the finite volumes, the solution over the new (adapted) grid is computed by simply integrating the arbitrary Lagrangian-Eulerian formulation of the Euler equations, without any explicit interpolation step.

An adaptation strategy is proposed for unsteady problems. A suitable mix of mesh deformation, edge-swapping, node insertion and removal is performed to adapt the grid to a new configuration of the geometry or to redistribute the discretization error amongst the grid elements.

Both steady and unsteady simulations over adaptive grids are presented that demonstrate the validity of the proposed approach. In the final chapter typical two-dimensional problems for rotorcraft blade sections are tackled. The adaptive ALE scheme is used to perform high-resolution computations over three selected problems of interest for rotorcraft aerodynamics: an oscillating airfoil, an impulsively started airfoil and parallel blade-vortex interaction. Resorting to mesh adaptation is of primary importance to perform unsteady computations in such problems, where the need of efficiency is combined to the necessity to highlight relevant flow features, such as shocks, wakes or vortices.

To perform computations over dynamic grids, the Arbitrary Lagrangian-Eulerian approach, in which the control volumes are allowed to change in shape and position as time evolves, is to be preferred to the classic Eulerian one. In the ALE approach an additional contribution to the fluxes is present, that is proportional to the velocity component normal to the interface of the control volume. An additional constraint over the interface velocities exists within the ALE framework, the so called Geometric Conservation Law.

The flow solver is based upon an unstructured finite-volume formulation used to discretize the ALE formulation of the Euler equations on the median-dual mesh. The median-dual mesh can be easily drawn on top of the original mesh, connecting each cell center to its edge mid-points. The result of the construction is a mesh where the control volumes can be located on the nodes of the original mesh. To automatically satisfy the GCL constraint the velocity integrated along the cell boundary is computed as the time derivative of the area swept by the interface during the movement.

The flow solver employs a Flux Limiter approach in which a second-order centered flux contribution is blended with a first-order one. To avoid numerical oscillations a van Leer limiter is used, which enforces monotonicity in the solution. A piecewise constant representation of the solution is used, therefore the variables have different values across the control volume interfaces and therefore a discontinuity exists. Roe's approximate Riemann solver is used to evaluate the flux given the discontinuous states. The boundary conditions are imposed in a weak form, i.e. by evaluating the boundary fluxes on a suitable boundary state which depends on the type of boundary condition to be enforced.

A standard BDF scheme is adopted to approximate the derivatives with respect to the time. To enforce the time-discrete version of the Geometric Conservation Law the same BDF scheme is adopted to compute the grid velocity, which is therefore proportional to the area swept by the interfaces during each time-step.
The solution of the flow equations at a given time is found by means of an implicit dual-time stepping scheme. The scheme is obtained as an application of the defect correction method to the semi-discrete form of the equations. A local pseudo-time step is added to each control volume and is gradually increased to infinity according to the level of convergence of the solution. In practice, the scheme coincides with a backward Euler method that uses an approximate Jacobian.

The implicit unsteady finite-volume scheme described above is extended to the case of adaptive grids. The application of local modifications of the mesh topology, e.g. edge-swapping and mesh de/refinement, causes a modification in the shape of the cells. In principle, due to this modification the solution at new time is to be interpolated over the new grid. The changes in the topology are interpreted as continuous deformations of the finite volumes happening in the time lapse from t to the next timestep. This is reflected in the application of a correction term to the interface velocities given by the grid movement. The solution over the new grid can be therefore computed by simply integrating the governing equations.

To conserve the solution an additional flux term is to be included in the system for every edge that has been removed from the mesh. Similarly an additional governing equation has to be taken into account for every deleted cell. The nature of such additional contributions depends strongly on the type of time integration scheme adopted.

A mesh deformation technique is adopted to permit the movement of the boundaries, while maintaining high level of grid quality reducing numerical errors. A two steps procedure is carried out: first each boundary node is displaced as prescribed by a given law, then the position of the inner nodes is modified accordingly. The used internal node-displacement algorithm extends to idea of the elastic analogy that represent each element as a deformable body presented by Belytschko, Liu and Moran. The obtained algorithm works well with grids made of triangles and the provided examples demonstrate both its robustness and computational efficiency.

For large displacements of the mesh nodes the topology is altered with an edge-swapping technique, which allow to preserve the total number of grid nodes. The edge-swap consists in altering the connectivity of a given couple of triangular elements by deleting the edge connecting the two vertices shared by the two elements and by adding a new edge connecting the other two vertices.

In the present work the spacing distribution is controlled in two ways: as proportional to the distance from the boundaries and as proportional to a suitably defined error indicator. The first approach is specifically suited for aerodynamic applications, indeed in most of the cases of interest the smaller elements are gathered close to the solid walls and the size smoothly increase as the maximum dimension is prescribed on the outer boundary. The second approach aims to capture the local features of the flow-field locally changing the grid spacing according to the principle of error equidistribution. In this way, if a computational region has a numerical error higher than the average, it will be refined using a technique of node insertion; on the other hand, regions with a lower numerical error will be derefined thanks to a deletion node procedure. An estimator is defined to identify regions with high and low numerical error which is usually a function of the flow gradients, of the Hessian matrix of a convenient sensor variable, of the vorticity or of the substantial derivative of the density.

In the present work a an approach similar to the one proposed by Alauzet et al. is followed, which consists in a iterative procedure which alternate a solution prediction phase with the adaptation one, when the grid has converged to a stationary state a new time step is tackled. By doing so the grid is essentially adapted over the solution computed at a current time, instead of the previous one. To further increase the grid-convergence rate and the overall efficiency of the algorithm an error interpolation technique has also implemented that allows to repeatedly apply the adaptation procedure without computing the solution over the new grid.

BALLISTICS OF INNOVATIVE SOLID FUEL FORMULATIONS FOR HYBRID ROCKET ENGINES

Christian Paravan

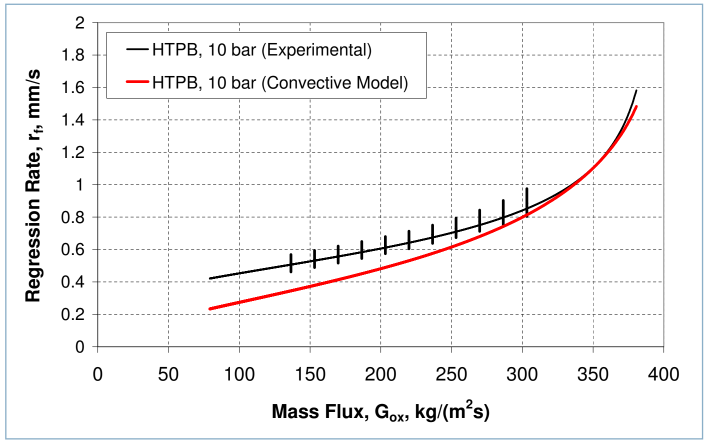
In this work ballistics of solid fuel formulations for hybrid rocket propulsion was investigated with experimental and numerical approaches. Experimental activity was conducted by a lab-scale 2D radial burner enabling visualization of the combustion process of cylindrical, central port perforation strands. A non intrusive, optical time-resolved technique for regression rate measurement was designed and validated. The technique is based on central port diameter sampling during combustion. Combustion tests were performed for relative ballistic grading of different fuel formulations and for investigation of hybrid fuel ballistics under forced transient regime.

For the relative ballistic grading, combustion tests were performed on fuel formulations based on HTPB (Hydroxyl Terminated PolyButadiene) and SW (Solid paraffin Wax) with chamber pressure ranging from 7 to 16 bar, under gaseous oxygen (GOX) with initial oxidizer mass flux (G_{ox}) of nearly 400 kg/(m²s).

Under the investigated conditions HTPB exhibited a regression rate dependent from oxidizer mass flux but not influenced from chamber pressure. Achieved results underlined influence of radiative heat transfer and the (minor) contribution of solid fuel fragmentation to the measured regression rate for values of G_{ox} lower than 120 kg/(m²s). HTPB was then considered as baseline for relative ballistic grading of the investigated fuels. In spite of a relatively high data scattering due to poor mechanical properties of the solid fuel grain, SW-based fuels exhibited a marked dependence of regression rate from chamber pressure. With respect to baseline at an oxidizer mass flux of 300 kg/(m²s), regression rate enhancement for SW burning decrease from 500% to 260% when chamber pressure is increased from 7 to 16 bar. Commercial and lab–scale energetic additives of different kind and particle-size were used for solid fuel loading. Considering commercially available additives, different variants of nano-sized aluminum powder (ALEX™) and micron-sized magnesium-boron (MgB) powders were tested. Under the investigated conditions, tested ALEX™ exhibited a marked regression rate increase with respect to baseline for high oxidizer mass fluxes [up to 80% at 350 kg/(m²s) for fluoroelastomer alcohol-coated powder]. Nevertheless due to high sensitivity to oxidizer mass flux, this performance enhancement is lost during combustion. A remarkable exception is the fluoropolymer-coated nano-sized aluminum (VF–ALEX™). This additive can provide a significant regression rate increase over the whole oxidizer mass flux range, providing an average regression rate enhancement with respect to baseline of 30%. Considering MgB powders, MgB90 (20% Mg) can provide significant regression rate enhancement of 64% for oxidizer mass fluxes of 350 kg/(m²s). HTPB doped with this additive is less sensitive than the common ALEX-doped counterparts to oxidizer mass flux changes. With SW-based fuels promising high performance without granting mechanical properties, regression rate enhancement achievable by HTPB-based solid fuel loaded with MgB and VF-ALEX offers interesting possibilities for hybrid propulsion development.

Ballistic characterization of a HTPB-based fuel loaded with aluminum hydride (AlH_3) was conducted under pure oxygen and under an oxidizing mixture 70% oxygen + 30% nitrogen. Test conducted in presence of nitrogen exhibited a regression rate enhancement with respect to baseline that was not achieved when conducting similar tests in oxygen.

Investigation of hybrid solid fuel ballistics was conducted also by a numerical approach aiming to the determination of the regression rate of the solid fuel grain under convective heat transfer regime. Analysis focused on HTPB burning in gaseous oxygen. The proposed approach is based on the definition of effective values of thermo-physical parameters considered for the determination of Reynolds number (Re) and convective heat transfer coefficient. Effective values are determined considering the actual, instantaneous oxidizer to fuel ratio determined during the experimental sessions. A typical result achieved by the numerical simulation is reported in Figure 1 where the regression rate of HTPB burning under GOX with chamber pressure of 10 bar is considered. With the proposed approach the model can properly estimate the experimental regression rate for G_{ox} values above 250 kg/(m²s), while for lower oxidizer mass fluxes higher differences between experimental and numerical values are achieved. This result underlines the relative importance of radiative heat transfer in the heat feedback from flame to the regressing surface for low values of G_{ox} (in turn inducing a reduced convective heat transfer).



1. HTPB burning under G_{ox} with chamber pressure of 10 bar, comparison of experimental data and convective model evaluation. Note high agreement between experimental and numerical data for Gox higher than 250 kg/(m²s). Differences in rf for lower G_{ox} values mainly due to radiation effects.

Investigation of hybrid fuel ballistics under forced transient condition was performed considering HTPB burning with oxidizer mass flow throttling during combustion. In particular, during the combustion tests oxidizer mass flow was throttled down in a first transient leg followed by a second transient leg in which oxidizer mass flow rate was increased. Under the investigated conditions during the throttling down transient, regression rate exhibits a monotone decrease of regression rate with no marked overshoot/undershoot phenomena. The throttling up transient is characterized by a regression rate increase possibly yielding to overshoot phenomena. The latter could be caused by thermal lag effects in the solid phase. Nevertheless, under the investigated conditions, HTPB behavior revealed an intrinsic stability in transient phases related to throttling events.

INDEPENDENT FIELDS FULL POTENTIAL FORMULATION FOR AEROELASTIC ANALYSES

Andrea Parrinello

A Full Potential (FP) model for non isentropic unsteady transonic flows is presented. The formulation is based on independent approximations of the density and potential fields that satisfy mass conservation and Bernoulli equation.
The potential flow approximation has been the dominating model for transonic aerodynamics for many years. It can be effectively used in aerodynamic design and analysis. Because of its comparatively small computational cost it remains of interest in multidisciplinary methodologies, for conceptual and preliminary design phases especially. Through the 1990s and 2000s, research and development on potential flow lost appeal in favor of Euler and Navier-Stokes solvers, the speed and memory capability of new computers making their use affordable more and more. Nonetheless, significant interest in FP solvers still persists. The shorter computational time required by FP solutions makes them appealing for aircraft conceptual and preliminary design phases and for linearized aeroelastic analyses. So, even though FP solutions cannot be as accurate as Euler ones, the quintessence of the physics of an inviscid flow can be captured anyway. Furthermore, FP solutions can be used as starters of Euler|Navier-Stokes flow solvers, significantly reducing the iterations required for convergence.
As fast and reliable Euler solutions became routinely available for transonic flow calculations, it was found that FP solutions were seriously in error when shocks became even moderately strong. Both shock strength and position were wrong and the magnitude of the related errors could have been significant. The inaccuracies of an FP model in predicting transonic aerodynamic loads is primarily a consequence of neglecting the jump in entropy that a fluid particle experiences as it crosses a shock. FP formulations allow a shock discontinuity to appropriately occur for mass and energy, but the shock remains isentropic and the momentum balance is not satisfied across it. Therefore, the calculated shock waves can have a wrong strength and location. When shocks appear in transonic flow fields, the aerodynamic loads predicted using an FP can even be multivalued. Through the 80s, as Euler solutions began showing the FP inaccuracies in predicting transonic aerodynamic loads, many researchers devoted much energy to the formulation of numerical schemes aimed at correcting the related transonic results, mainly for steady flows though. An FP formulation prevents the proper entropy and vorticity production at the shock surface but these phenomena can be neglected for a moderate upstream Mach range, so a potential model represents an acceptable and effective approximation. Indeed, despite the intrinsic differences between an isentropic and a R-H shock, FP formulations lead to non-lifting transonic results which are very close to Euler calculations. This proves that an isentropic shock can be a good approximation of the real shock. The situation is much different for lifting cases. The inaccuracy of the FP model in predicting transonic aerodynamic loads may become considerable. The wake treatment is the keystone for possible improvements. It ensures an appropriate pressure balance at the trailing edge and determines the amount of vorticity that leaves the body. Usually the wake surface is a discontinuity for the potential function and the Kutta condition imposes the continuity of both the pressure and, because of the isentropic assumption, the density across it. However, in its usual form, the wake condition cannot take into account the variation of stagnation pressure due to a shock on the body, thus leading to an incorrect pressure balance at the trailing edge with a consequently wrong shock position. The present formulation retains the advantage of the existence of a velocity potential while granting a unique solution by combining a correction of the stagnation pressure behind a shock with a non-isentropic form of the Kutta condition.
An important consideration when simulating fluid flow problems by any numerical method is the choice of an appropriate kinematical description of the flow field. The algorithms of continuum mechanics make use of three distinct types of description of motion: the Lagrangian description, the Eulerian description and the Arbitrary Lagrangian Eulerian (ALE) description. Lagrangian algorithms, in which each individual node of the computational mesh follows the associated material particle during motion, are mainly used in structural mechanics. Classical applications of the Lagrangian description in large deformation problems are the simulation of vehicle crash tests and the modeling of metal forming operations. Numerical solutions are often characterized by large displacements and deformations and history-dependent constitutive relations are employed to describe elasto-plastic and visco-plastic material behavior. The Lagrangian description allows easy tracking of free surfaces and interfaces between different materials. Its weakness is its inability to follow large distortions of the computational domain without recourse to frequent remeshing operations. Eulerian algorithms are widely used in fluid mechanics. Here, the computational mesh is fixed and the fluid moves with respect to the grid. The Eulerian formulation facilitates the treatment of large distortions in the fluid motion. Its handicap is the difficulty to follow free surfaces and interfaces between different materials or different media (e.g., fluid-solid interfaces). ALE algorithms are particularly useful in flow problems involving large distortions in the presence of mobile and deforming boundaries. Typical examples are problems describing the interaction between a fluid and a flexible structure. The key idea in the ALE formulation is the introduction of a computational mesh which can move with a velocity independent of the velocity of the material particles. With this additional freedom with respect to the Eulerian and Lagrangian descriptions, the ALE method succeeds to a certain extend in minimizing the problems encountered in the classical kinematical descriptions, while combining at best their respective advantages. The ALE formulation seems the best choice for typical aeronautics applications where the vehicle deformation must be taken in to account for a proper evaluation of the fluid-solid interaction.
The proposed ALE formulation ensures that mass conservation and Bernoulli equation are satisfied in a domain moving with a generic velocity field avoiding the need of enforcing any geometric conservation law. When the unsteady solutions of interest are mainly aimed at linearized transonic flutter calculations the ALE formulation can be taken to the limit of an unmoving mesh, so producing a transpiration formulation at the body boundary allowing to deal with the related analyses using fixed meshes.
The solution procedure relies on an unstructured, node based, finite volume approximation, with linear|quadratic shape functions. The use of nonreflecting far field boundary conditions allows a relatively limited calculation domain. An improved upwind technique is used to better establish the right sub-supersonic dependence and allows to treat both subsonic and supersonic asymptotic conditions. A special tool to generate the wake discretization within generic unstructured meshes leads to an easy adoption of potential flows for complex configurations. Time marching solutions are dealt using first|second order implicit schemes, whose unconditional linearized stability properties are demonstrated for sub-supersonic asymptotic conditions.
Numerical results validate the method and show that it can model Euler solutions more accurately than an isentropic full potential formulation, for both steady and unsteady conditions. Applications to asymptotically supersonic flows, flutter analyses and static trim evaluations complete the numerical validation.

ADVANCED CONTROL LAWS FOR VARIABLE-SPEED WIND TURBINES AND SUPPORTING ENABLING TECHNOLOGIES

Carlo E.D. Riboldi

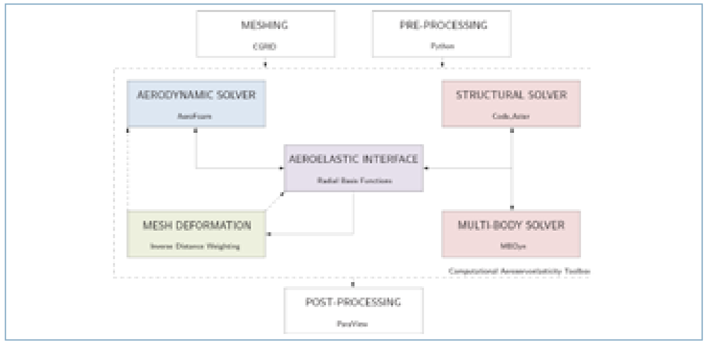
The increase in size of horizontal-axis wind turbines of new generation poses important challenges from the viewpoint of the design of the plant as a whole and of its sub-systems. The design of such turbines can be seen as a multi-disciplinary, highly integrated process, where structural and aerodynamic (aero-elastic) characteristics, as well as an appropriate active control system are all key aspects which play a part in the determination of the performance, both in terms of overall power production and of the intensities and frequency spectra of the loads. The characteristics of the control systems are extremely relevant for the sizing of the machine components, besides playing a key role in the stabilization of the machine in order to achieve the desired power output in every design wind condition.
Because of their relevance in the design of the wind turbine, control systems have been studied since the time of the first applications of engineering methods in the field of wind power, as witnessed by the extensive literature about the topic. The activities of the researchers in this field of study only rarely translate into real-environment experimentation or into application in the field, often because little attention is devoted to the development of readily applicable control tools, i.e. control systems accounting only for realistic sensors and able to manage several fault conditions, validated through a testing phase carried out using reliable tools and considering several wind conditions.
Starting from these issues, the present work is focused on the development and verification of complete control systems, based on novel advanced control laws and embodying all the necessary observation and supervision tools necessary for their realistic operation. Furthermore, all demonstrations and performance assessments are completed in a high-fidelity and well validated simulation environment, where the wind turbine is modeled following a multi-body/finite element approach. The aerodynamic routines implement stable and validated models made specifically for rotors, and able to account for the non-uniform nature of the incoming wind, as well as for the interaction effects between the rotor and the tower/nacelle assembly. The considered wind conditions are always both deterministic and turbulent, and the wind profiles are based on the suggestions of the IEC standard. The control routines and all enabling algorithms (e.g. observers) communicate with the simulator by a straightforward standard interface, thus allowing a cost-free porting on other controlled platforms. Moreover, as all control and support routines have been designed to cope with a real-time working environment, it is possible to use the developed control systems with real turbines without alterations to the code.
In order to provide a better proof of the quality of the results presented throughout this work and of the general applicability of the designed control systems, models of some different turbines have been used to both develop and cross-check many algorithms. This was possible thanks to several ongoing collaborations with relevant industrial and academic subjects active in the field of wind energy.
A brief review of the topics treated in the present work is presented next.
It is widely known that a major issue related to the use of model-based controls in a linearized design framework arises when the controlled system shows a non-linear behavior. As a consequence of this, some gain scheduling technique must be implemented in order to cope with the varying operating condition of the system. When using such techniques, the stability of the system is not always guaranteed at a theoretical level. This, together with the necessity to know an array of states to perform a feedback step, puts an obstacle to the widespread adoption of model-based control and in particular the very advantageous LQR design technique by wind power industry. In this work, a family of LQR controllers based on displacements and rotations is compared to an industrial PID control law. The performance of both controllers is evaluated in terms of power quality and load mitigation capability, under several wind conditions covering the full spectrum of operational speeds and with extreme turbulence intensities. The controllers provide very similar results, and no stability issue shows up hampering the normal operation of the turbine. Moreover, the LQRs give better results on tower loads, which are directly accounted for in the fed-back state. A hierarchy of full-state and output-feedback LQRs is designed to deal with possible faults in the sensor part.
Recent advances in the design of LiDAR wind sensors makes the anticipate knowledge of the incoming wind possible. To fully exploit the potential of such sensors, a predictive control system is proposed in this work, basically extending the classical feed-back LQR approach in order to account for a predictive control component, bound to the value of the incoming wind. This approach has the advantages of great simplicity and ease of use. The performance of this novel controller has been tested against that of a more complex receding horizon controller (RHC). The comparison shows that these predictive controllers perform in a similar way to each other, in spite of a higher computational cost of the RHC.
Besides the trimming problem, dealt with by means of collective pitch and torque controls by all the controllers just described, the use of cyclic pitch control was investigated in a multi-layer decoupled design approach to target some loads on the fixed part of the machine. In that architecture besides a standard trimming layer, a load mitigating part is implemented based on the higher harmonic control (HHC) theory. This is based on the preliminary identification of a model between relevant harmonics in the target load and some harmonics in the pitch input with an influence on those of interest in the target load. Then an optimal control law is used to evaluate the load-mitigating pitch contribution at each control time step. To better target some load components at higher frequency, an IPC control as proposed by Bossanyi is also superimposed to the first two loops, thus creating a multi-layer architecture. The performance of the complete multi-layer controller is better than that of the sole Bossanyi's IPC. A slightly different decentralized approach is used to effectively target blade loads.
In order to get all the necessary measurements for the application of model-based control laws some structural observers for the tower and blade motion are presented and tested separately, based on the Kalman theory. These observers are used also to formulate an observer of some wind states, based on the idea that from the deformation of some relevant structural states of the machine it is possible to dig out an information about the wind over the rotor. By characterizing the wind with some scalar wind states (e.g. horizontal speed, shear coefficient), it is possible to get a measurement of wind states starting from those of the structural deformations of the turbine, provided there exists a model connecting the set of structural states to that of wind states. This observation approach, based on a suitable reduced model and set up into the Kalman framework, shows good results when tested even with measurements coming from the high-fidelity multi-body simulator.
A totally different approach to wind estimation is based on model identification, and is aimed at the robust observation of yaw misalignment. This approach is based on the preliminary identification of a linear scheduled model linking the 1P amplitudes of some blade specific loads to the intensity of yaw misalignment. The feasibility of this model is supported by some analyses at the theoretical level. The observer synthesized in this way shows robust observation results even under very requiring wind conditions.

COMPUTATIONAL AEROSERVOELASTICITY OF FREE-FLYING DEFORMABLE AIRCRAFT

Giulio Romanelli

The reduced weight and improved efficiency of modern, highly flexible, aeronautical structures (as a consequence of multidisciplinary optimization procedures and the extensive use of composite materials) result in a smaller and smaller separation of rigid and elastic modes frequency ranges. Therefore the availability of an integrated environment for tackling both static (stability derivatives correction, control surfaces efficiency, non-linear trim of maneuvering flexible aircraft) and/or dynamic (flutter, gust and turbulence response, active control systems design) aeroservoelastic problems is almost mandatory from the very beginning of the design process.

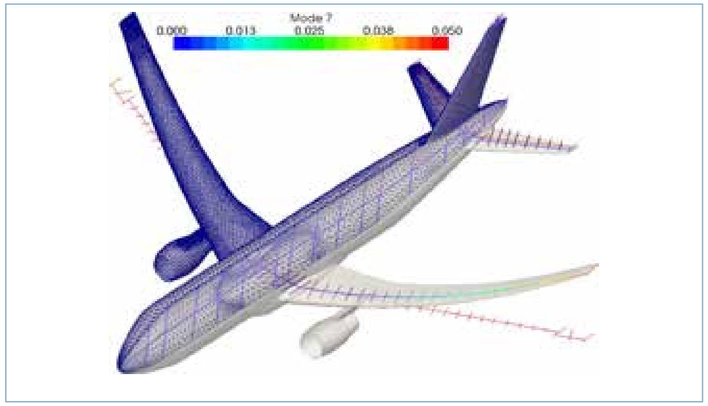
In recent years some challenging aeroelastic problems have been tackled for the very first time, such as the study of the highly non-linear transonic flutter, buzz and buffeting phenomena. A better understanding of these phenomena is important to design more efficient and safer aircraft. In fact the inability to model and predict such non-linear aeroservoelastic behavior can only be resolved by means of extensive flight test programmes, informed through experimental, empirical or simplified modeling techniques. This is an expensive approach to qualification and has the major disadvantage that should an aeroservoelastic susceptibility be identified, redesign must take



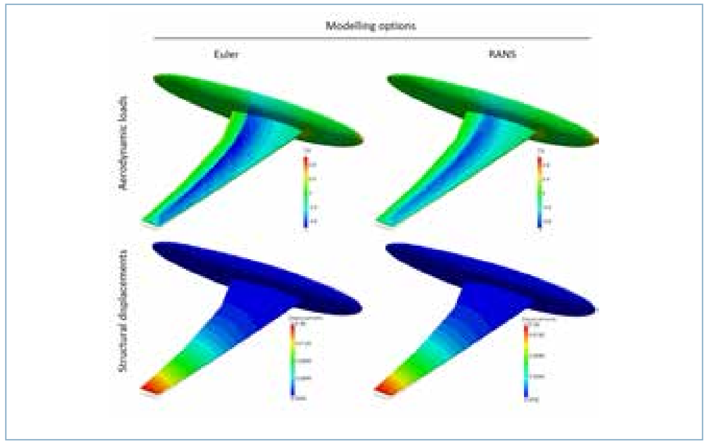
1. Block diagram of the proposed aeroservoelastic analysis toolbox.

place late in the development cycle: again this can be (and usually is) extremely costly. New approaches to high-fidelity aeroservoelastic modeling and prediction tools are needed to reduce the costs and risks of current processes. This is true, not only for new designs, but also for existing aircraft that may go through several major upgrades when re-certification is required. It is then necessary to focus on the more sophisticated mathematical models and numerical methods within the very active and fruitful research field of Computational Aeroservoelasticity (CA). Together with the availability of more and more powerful computing resources, current trends pursue the adoption of high-fidelity tools and state-of-the-art technology offered by Computational Structural Dynamics (CSD), Multibody System Dynamics (MSD) and Computational Fluid Dynamics (CFD). At the same time it is also important to carefully monitor the run-time and memory requirements of such tools, since a very large number of numerical simulations must be accounted for in order to complete the aeroelastic analysis even only of an isolated wing.

In the present work we illustrate the design and implementation of a platform for solving multidisciplinary non-linear Fluid-Structure Interaction (FSI) problems with a partitioned approach, that is coupling high-fidelity state-of-the-art CSD/MSD and CFD tools by means of robust and flexible aeroelastic interface and mesh deformation schemes. An innovative contribution to the challenging research field of Computational Aeroservoelasticity (CA) consists in demonstrating that such a platform can be assembled using only free software. Within such a framework the structural sub-system can be modeled with the Finite-Element (FE) solver *Code_Aster* or the Multi-Body (MB) solver *MBDyn*.



2. Aeroelastic interface and aerodynamic mesh deformation.



3. Aerodynamic loads and structural displacements for the static aeroelastic analysis of the HiReNASD wing as a function of modeling options (Euler vs. RANS).

The aerodynamic sub-system is modeled with the Finite-Volume (FV) aerodynamic solver *AeroFoam* which kicked-off back in 2008, as an ambitious academic experiment with the challenging target of filling the empty space left in *OpenFOAM* software for a density-based compressible RANS solver (still growing today, with more and more original features being released and pushing it towards real-world industrial applications). Among the innovative contributions it is worthwhile to remark: the dedicated aeroelastic interface scheme based on Moving Least Squares (MLS) interpolation strategy, providing all the functionalities necessary to link the structural sub-system with the aerodynamic one, and the dedicated hierarchical mesh deformation tool based on Sparse Inverse Distance Weighting (SIDW) strategy for dealing with moving boundary problems in Arbitrary Lagrangian Eulerian (ALE) formulation.

The credibility of the proposed aeroservoelastic analysis toolbox is successfully assessed by tackling a set of realistic static and dynamic problems and comparing the results with reference experimental and numerical data available in literature. More in particular we investigate the sensitivity to different modeling options for representing the aerodynamic sub-system. In order to strike the best balance between accuracy of the results and computational efficiency, we choose, within the hierarchy of tools available the lowest-fidelity Doublet Lattice Method (DLM) or the Non-Linear Full Potential (NLFP) equations or the Euler equations or the highest-fidelity Reynolds Averaged Navier-Stokes (RANS) equations. To begin with we illustrate the static aeroelastic benchmark test problem of computing the reference equilibrium or "trim" configuration of the HiReNASD wing. Such an example is particularly interesting because it was selected as benchmark test problem for the 1-st AIAA Aeroelastic Prediction Workshop series with the objective of providing an impartial forum for the assessment of state-of-the-art CA methods. Successively we present the numerical results for the non-linear aeroservoelastic trim of a free-flying A320 aircraft equipped with innovative passive aeroelastic wing tip devices and carried out a detailed comparison with the results of *Nastran*, a "de-facto" standard tool within the aeronautical industry. Moreover we tackle the classical dynamic aeroelastic benchmark test problem of computing the transonic flutter boundary of the AGARD 445.6 wing. Finally we survey an example aeroservoelastic problem of how to design a flutter suppression active control system to operate within the highly non-linear transonic regime with a linear, low-fidelity but efficient model and then verify the performances with a non-linear, high-fidelity but expensive model.