DOCTORAL PROGRAM IN AEROSPACE ENGINEERING

Chair:
Prof. Luigi Vigevano

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 program and credits are divided in three main educational areas:

1) Main courses (30 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 (30 credits), gained in the second year: specific and personalized 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 centers, 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 past 24 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 modeling 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, 24 years ago, the doctoral course on Aerospace Engineering graduated more than 70 PhDs.

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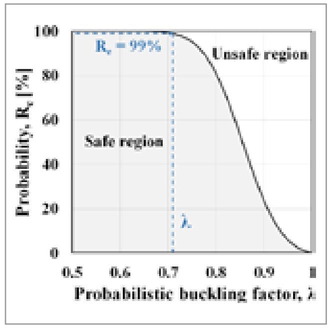
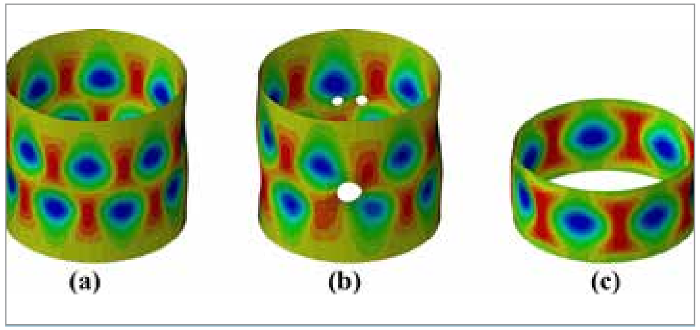
A PROBABILITY-BASED METHODOLOGY FOR BUCKLING INVESTIGATION OF SANDWICH COMPOSITE CYLINDRICAL SHELLS

Michela Alfano – Supervisor: Prof. Chiara Bisagni

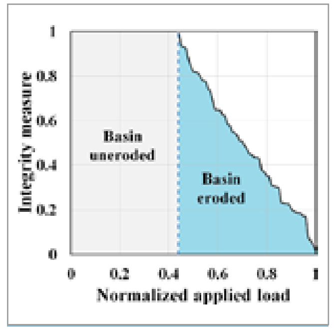
Due to their low weight and high performance, sandwich structures are widely used in the design of space launch vehicles, where buckling is a dimensioning criteria. Currently, shell design relies on NASA SP-8007 guideline, dated from 1968. It recommends the use of an empirical knockdown factor to account for imperfections, which can greatly reduce the buckling load predicted for a nominally-perfect shell.
The thesis aims to meet the demand of aerospace industry for the development and the validation of improved shell design criteria, which allow, if possible, for reducing development and operating costs. Two approaches, a probabilistic approach and a chaos approach, are developed to investigate buckling response of cylindrical shells under axial compression.
The probability-based methodology for shell design is developed within the European Project DESICOS (New Robust DESign Guideline for Imperfection Sensitive COmposite Launcher Structures), started in 2012 with the goal to investigate the combination of probabilistic and deterministic approaches. Probabilistic methods have found many successful applications in engineering fields, because they allow to include directly uncertaines in the design.
This thesis provides a unified framework for probabilistic buckling analysis of shells subjected to compressive loading. The probabilistic methodology combines the Stress-Strength Interference Method and the Latin Hypercube Method in order to define the structural reliability of shells with imperfections in function of a loading parameter, named probabilistic buckling factor, as illustrated in Figure 1
The reliability curve provides a graphical visualization of the imperfection sensitivity of shell. Indeed, the region below the curve represents the safe region where shell withstands axial compression without undergoing buckling. The safe region is larger for shells with low imperfection sensitivity.
The probabilistic buckling factor enables to define the individual or combined influence of different types of imperfections, but it depends on chosen reliability level, on adopted sample size and on considered imperfections.
The main advantage of the procedure is the versatility as it can be applied to buckling investigation of laminated composite shells and sandwich composite shells including different sources of imperfections and using different sampling techniques.
The methodology would be useful in predicting the lower bound buckling load of shells, by having experimentally-measured data concerning manufacturing processes, loading conditions and boundary conditions.
The probabilistic procedure is illustrated with application to buckling analysis of two structures of Ariane 5 launcher, the Dual Launch System (SYLDA) and the Interstage Skirt Structure (ISS). The structures are sandwich composite cylindrical shells, designed by Airbus Defence & Space. One of them is investigated in a second configuration, with three circular cut-outs (SYLDA with cut-outs).
The post-buckling deformation of the shells at 3 *mm* of shortening is shown in Figure 2.



1. Structural reliability.



2. Sandwich shells: (a) SYLDA; (b) SYLDA with cut-outs; (c) ISS.



3. Erosion profile.

The statistic characteristics of imperfections are appropriately assumed by literature. Geometric imperfections, boundary imperfections, variability of longitudinal Young's modulus and ply misalignment are considered. Next, imperfections are measured on an experimental shell manufactured by GRIPHUS, a partner in DESICOS, and are incorporated into the numerical analysis. The objective is to describe how experimental data can be taken into account using the developed probabilistic methodology.
An alternative method to the probabilistic one is the chaos approach, which exploits concepts of chaos for the buckling analysis of axially-compressed shells. This research aims to contribute for best comprehension of chaos. Chaos concerns nonlinear dynamic systems which exhibit seemingly-random behavior, but having actually an underlying order and a high sensitivity to input conditions. The buckling behavior of axially-compressed shells can be considered as chaotic because of the high imperfections sensitivity.
Moreover, the transition from pre-buckling equilibrium state to post-buckling equilibrium state is a dynamic process which induces nonlinearities.
The chaos approach uses the concept of basin of attraction in order to obtain an erosion profile as a function of increasing axial load, as shown in Figure 3. Such a profile illustrates concisely the imperfection sensitivity of shells by showing the erosion due to imperfections of the load-carrying capability of shells as axial compression increases.
The chaos approach could be adopted when test-originated imperfections database is not available for a first assessment of imperfection sensitivity of shells.
The erosion profile differs from the reliability function in Figure 1, because it represents the maximum allowed reduction of the load-carrying ability of shells, whereas the reliability is the probability that shell does not buckle under axial compression.
The chaos approach is adopted for buckling analysis of one of the three shells, taking into account geometric imperfections. Nevertheless, it needs to be further enhanced with the goal to investigate buckling behavior of both laminated composite shells and sandwich composite shells including other types of imperfections.

AEROSERVO ELASTICITY OF SMART ROTORS

Claudio Brillante - Supervisor: Prof. Paolo Mantegazza

Tutor: Prof. Giuseppe Quaranta

Helicopters experience a severe level of vibrations on the main rotor due to the asymmetrical airflow in forward flight. These vibratory loads are transmitted to the fuselage and degrade the flight comfort, while causing structural components wear. Therefore the objective of this research is the study and design of actively controlled systems that are able to suppress these loads, with the aim to set the basis for further investigations about the presented topics.

Due to the necessity of reproducing the complex behavior of the rotor with a sufficient level of accuracy in forward flight, before designing control systems, the first part of the thesis focuses on the development of a computationally efficient aeroservoelastic rotor simulation toolbox. A high level of fidelity can be achieved for the structural modeling with low computational effort through multibody softwares, taking into account both nonlinear structural couplings and generic complex motions, as done in this work. Without using full three-dimensional finite element representations, the flexibility of the blades is correctly taken into account through geometrically nonlinear beam models and precise properties computations. The first contribution of this thesis is the development of a new semi analytical algorithm to compute the section properties of a generic beam section with embedded piezoelectric and piezomagnetic actuators. The equations of motion are then solved within the multibody software, without reducing or linearizing the resulting rotor dynamic system. Starting from the simple aerodynamics integrated in the multibody software, more sophisticated aerodynamic models have been developed. The best way to alleviate the computational cost of the aerodynamic simulations, as outlined in the literature, is to exploit the hybrid methods, in which the blade near field aerodynamics is analyzed through a different method, often more accurate, than the one used to model the far field released rotor wake. Because of the need to keep the simulation time within reasonable levels and of the different degree of approximations available, two methods are exploited and compared, with the aim of understanding which effect is predominant and requires a more accurate modeling. In the first proposed method a full potential solver is used to simulate the blade unsteady aerodynamics coupling it to a generalized wake mathematical model. In the second method the computational time is invested into the rotor wake modeling through vortex filaments, while the blade aerodynamics is approximated with the well known blade element theory, adding unsteady corrections by using the Theodorsen and the Kussner function. It is important to emphasize that such methods are not meant to replace full computational fluid dynamics aeroelastic models, which are very useful for high fidelity loads prediction and validation studies for the final design stage, but the whole work is aimed at enhancing the controller design by providing more accurate and computationally fast mathematical models.

The thesis focuses on actively twisted blades having distributed piezoelectric actuators along the blade span and the second part of this work compares three advanced active control algorithms in order to assess their advantages and limitations. At first, linearized model-based periodic controllers are designed on the multibody model and then their robustness is verified on the more accurate aerodynamic models. The second approach is a nonlinear adaptive recurrent neural network control and does not require the knowledge of a numeric rotor model. One of the main problem that one can encounter during experimental tests is the actuator saturation due to undesired control activity. Therefore, the classical adaptive higher harmonic control is enhanced to properly take into account actuator saturations. These controllers show satisfactory results and they are all computationally efficient, thus having real time capabilities.

The last objective of the thesis is to compare the chosen actuation mechanism with other SMART rotor approaches and therefore, the rotor vibrations are reduced through active trailing edge flaps to study the most effective solution. To do so, the aeroservoelastic code is extended to include the modeling of movable aerodynamic surfaces. Using the higher harmonic control, the active twist solution is compared to the active trailing edge flaps approach, which has shown to be much more effective for vibrations reduction, at least for the considered trim configuration and with the current position of the piezoelectric actuators.

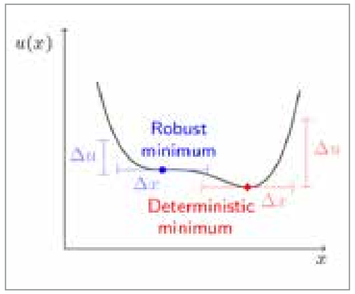
The last part of the thesis is related to an experimental activity carried out at the German Aerospace Center (DLR). Individual blade control is here achieved through actuators in the non rotating frame by using the multiple swashplate system. In this activity the enhanced higher harmonic control algorithm with the actuator constraints handling is implemented within the real time environment and blade tracking control is performed in order to suppress vibratory loads in hover due to the blades dissimilarity. This application is of significant value because it widens the possibility that actively controlled rotors will be employed in the near future to ensure a more comfortable and safer flight.

ROBUST SHAPE OPTIMIZATION OF FIXED AND MORPHING ROTORCRAFT AIRFOILS

Francesca Fusi - Supervisor: Giuseppe Quaranta

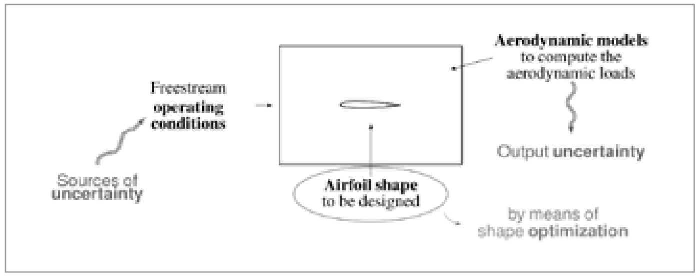
Shape optimization has been widely used in aerodynamics for aerospace vehicles design to define the design which provides the best performance given a set of objectives and constraints. The case of helicopter rotor blades poses a challenge, due to the necessity to employ accurate, expensive Computational Fluid Dynamics tools and the requirement of satisfactory performance in different operating conditions. In fact, in forward flight the advancing side of the rotor encounters transonic flow condition, while the retreating side is close to stall conditions. Furthermore, unsteady effects due to the blade dynamics and flexibility, as well as the interaction with vortices and wakes trailed from preceding blades, affect the blade operating conditions. Thus, even when optimization is employed, the aerodynamic performance in the flight envelope may be often sub-optimal. An attractive solution to this problem is the employment of a morphing blade, that is a blade capable of changing its shape during flight. Recent studies have focused on blades with adaptable span, chord or twist, as well as conformable airfoils.

Another aspect limiting the optimality of the solutions obtained via numerical optimization is the discrepancy between the real-world performance and the estimate coming from the modelling of the system under consideration. As a matter of fact, engineers generally employ design and optimization methods modelling all relevant aspects of the system operating cycle, in which inherently exist numerous sources of uncertainty. For instance, the system operating conditions are affected by the status of the surrounding environment which is not deterministically known. In addition, some model parameters used to represent the physical system are affected by a lack of knowledge of the system itself. These uncertainties may alter the system's expected performance, and in order to take this into account from the beginning of the design, the research community focused on uncertainty-based optimization techniques, such as robust optimization methods which seek an optimal design that maintains satisfactory performance when considering the variability of system parameters (see Fig.1).



1. Robust vs. classical, deterministic minimum of function u(x).

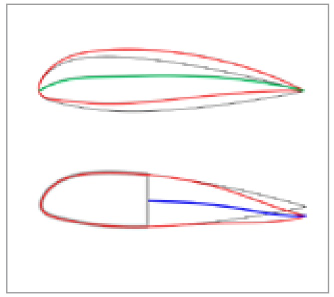
In this context, the thesis focuses on the development of a methodology for robust optimization to tackle the problem of designing fixed and morphing airfoils of helicopter rotor blades. In particular, the shape optimization seeks the airfoil providing a high mean performance and a low sensitivity with respect to changes in the operating conditions (see Fig. 2).



2. Scheme of airfoil shape optimization under uncertain operating conditions.

Because robust optimization increases the computational cost of the optimization process, new uncertainty-based optimization methods are developed. The goal of this development is to improve the numerical efficiency, thereby making robust approaches more attractive to aerodynamic applications. The first method is based on a multi-fidelity approach to the estimation of the aerodynamic performance. The second strategy leverages an adaptive uncertainty quantification method to reduce the computational cost associated with poor design vectors inside the optimization loop. The methods are applied to algebraic test cases and to the robust optimization of fixed airfoils in the hovering condition. This first application demonstrates the effectiveness of the proposed strategies and it also provides the mean for a discussion on the impact of robustness criteria on airfoil design.

In addition, the robust optimization framework is used to tackle the forward flight case. In this flight condition, two representative position of the blade over the azimuth are considered, i.e. the advancing side and the retreating side. Deterministic and robust optimal shapes are compared and robust airfoils demonstrate to be able to trim the helicopter with performance close to the deterministic values. The post-processing analysis of this application includes the comparison of the estimate computed by the steady models used in the optimization loop throughout the thesis and the objective function estimates obtained from an unsteady CFD model. Finally, the application of morphing airfoil is considered. The morphing strategy consists in a variable camber airfoil and it is conceived with the intent of changing its shape at the 1/rev frequency to enhance aerodynamic performance. The optimization of morphing airfoils presented in the thesis takes into account the aerodynamic performance, while technological aspects are accounted for by means of geometrical constraints. Two solutions are considered: a complete camber morph airfoil and a trailing edge morph (see Fig.3). The gain of the morphing airfoil strategy is assessed not only from a deterministic point of view, but also when considering uncertainty in the operating conditions.



3. Types of conformable airfoil: camber morph (top) and trailing edge morph (bottom).

The employment of robust optimization proves to be of great interest, owing to the fact that even the airfoils with higher mean values achieve low values of the variance of the aerodynamic efficiency with respect to variations of the angle of attack. The reduction of the variance could lead for instance to a reduction of the required rotor shaft torque in variable operating conditions. Furthermore, in the different applications presented in the thesis, results demonstrate how the robust optimization formulation represents a formal procedure to guarantee that the optimal airfoils would not incur in lift loss, drag increase or moment penalties throughout the uncertainty range.

HYBRID ROCKET FOR IN-SPACE PROPULSION

Jakub Glowacki - Supervisor: Prof. Luciano Galfetti

The dawn of XXI century show new frontiers of the rocket technology dictated by private entities with the ambitious plans for both near earth space and deep space exploration. However, this target will be never achieved without appropriate propulsion systems able to fulfill the requirements of effectiveness and cost reduction. One of the most promising technology for space access is based on hybrid rocket engines (HRE). HREs are characterized by the use of oxidizer and fuel kept in different state of matter (usually liquid and solid). The relatively low technology readiness level of this propulsion solution is due to the higher interest of since community in solid and liquid rocket systems in previous decades. However, the success of SpaceShipOne proves that hybrid rockets can be a propulsion mechanism of the future providing safety, flexibility and cost-reduction to the operator.
The international effort towards the development of hybrid rocket propulsion system is mainly targeting high-thrust applications such as launcher stages. Other branch of propulsion, which cover in-space propulsion missions such as satellite maneuvering, deorbiting, attitude control, soft-landing have not been investigated in-depth so far. In this respect, the missions can benefit of some important advantages of HREs as throttleability and re-ignition capability. Nevertheless, the performance of HREs is currently limited by the low regression rate of the fuel and the poor combustion efficiency. Typical solutions to address the problem is by the use of:

- high energy additives;
- liquefied fuels;
- large regression surface (multi-port grains);
- swirling and vortex flows.

Special place in this investigation is covered by alternative geometry engines. One of them, named vortex end-burning hybrid engine (VEBH) or vortex flow pancake (VFP) engine shows a great potential to solve the problems of hybrid rocket engines. In a VEBH a grain disks of cylindrical shape is burnt with a tangential injection of the oxidizer. The oxidizer flow is injected into the combustion chamber by multiple inlets creating a vortex in the plane parallel to the fuel surface. The potential advantages of the VEBH configuration are:

- regression rate enhancement ;
- high volumetric packing;
- high combustion efficiency due to the increased residence time and the centrifugal acceleration of the flow;
- possibility of external mounting for better cooling;
- no oxidizer-to-fuel shift.

In this work the possible application for deorbiting mission is investigated both in terms of classic and alternative geometry of the hybrid rocket. The results show that the optimal length-to-diameter ratio is less than 1, while for conventional system is higher than 10. These geometrical properties play an important role for in-space propulsion, and this research show that VEBH are a much better solution for in-space applications. Moreover, for the mission profile the engine with 144 kg of total mass should be able to deorbit most strategically important debris, while for a conventional engine the mass is estimated for around 160 kg.
The uncertainty investigation based on Monte Carlo method points out that the most important parameters for VEBH are the ones which that describe fuel release. Therefore the complex computational fluid dynamic model was proposed to investigate the problem. The investigation includes the modeling of advanced radiation, turbulence and chemical kinetics models and results in first flow field analysis of the VEBH engine. Covering the results high fuel release regions and the mechanism responsible for this is identified. Several different configurations varying the amount of oxidizer inlets were considered, giving the most optimal configuration for the combustion chamber.
The research addresses some problems which are the state of the art of hybrid rocket technology:

- Provides a systematic approach for the vortex hybrid engine in pancake configuration, evaluate in the quantitatively way the benefits of alternative configurations for deorbiting mission.
- Uncertainty analysis which point out the sensitivity of the solution on different input parameters using Monte Carlo approach.
- Reliable computational model which contains the complex chemical kinetics, turbulence and radiation model. Due to the unique complexity it can be considered as a benchmark for future investigations.
- Computational approach to understand the VEBH flow field, including both cold and hot flow simulation, with emphasis on high fuel release zones.

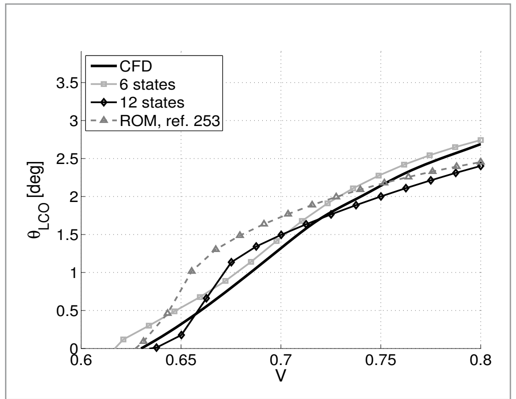
1. vortex flow pancake

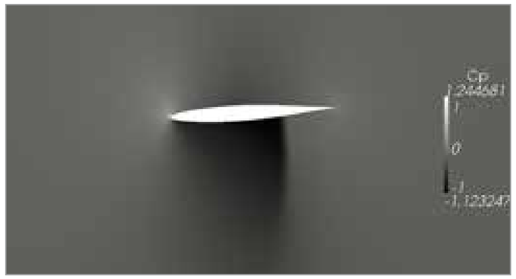
2. vortex flow pancake during in-space mission

NONLINEAR AEROSERVOELASTICITY
REDUCED ORDER MODELING AND ACTIVE CONTROL

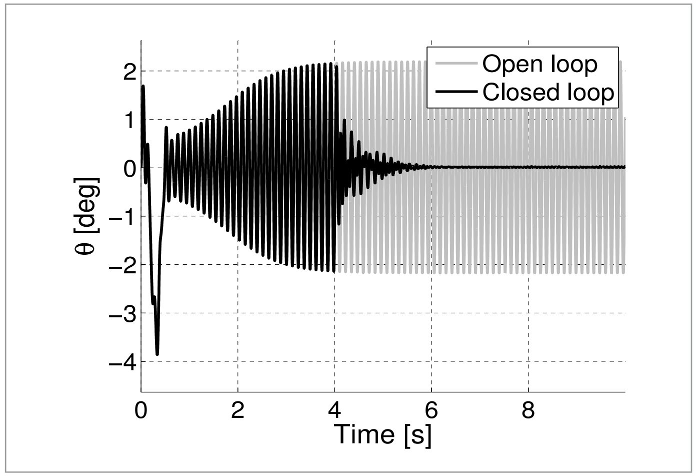
Andrea Mannarino - Supervisor: Prof. Paolo Mantegazza

This thesis presents an insight into the behavior of aeroelastic systems in presence of aerodynamic and structural nonlinearities. It is shown that such effects that often are not accounted in classical aeroelastic analyses might greatly affect the system stability properties and shape peculiar dynamic responses. Their early inclusion in the design process of aircraft components may therefore lead to substantial weight saving and to a paradigm shift in control law design.
Particular emphasis is given here to the mathematical modeling of aerodynamic nonlinearities, such as large shock wave motions that induce limit cycle oscillations in flexible wings. Reduced order models based on neural networks are developed to extract information from computational fluid dynamics codes and reconstruct unsteady nonlinear behaviors of the aerodynamic system in a compact way.
A systematic approach in the training signal design is presented, exploiting the underlying problem physics. The convergence of such methodology is studied comparing aerodynamic and aeroelastic responses with the related outcomes of the parent high fidelity models.
Structural nonlinearities are instead studied through simpler static models, which nonetheless permit a physically meaningful representation of the responses of interest. The coupled effect of structural and aerodynamic nonlinearities on a typical aeroelastic test case is assessed, showing a very particular behavior that depends on the problem initial condition and on the disturbance type and amplitude that is used to excite the system dynamics. Limit cycle oscillations are studied and their dependence on the flight speed and other key parameters is assessed.
The results computed by the reduced order model are then validated through computational fluid dynamics-based aeroelastic simulations.
Having available a tool to describe compactly nonlinear unsteady aeroelastic responses, classical and adaptive controllers are developed aiming at improving the system performance and eliminating possible instabilities.
It is found that the suppression of aerodynamic nonlinearities well differs from the approaches used to compensate effectively the presence of structural nonlinearities such as free-play and friction in control surfaces actuation chains.





1. Left: limit cycle amplitude trend predicted by the reduced order model
Below: snapshot of a computational fluid dynamics-based simulation



2. Left: suppression of aerodynamically induced limit cycle oscillation.

At first these kind of nonlinearities and their related suppression techniques are studied separately, while at the end a systematic approach is presented to design a controller that compensates both effect through an integrated approach.
Aerodynamic nonlinearities are suppressed using the quite novel concept of immersion and invariance of dynamic systems. Such a controller basically follows the approach of a sliding mode controller, nonetheless using approximating nonlinear functions instead of discontinuous control terms for making the target manifold invariant to perturbations.
The required feedback of the system state is realized through a sliding mode observer, which has shown good robustness properties while maintaining its design as systematic as possible.
The presence of actuators and sensors is also simulated to increase the model fidelity and to present an approach that can be easily extended to experimental applications, which take into account all of these additional elements.

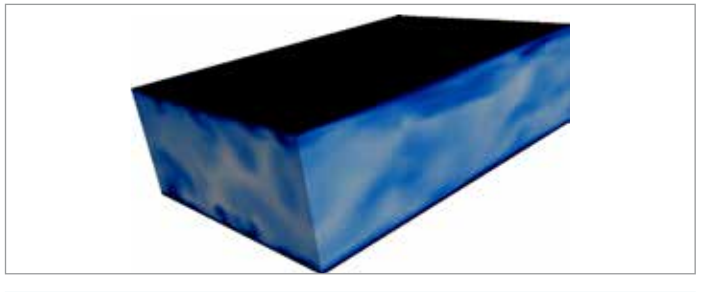
The compensation of structural nonlinearities such as free-plays and frictions is instead tackled from another perspective. At first, an approach based on industrial PID controllers is followed, combining them in order to compensate the loss of the system controllability inside the free-play region.
This methodology has shown to work well in purely mechanical applications, effectively suppressing the presence of this kind of nonlinearities. This is not the case when aerodynamic loads are present and affecting the system stability. In fact in this case such a simple approach is not sufficient to completely compensate the free-play effect, leading to residual small amplitude limit cycle oscillations in closed loop. The problem is solved implementing more complex adaptive solutions which estimate on-line the main nonlinearities features and try to compensate them through a direct inversion of the estimated relation. This approach has led to a much more efficient suppression of the related limit cycle oscillations, robust to measurement noise and unmodeled dynamics.
The studied methodologies are finally combined to suppress the effect of aerodynamic and structural nonlinearities on the stability of aeroservoelastic systems. Problems of increasing complexity are studied, proving the efficacy of the proposed control laws.

ANALYSIS OF A NOVEL HYBRID RANS/LES TECHNIQUE BASED ON REYNOLDS STRESS TENSOR RECONSTRUCTION

Michele Nini - Supervisor: Antonella Abbà

Although the huge progress of computer science, the computational cost associated to the numerical simulation of Navier-Stokes equations is still remarkable. In particular, the direct numerical simulation (DNS) is unfeasible for the great part of the applications. A possibility to obtain fluid simulations with relatively cheap cost is represented by a statistical approach like Reynolds-averaged Navier- Stokes (RANS) equations, but unfortunately RANS does not provide the informations required to understand the unsteady behavior of the turbulent flows. Those informations can be obtained by Large Eddy Simulation (LES), this approach is based on filtering the Navier-Stokes equations in order to resolve only the large eddies and using a model for the smaller ones, however also LES is still too costly for many applications.
Summarizing: LES is sufficiently detailed but too expensive, RANS is sufficiently cheap but too superficial. As a consequence combine LES and RANS seems to be a reasonable choice in order to obtain a detailed description of turbulent flow without incurring in problem of cost. For this reason in the last decades hybrid RANS/LES models have been one most important topic in computational fluid dynamics research.

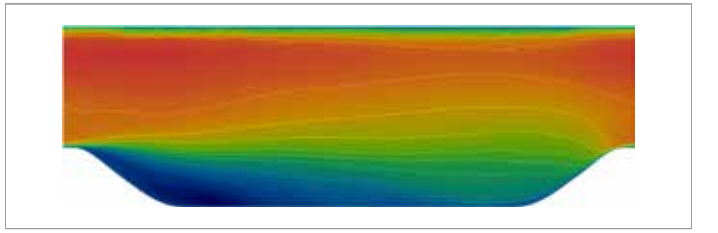
However, RANS and LES are very different approaches and coupling them is not trivial. A promising framework is represented by the hybrid filter approach proposed by Germano in 2004. This filter, *H*, is composed by the LES filter *F* and the statistical operator RANS *E* : $H= kF + (1-k)E$, where *k* is a blending factor which varies from 0 (pure RANS) to 1 (pure LES). Applying this filter to the Navier-Stokes equations it is possible to obtain a new set of formally correct equations.
In this thesis the hybrid filter approach has been studied and analysed, in particular the attention has been focused on a new treatment for RANS term, i.e. the Ryenolds stress tensor. This term is usually modeled by means of an explicit RANS model. In this work the RANS contribution is reconstructed, exploiting the properties of the hybrid filter, from the LES subgrid stress tensor and the resolved velocity field. As a consequence, no explicit RANS model and then no additional equations are required, this result in a very simple and cheap methodology. The main drawback is related to the limitation of the blending factor *k*: in fact, the RANS reconstruction procedure does not allow to use low values of *k*. This avoid the possibility of using pure RANS. Therefore, the methodology proposed is different from a standard wall- odeling LES, in which pure RANS is used to model the flow near to the wall. Here, in fact the RANS contribution is used to integrate, and not to substitute, LES in the context of coarse grid, i.e. for grid coarser then the ones required for a well resolved LES.
The methodology has been studied using FEMilaro, a gnu license software originally developed at the mathematics department of Politecnico di Milano, and improved during this work. The space discretization of the hybrid filtered equations has been obtained by means of the discontinuous Galerkin (DG) finite element method.



1. Streamwise velocity visualization for the turbulent channel flow

Initially the attention has been focused on the analysis of the role of the blending factor *k*. The simulations performed for the turbulent channel flow testcase (Fig.1), using constant and uniform *k* have been highlighted a clear dependences between k and the quantities of turbulent energy modeled and resolved. As the *k* decreases the RANS contribution increases, and, as a consequence, the modeled energy increases and become greater then energy resolved for *k~0.7* .
The simulations performed with constant blending factor have been also compared with DNS results, showing a greater agreement with respect to the results obtained with pure LES.

However, using a constant blending factor is not an optimal choice: its value should be related to the accuracy of the mesh, and in particular to its capability to resolve a certain number of turbulent scales. Therefore, using a variable *k* can be useful to set the optimal value of RANS contribution in the different parts of the domain. On the other hand, introducing a space or time dependent *k* make the equations very complex because of the additional terms related to the non commutativity of *k* and space and time derivatives.
The strategies analysed in this work is using a piecewise constant blending factor. In fact, keeping the blending factor constant in the element, the additional terms go to zero and the discontinuity between two consecutive elements do not represent a problem considering the DG approach used for the space discretization.
The approach has been successfully tested for the turbulent channel flow testcase. Here, using a blending factor dependent to the wall distance a significant improvement of the LES results has been obtained.
In order to test the method for more complex geometries also periodic hill flow (Fig.2) has been studied. Despite the apparently simple geometry, the periodic hill test case presents some challenging feature, like the massive flow separation from a curved surface, the high sensitivity of the reattachment point location to the separation and the strong acceleration of the flow. From the simulations performed, the hybrid method is able to well describe the flow but does not show significant benefits with respect of the pure LES simulations. This can be related to difficult choice of the blending factor function in a more complex geometry.



2. Averaged streamwise velocity in the period hill flow test case. The velocity has been averaged both in time and space over the spanwise direction.

The results obtained both with fixed and variable blending factor confirm that the hybrid filter with RANS reconstruction approach can be a promising technique for fluid simulations. In fact, it can reasonably be expected that, introducing an optimal blending factor, the methodology analysed can be suitable for improve accuracy of the turbulence description for coarse grids. Future work will be focused on this point: understand how to find a reliable criterion for the choice of the best value of the blending factor, element by element.

AN ADAPTIVE INTERPOLATION-FREE CONSERVATIVE SCHEME FOR THREE-DIMENSIONAL EULER EQUATIONS ON DYNAMIC MESHES FOR AERONAUTICAL APPLICATIONS

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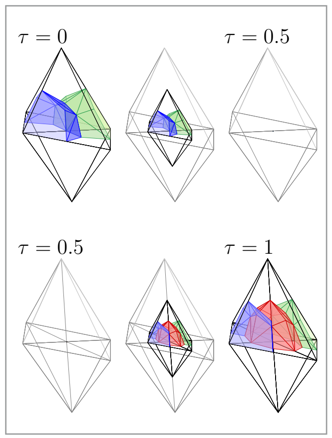
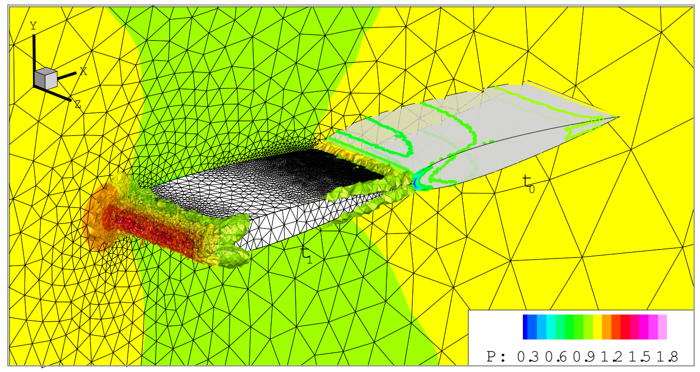
Computational Fluid Dynamics (CFD) has been proved to be an effective tool for analysis, design and troubleshooting in many research and industrial areas, including aerospace. Physics, numerical analysis and computer science are exploited to model and solve the flow field at the required level of accuracy, which often depends on the available resources. Despite the improvements in numerical techniques and the steady rise of computational power with better performances, geometrically complex and three-dimensional (3D) moving-body problems still represent a challenge for the CFD community. Examples of problems that fall in this class include, for instance, the simulations of the complete flow field around a rotor-craft in advancing flight, the deployment of control surfaces, the prediction of the aeroelastic behavior of wind turbines and load separation experiments. Moreover, in all these problems it is often relevant to capture peculiar flow features, whose exact location is not known a priori. To this end, the present work aims at developing a robust and accurate strategy to handle 3D complex moving geometrical configurations and, at the same time, to locally modifying the grid resolution according to the solution itself through mesh adaptation techniques. More specifically, a novel approach to solve the finite volume formulation of the unsteady inviscid compressible governing equations over 3D dynamic grids is proposed. Mesh adaptation is widely used in CFD simulations to tackle the large variety of phenomena characterized by different spatial scales and in all problems where the location of relevant flow features is not known a priori. Thanks to a suitable sequence of node insertion, node deletion, edge swapping and point relocation, the grid spacing can be efficiently modified according to the behavior of the solution without manual intervention. Furthermore, local mesh adaptation techniques can be used to monitor mesh quality and to avoid invalid elements when dealing with large boundary movements, especially when simple deformation is not sufficient to perform the whole displacement. When a new mesh is obtained, the solution computed on the old grid has to be interpolated over the new one. This step is critical since interpolation can undermine the stability and conservativeness of the scheme. In moving-boundary problems, a fundamental role is played by the kinematic description used to express the relationship between the deforming continuum and the computational mesh. The Arbitrary Lagrangian-Eulerian (ALE) method is usually adopted to deal with strong distortions of the domain and to precisely follow the boundaries, because it allows to enforce the governing equations on deforming control volumes that can move independently from the fluid velocity. To ensure conservativeness when solving flow problems over deforming grids, the so-called Geometric Conservation Law (GCL) needs to be satisfied to avoid errors due to mesh motion. Thanks to the node-pair formulation of the finite-volume scheme used to discretize the governing equations over the computational grid, this requirement is here fulfilled by an appropriate computation of the interface velocity. This quantity is defined as the normal velocity integrated over the cell interface, which is the portion of the boundary cell shared by two adjacent cells. According to the GCL, the volume swept by this interface during a time interval should balance the variation in volume during the same interval. The standard ALE methods allow no variations in grid connectivity and in the total number of grid points. This constraint limits the displacement that the mesh is capable to handle without adversely affecting the accuracy of the solution because of excessively stretched elements. Therefore a different strategy has to be used to tackle significantly large displacements of the boundaries. The robust strategy adopted in the present work consists in moving the mesh keeping the topology fixed until the quality falls below a certain threshold, then local mesh modification is performed to restore mesh quality and prevent element entanglement. The major novel aspect of the proposed approach concerns the interpretation of the local mesh modifications, which allows to automatically satisfy the GCL even in presence of topological changes. Following the method proposed for bi-dimensional problems by Guardone *et al.*, a three-steps procedure is developed to interpret the connectivity changes due to mesh adaptation as series of fictitious continuous deformations of the finite volumes, as illustrated in Figure 1. First (at τ=0), the elements involved in the local modification collapse over an arbitrary point. When all involved elements reach null volumes (at τ=0.5), the new node is inserted or deleted. Finally (at τ=1), the elements expand to their final configuration (if they are not deleted). The collapse and expand steps consists in simple continuous deformations, while the topology change occurs at null volumes, therefore it has no effects in terms of GCL fulfillment. Then, the computation of the geometrical quantities related to mesh motion is carried out in a way that automatically satisfies the GCL. Thanks to this three-steps procedure, the solution on the new grid is recovered by exploiting the ALE formulation of the Euler equation without any explicit interpolation. This allows to preserve the scheme properties, especially conservativeness and monotonicity. Moreover, the implementation of multi-step time schemes does not require to store all the previous grids but only the history of local modifications. This innovative 3D adaptive conservative strategy has been implemented in the software FlowMesh, currently under development at the Department of Aerospace Science and Technology of Politecnico di Milano. Moreover, to overcome the difficulties of performing local grid modifications in three-dimensions, the external open-source library Mmg3d has been linked to the flow solver. The validity of the proposed approach is proved by steady and unsteady simulations of reference problems, both in the ideal gas region and within the so-called non-ideal compressible fluid dynamics regime. Finally, three-dimensional accurate simulations of aeronautical interest are carried out by exploiting the proposed conservative adaptive interpolation-free strategy. In Figure 2 the result of an unsteady simulation are shown: a wing flights through the domain at Mach 0.755. The picture shows the wing initial position (in gray) and the pressure contour plot at the final position, after one-chord displacement.



1. Three-steps procedure for edge split. In blue, green and red, portions of the finite volumes associated to the endpoints of the edge to be split and to the new point.



2. Pressure contour plot with one iso-surface of vorticity of a wing traveling through the computational domain at Mach 0.755.

PYPAD: A FRAMEWORK FOR MULTI-DISCIPLINARY AIRCRAFT DESIGN

Lorenzo Travaglini

The design of an aircraft is an extremely complex task involving a lot of different disciplines, by nature is strongly interdisciplinary. It is becoming more challenging in the future due to the reduced budget and compressed time.
At the same time new projects present new technical challenges due
to the request for highly demanding performances, in order to reduce the fuel consumption (cost and environment impact) and to increase the payload.
Starting from the first day, the design of a new aircraft is an iterative process, where the objective is to find the best compromise between all the different requests of the several disciplines.
Nowadays new technologies are becoming large used in several fields and each of them is increasing the complexity and the multi-disciplinary nature of the project. Some examples are:

- The composites materials in the structures give new structural design solutions, reducing the weight and increasing the aeroelastic effect;
- The laminar flow wing, reduce the drag of the wing and therefore the fuel consumption, but increases the sensibility to the structural deformation;
- New control systems design are developed to reduce the gust loads and therefore modify the structural design of the different components.

These are just few examples of technologies already used or that will be available to the engineers very soon. Clearly new technologies are available for the analysis too. CFD (Computational Fluid Dynamics) and CSD (Computational Structural Dynamics) are essential tools for the engineers, but generally not used during the early phases of the aircraft project, because typically there are not enough informations to define complex models and moreover the number of analysis to performe is extremely large and an extensive use of CFD and CSD is too time demanding and to complex to handle. Generally high fidelity simulations, coupling CSD and CFD, are performed to analyze the most critical conditions, when most detailed models are available and the design of the aircraft is in the most advanced phases. These considerations underline some key points, that motivates this work:

- New projects request high performing design, and the multi-disciplinary nature of the problem must be taken in consideration as soon as possible during the project;
- High fidelity tools like CSD and CFD are extremely powerful, but not suitable for the early phases of the project, when thousand of analysis must be performed;
- While several ad-hoc tool have been developed during the years for the conceptual design of new aircraft using simple models, frameworks suitable for the early phases of the project, able to handle complex models seems be lacking.

These key points can be translated in requests that this work tries to meet:

- To define a framework suitable for the early phases of the project of a new aircraft, using tools able to catch the multi-disciplinary nature of the problem by means of complex models;
- These tools should represent the best compromise between the level of fidelity of the results and the time needed to analyze the large number of conditions taken in consideration during the early phases of the project.

At the start of the Ph.D. program three tools have been considered fundamental to be able to meet the requests and to be able to define a more automatized workflow:

- A model generator able to define both structural and aerodynamic models;
- An aeroleastic solver able to compute all the aeroelastic responses and loads needed to design the structures of the aircraft;
- A sizing package able to size the different components using several sizing criteria.

Keeping in mind these requirements the PyPAD framework has been developed and its principal packages are:

- PyGFEM (Python modules for the Generation of Finite Element Models) is an object-oriented tool,
- developed in Python under Abaqus-CAE, able to define structural and aerodynamic models fully automatically It is also able to handle the different structural proprieties definition and to export a parametric structural model. The generation process starts simply by an available CPACS file describing the aircraft under consideration.
- PyAERO (Python module for the AEROelastic analysis) has been developed to compute all the aeroelastic responses such as Trim, Flutter, Dynamic Analysis, and the sizing loads of the structures, coupling the structural model defined by PyGFEM and an aerodynamic solver based on the Morino method. It is written using Python and FORTRAN, exploiting the power of parallel computing using OpenMP.
- PySIZE (Python module for MDO SIZing), is developed using the \verb|pyOpt| library and it can handle several kinds of structural parameters. It can compute both the value and the sensitivity of several kinds of structural and aeroelastic responses, using Abaqus for the computation of global matrices and stress derivatives.