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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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A TWO LEVELS APPROACH FOR THE OPTIMAL DESIGN OF MORPHING WINGS BASED ON COMPLIANT STRUCTURES

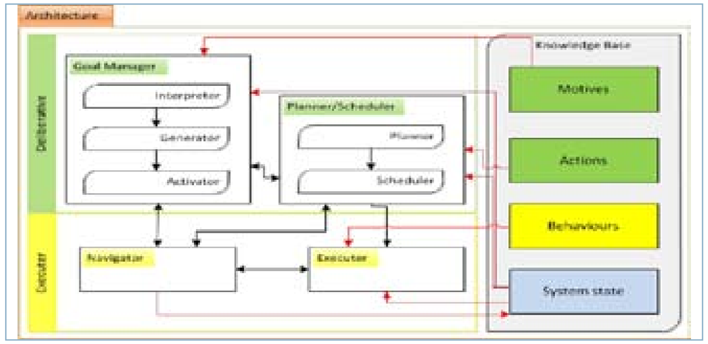
Alessandro De Gaspari

The great interest in developing morphing aircraft is mainly based on their potential capability to optimize specific aircraft performance index during the mission by adapting their shape. The idea of morphing aircraft proposed in this work is based on the concept of a wing composed by a traditional wing-box equipped with morphing leading and trailing edges, better known as conformable or gapless control surfaces based on the adaptive structure concept, attached to it. This hybrid wing represents an acceptable, even for industries, smooth transition from conventional aircraft wings to more futuristic fully-morphing wings.
In many cases these new structural concepts are strictly related to the currently available technologies. Smart material based technology may be applicable to the design of adaptive structures by means of embedded and distributed actuation devices, but their scalability is uncertain when realistic scale problem are considered.
In this work is proposed an alternative approach to obtain the required shape change by efficiently distributing the elastic energy into the optimized structure by means of few actuators. This approach is based on the distributed compliance concept instead of the distributed actuation one and leads to the compliant structures, that are both flexible and bearing bio–inspired structures. In this way, the structural design depends on the choice of the actuation device and produces a structural configuration suitable to host it. In the aeronautical field, this concept leads to Adaptive Compliant Wing (ACW) that is a single-piece flexible structure able to adapt itself and the whole airfoil for matching the desired aerodynamic shape.
The design of this wing does not represent an easy task and would require the availability of ad-hoc developed procedures able to tackle the conflicting requirements such as the high deformability requested to change the airfoil shape coupled to the load carrying capability and low weight. A specific design tool that could assist the engineers in the design of the optimal internal structure has been implemented.
One of the most important obstacle in the transition from a conventional control surface to morphing leading or trailing edges is due to the structural contribution of the wing skin. The skins, through the wing joints, are an obstacle to the motion to achieve the shape change and they have the important task of transferring the aerodynamic loads into the wing structure.
In this work, an approach for optimal airfoil morphing design based on a two levels optimization procedure has been proposed. In the first level the best deformed airfoil shape is determined as the most efficient aerodynamic shape which at the same time limit the requested energy to deform the airfoil skin, using the Class/Shape function Transformation (CST) technique to describe the airfoil geometry changes. The technique is based on analytically merging a class function which mathematically defines a variety of airfoil shapes with a shape function which is decomposed into scalable shape components represented by the Bernstein polynomials. It is used to implement the morphing airfoil shape optimization and it simultaneously allows to combine the estimation of the aerodynamic performances and the stress distribution along the airfoil skins.
In the second optimization level the best internal structural configuration is obtained using a topology optimization tool based on genetic algorithms that synthesizes a compliant structure able to adapt itself for matching the optimal shape coming out from the first level.
Compliant mechanisms are devices which use the elastic deformation as a source for motion. The compliance is intended as the ability to perform useful work and leads to joint-less, single-piece, no-assembly structural/mechanical devices. Their hinge-less nature eliminates the backlash error and effectively reduces the production and maintenance costs, associated with the multiple piece assembly.
The problem of aerodynamic loads trasferring changes the concept of compliant mechanism which must be designed considering motion and load-carrying requirements. It must simultaneously be designed as a mechanical system able to generate the desired motion and a structure subject to the aerodynamic loads and able to bear the load variations required by the new configuration.
This approach can be adopted by all topology optimization methods, in this work the load path representation is used and beam element based models allow to employ flexural links instead of flexural joints in order to offer advantages such as high fatigue life, no stress concentration and easy manufacture.
In the the load path representation, the single elements are replaced by load paths which are physical connections able to transmit force between different types of points. There are three types of characteristic points, the input actuator, the structure constraints and the output points, respectively. The three types of characteristic points define as many load paths connecting load input and active output points, load input and constraint points, and constraint points and active output points. A fourth type of characteristic points is represented by the structure internal points which are the load path intermediate connections.
The load path representation reduces the number of design variables, ensures structural connectivity by excluding infeasible solutions from the design space, it is free of gray areas problems and it is suitable to be solved by Genetic Algorithms. This feature leads to writing dedicated crossover and mutation strategies which allow to combine the topology synthesis and the size and shape optimization into the same process. Moreover the kinematic and the structural requirement and multiple load conditions can be combined by using some multiobjective optimization algorithm.
When the load path representation is applied to shape control problems, the design variables include path sequence, binary path existence variable, internal connection point locations, cross sectional load path sizes, load path output destinations and structure boundary sizes.
Unlike typical Single-Input Single-Output (SISO) compliant mechanisms, the shape control problem has a Multiple Output (SIMO) nature. Thus a number of points placed along the structure boundary, greater or equal to the number of active output points placed along the structure boundary, is used to minimize the least square error between the deformed curve and the target curve. In order to calculate the deformed curve every set of load path is transformed into a corresponding structural model where each load path is translated into a sequence of beam element connections.
An implementation of the Finite Volume Beam element is used and the design tool is coupled with a Finite Element tool which incorporates modal, buckling, static linear, non-linear analysis solvers.
During the genetic process, the crossover randomly selects a pair of parents who produce a new pair of offsprings by switching information about a designer-defined number of load paths and boundaries, preserving load path cross-sectional dimensions. The effect of the crossover strategy is to mix load paths between different individuals and the cross-sectional dimensions between different load paths. The mutation can act on the binary variable, turning on or off a designer-defined number of load paths, change their destination active output points, modify the dimensions of the boundaries and move the internal points.
The design tool described above is valid for all compliant mechanisms and it is applied to the design of morphing airfoil structures able to match the desired morphing shape which comes out from the first level optimization and represents the target curve.
Once the optimal morphing airfoil is obtained, the finite element models are automatically generated for both the single airfoil and for a complete wing section as well.

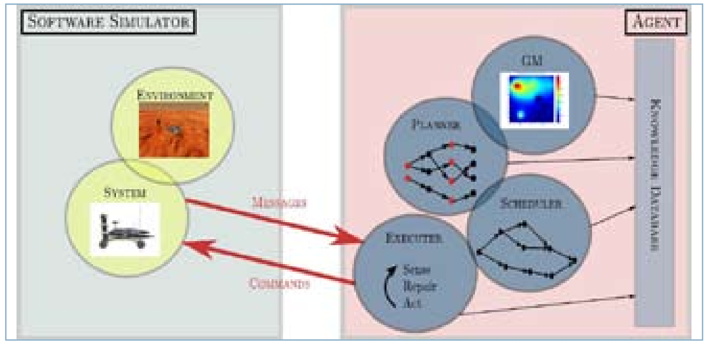
HYBRID AGENT ARCHITECTURE FOR SURFACE EXPLORATION ROVERS

Pietro Francesconi

The space community is paying increasing attention to the space vehicles autonomy enhancement as an obliged path to gain better performance, higher quality product return and even mission feasibility. Autonomy, strictly related to the system operative phase, can be focused on getting rid of limited decisional mechanisms the vehicle operations have to deal with; for instance, the autonomy goal can be either focused on the robust behavior to face an uncertain environment, that means to make systems be reactive by timely reasoning, or on the goal-oriented behavior to accomplish high-level, complex-tasks by deliberative decision making processes over longer time span.
State of the art architectures generally present a multi-layers framework, typically three layers, to cope with different reasoning mechanisms and to give an higher autonomy level to the system.
To focus on either one or the other reasoning mechanism gave rise to a lot of different solutions and agent architectures based either on the reactive approach, with a very limited preloaded knowledge on the system, or on the goal-based approach, which asks for large preloaded system knowledge the agent reasons on, to make decisions about its future. The drawbacks each approach comes with tried being overcome by designing an agent with both deliberative and reactive capabilities, harmonized through an interface module, usually identified with the nucleus in charge of commands execution.
Related literature proposes different solutions depending on part of the whole decision making mechanism the agent has to be provided with: Gat proposed the three layers architecture, in which the highest level world representation, fundamental to support the deliberative process, is connected to the lowest level which manages, by perceiving the data related to the operative environment, the reactions; the Remote Agent, flown on the 1999 NASA Deep Space 1 mission, is a successful attempt to obtain robust deliberative performance for an autonomous decision-maker, through a model-based approach. A complete behavior-based approach is preferred in the CAMPOUT architecture, to provide the agent both deliberative and reactive capabilities; CAMPOUT is further of interest because of the added challenge to deal with a multi-agent scenario. A collaboration among JPL, ARC and CMU led to the CLARATy two-level architecture that proposes an object oriented software to better fit a building blocks philosophy, well mapped in the system hardware too.
As soon as the decision-making and the system low level control want to be harmonized to increase the system intelligence attention must focus on the execution task, in charge of activating commands to act on the state vector consistent with both goals, coming from long term decisions and information on the actual current system status, coming from the sensors.
Related literature offers some solutions to develop the executer module from both the theoretic and software point of view. The MDS (Mission Data System) is the JPL extension of the RAX, based on states history and temporal constraints matching; a reactive fuzzy control is the tool to obtain an executer module that merges the high level goal-oriented decisions together with local perceptual inputs to output the control commands. Unfortunately, related literature does not provide a module for the mission goal generation, necessary to improve the performance of a space system that operates far from Earth.
The thesis offers a possible architecture to merge the three fundamental behaviors an agent should have to correctly simulate the human decision-making and uncertainties facing. A dynamic module of high-level goal generation and activation to deliver new mission objectives to the causal and temporal reasoner. A top-down reasoning to generate a feasible activities



1. Proposed architecture: Goal Manager, Planner/Scheduler, Navigator, Executer and Knowledge base



2. Interactions between agent and simulated system

schedule from goals together with a bottom-up strategy to assure robustness to unavoidable uncertainties are applied to make the agent be reactive, on the very short term, and deliberative, on the long-term scenario. Attention is focused on the goal manager, planner/scheduler, and executer modules: the first devoted to generate new motivated goals, the second translates mission objectives into a feasible sequence of activities allocated in time, and the last one dedicated to map the solution space formalized in time into the states hyperspace, the basis of the behavior-based systems formalism. Moreover, connected to the planning system a navigator is provided to assure the spatial consistency of the chosen goal. The proposed architecture is characterized by high modularity, that assures great adaptivity to different applications, and flexibility due to the techniques adopted for the causal (Graphplan-like planner) and temporal reasoning (Simple Temporal Networks); the agent enables plan repairing to face domain's unpredicted changes. The code, tested on multiple operating systems has been written in C/C++ language, because of the many programming tools available, the good data structure support, and the high efficiency.
Preliminary results for both nominal and anomalous run on a Martian robotic mission scenario, focused on ESA's ExoMars rover. The proposed architecture and a dedicated simulator are applied to a rover that must explore the surface and complete several experimental cycles, in compliance with the ExoMars requirements. The robot is a four-wheel rover: wheels can be controlled in terms of steering and rotational velocity; a simplified communication and thermal model has been also considered. The environment has been modeled according to the available data of previous NASA missions. Simulations, even if based on simplified problems to capture the agent challenges without marginal details, showed promising results and proved the soundness of the proposed architecture.

NUMERICAL SIMULATION OF THE TURBULENT, REACTIVE FLOW FIELD IN HYBRID ROCKET MOTORS

Gabriela Gariani

The aim of the thesis is to present the code HybridFOAM for the numerical simulation of combustion processes in hybrid rockets, developed at the Space Propulsion Laboratory of Politecnico di Milano (SPLab). Hybrid rockets born in the 1930s but only in the last years a renewed international interest is arisen for this kind of rocket, especially after the launch of SpacheShipOne. The main advantages of a hybrid rocket propulsion system are: safety during fabrication, storage, or operation without any possibility of explosion or detonation; start-stop-restart capabilities; relatively low system cost.
The total operational cost for hybrid system benefits greatly from the safety features and inert propellant; manufacture of the fuel can be done in a commercial facility that does not require the large acreage and many buildings as for solid propellant manufacture. As a consequence the fuel plant can be located near the launch site. The disadvantages of hybrid rocket propulsion systems are the low regression rate and the small resulting fuel web which means that most combustion chambers over a foot diameter require multiple ports to provide adequate burning surface to meet the required thrust.
The focus of the work is the analysis and modeling of combustion processes in hybrid rocket motors. Hybrid rocket combustion involves different processes. After the ignition, a chemically reacting boundary layer develops over the solid fuel grain due to the injection of oxidizer at the head end of the motor. The turbulent boundary layer is characterized by velocity, temperature, and species gradients normal to the surface; mass, momentum, and energy transport are controlled by the turbulent flow processes. A diffusion flame region forms in the boundary layer and the flame resides at a location approximately at 10-20 % of the boundary layer thickness above the surface. Heat from the flame is convected and radiated to the fuel surface; this energy flux causes the solid fuel pyrolysis. The pyrolyzed fuel vapor is then transported to the flame zone by convection and diffusion, where it mixes with the gaseous oxidizer, which has been transported through the boundary layer from the core flow region via turbulent diffusion. The two components react in the diffusion flame, a process that provides heat to sustain further fuel pyrolysis. The fuel mass flux due to pyrolysis, however, blocks some of the heat transfer to the surface, which causes a decrease in the regression rate and corresponding strength of the wall blowing effect and, in turn, a weakening of the blocking action, which in turns means that more heat can reach the surface and so on.
Classical analyses of hybrid combustion have relied on boundary layer assumptions to determine the heat flux to the fuel surface and, hence, the regression rate. However, such simplified analyses cannot account for many of the complex physical interactions, and more comprehensive computational fluid dynamic models are necessary for design quality prediction capability.
The first part of the thesis is dedicated to the study of the different physical phenomena involved in the combustion processes and an overview of the state of art is presented. In the second part, the code developed in the frame of the thesis, called HybridFOAM, is presented. The code deals with the coupled solution of the Navier-Stokes equations with RANS approach along with combustion, turbulence, solid fuel pyrolysis and radiation. The simulation is carried out with the solver developed using the opensource OpenFOAM platform, following a finite volume approach.
A computational model accounting for both solid and gas regions is implemented. The two domains are linked through an interface on which the heat flux imbalance is calculated, allowing the interface temperature updating through an iterative cycle. The computation of the regression rate is performed by the Arrhenius law and the fuel vapor inlet velocity is computed by the continuity equation. Attention is focused in this work on HTPB/GOx formulation and in particular a six reaction model is inserted for the combustion of HTPB in oxygen. Parametric studies are carried out in order to analyze the influence of oxidizer inlet velocity and chamber pressure. The code is validated with literature results with particular attention to the regression rate, the flame and surface temperature, the blowing parameter, the pressure influence and the radiative heat flux. High speed visualizations are carried out in order to compute the experimental flame height on the SPLab device. The numerical domain replicates the real experimental setup and is split into three areas including the pre-chamber, the slab zone and the post-chamber. The average experimental flame height is comparable with the numerical one. The average regression rates show a confidence with Chiaverini correlation.
Finally, HybridFOAM has been extended in order to simulate the physical regression of the solid fuel grain by moving mesh. Moreover, a multiphase flow model is inserted in the code in order to take into account the presence of Aluminum agglomerates during the expansion and a combustion model for aluminized particles has been developed starting from the Beckstead law.
Relatively low mass and linear regression rates of solid fuels have been among the major disadvantages of hybrid rocket engine technology due to the low density, inertness of conventional solid fuels, and diffusion controlled combustion processes. One of the method used to obtain performance enhancement in hybrid propulsion systems is to add energetic particles into the solid fuel grain. In the mid 1950s, interest in metal combustion was first stimulated in solid propellants when it was found that the addition of Aluminum particles substantially increased propellant performance. Combustion of metals is of great interest due to its inherent advantages such as damping of pressure oscillations by condensed phase products and increase in specific impulse and propellant density. Aluminum seems to be the best choice based on its thermal properties, ease of processing, and relatively low cost. However, the existence of alumina as an inert oxide layer on the external surface of the particle is undesirable and hard to avoid. The amount of active Aluminum in the particle depends on the manufacturing process and storage conditions. Fortunately, the oxide layer is brittle and can form many cracks when the Al particle expands during heating, allowing pure Aluminum to react with oxidizer.
The presence of Aluminum in the solid fuel increases the regression rate; it is attributed to the increase in radiative heat transfer to the surface as well as increase in flame temperature but it depends on the residence time of aluminium particles in the combustion chamber.
In HybridFOAM code the presence of Aluminum particles doesn't influence the regression rate. This is due to the fact that the particles have very short residence times (about 10 milliseconds) and so the diameter variation is really small leading to a neglectable increase in enthalpy.
The current interest in liquefying fuels opens the horizon to a code development for the treatment of the phenomenon of the liquid layer destabilization on the fuel surface and its consequent atomization (entrainment phenomenon) that leads to an increase in regression rate. Based on the results obtained is reasonable to assume, in the short to medium term, to be able to have a useful tool for calculating the assessment of motor full-scale starting from experimental work, mainly developed at laboratory scale, solving the problem of scale factor, which is of relevant importance in hybrid rocket motors design.

HIGH PRECISION SHAPE CONTROL OF MASSIVELY ACTUATED, MAGNETICALLY LEVITATED, SECONDARY ADAPTIVE MIRRORS FOR EXTREMELY LARGE TELESCOPES

Mauro Manetti

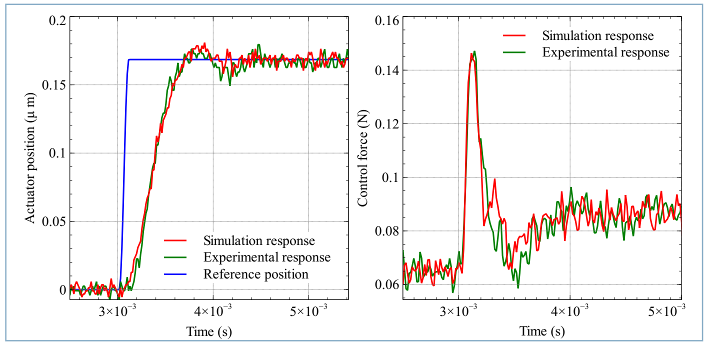
This thesis is focused on the study of deformable mirrors required by adaptive optics systems implemented on telescopes for astronomical observations. Adaptive optics is a technique to compensate through the mirror deformation for wavefront image aberrations introduced because of the atmospheric turbulence.
The work takes into account secondary adaptive mirrors, well suited to the need of the future extremely large telescopes. It is assumed that the system exploits a shape control technology based on a magnetically levitated solution, using electro-magnetic voice-coil motors, co-located to capacitive position sensors.

The design of massively actuated deformable mirrors requires the development of medium to high fidelity multidisciplinary simulation models, encompassing: deformable structures, fluid dynamics of the air interposed between the mirror and the reference body, sensor and actuators dynamics, signals modeling. A detailed description of all the multiphysics modeling aspects is provided in the first part of the work. Such models must serve the diverse needs for the analysis, design and verification of control solution and to simulate all the system operational phases, including system failures and identification of the stiffness, damping and inertia feedforward matrices.

A key point relates the development of a control scheme, which can provide precise active shape control of a deformable shell, using a very large number of control points. The here proposed controller combines a low frequency centralized feedforward and a high frequency fully decentralized feedback. To grant a precisely controlled shape the feedforward part requires an accurate knowledge of the system stiffness. For this purpose a viable experimental identification procedure for high dimension matrices, based on the system steady state response, is described and verified through simulations. Affine procedures based on system dynamic responses are introduced to allow the identification of the system mass and damping, which can be useful to improve the dynamic feedforward contribution efficacy.

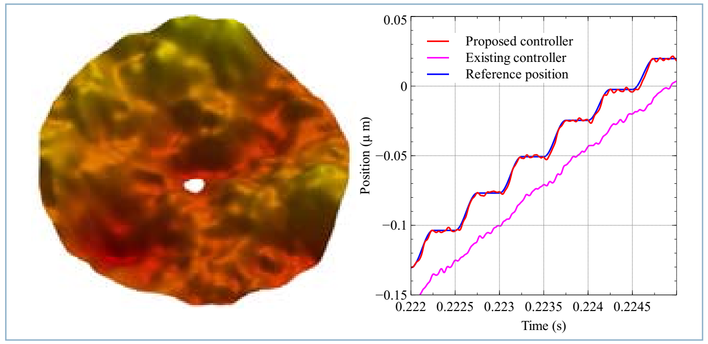
The work takes care to describe a viable development of a dedicated simulation code. The need to perform simulations of a multiphysics system, with control points in the order of several thousands, forces an accurate implementation, together with the need to develop ad hoc simulation strategies to make it feasible the numerical evaluation of some important operational phases. For example the simulation of the real static feedforward matrix identification procedure would end in involving an unacceptable computational time, and the choice of different fluid-elastic interfaces deeply affects the required computational resources, possibly limiting the use of the simulator on actual `standard' desktop machines. The aim of the present thesis is to provide a trade-off between simulation accuracy and computational time and resources required. The final goal is achieved through an effective mix between appropriate system modeling choices, efficient numerical implementation and clever simulation strategies.

A code validation is provided through experimental correlations entailing an adaptive shell prototype with 45 actuation points, dubbed P45. The aim is to prove the substantial correctness of the multiphysics model and the simulator reliability. Figures 1 shows the good numerical-experimental matching achievable for both the system response (left) and the control force (right).
Finally the simulation code is exploited to verify the deformable mirror capability to



1. P45 experimental vs numerical step response (left) and control force (right).

satisfy the adaptive optics system requirements of the future extremely large telescopes, such as the Giant Magellan Telescope (GMT) and the European Extremely Large Telescope (E-ELT). At the same time the performance improvements achievable with the introduction of the proposed control scheme are evaluated. Figure 2 shows a typical 3D shape command (left) required for Giant Magellan Telescope. The proposed control scheme effectiveness can be appreciated in figure 2 (right), where the improvement of the tracking capability with respect to the existing controller is remarked.



2. GMT shell deformation (left), proposed control scheme effectiveness with respect to the existing one (right).

The present work, on the base of a code which guarantees a very good numerical-experimental correlation, demonstrates the proposed control scheme capability to improve the existing adaptive mirrors performances and robustness. The effectiveness of the control system applied to a contact-less technology proved its scalability to system characterized by several thousands of control points.
The system ability to operate with a large number of control units out of order without endangering the system stability and with minor optical performances degradation has been verified as well.

EXPERIMENTAL INVESTIGATION OF COMBUSTION PROCESSES IN ADVANCED SOLID FUELS FOR HYBRID ROCKET PROPULSION

Laura Merotto

Introduction

When compared to traditional propulsion systems, such as solid and liquid propulsion, hybrid propulsion shows some important advantages in terms of high performance, safety, possibility of re-ignition and thrust modulation, low costs and low environmental impact.
Recent developments allow expecting hybrid propulsion to be a promising propulsive solution for the next decades, not only in space applications, such as space tourism, but also in aeronautics; for instance, combined propulsion systems for hypersonic atmospheric transport are currently being investigated.
The development of hybrid propulsion has so far been limited by the low solid fuel regression rates. Therefore, international researches currently focus mainly on the investigation of solutions for upgrading the propulsive performance in order to increase the competitiveness of hybrid technology with respect to other propulsive systems.
The present work aims to give a contribution to the hybrid propulsion maturity, as advanced thermochemical propulsion technology for aeronautical and space applications in a middle-term future. Thus, the essential objectives of this work are understanding the physics of hybrid propulsion combustion processes, which are indubitably the heart of hybrid propulsion technology development; exploring innovative fuels to improve current space propulsion applications, and obtaining a regression rate enhancement using different fuel ingredients.

Experimental set up

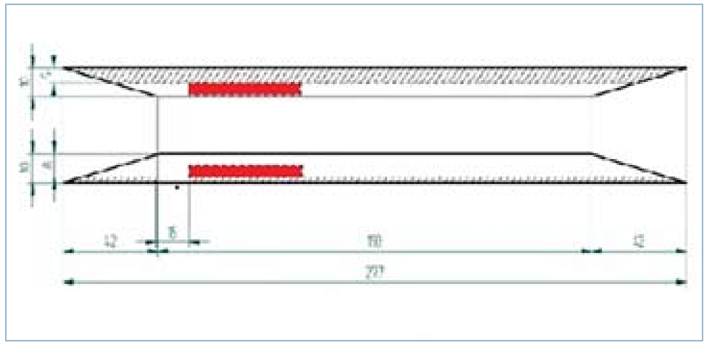
The experimental test rig set up for this work is based on a 2D slab combustion chamber. Some interchangeable sample holders, designed for this research and shown in Figure 1, allow performing firing tests both in single slab or in double slab configuration.

Firing tests were performed at ambient pressure, in pure oxygen, with oxygen mass fluxes ranging from 5 to 350 kg/m²s.
For each firing test, the average solid fuel regression rate (r_f) is measured.
Three groups of fuel formulations were investigated: HTPB-based formulations, used as a baseline for relative comparison; mixed HTPB- and paraffin-based fuels, manufactured in order to obtain a good compromise between performance and mechanical properties; and paraffin-based fuels, gel wax (GW) or solid wax (SW), manufactured with a poly-urethane foam strengthening structure. The formulations tested include fuels filled with metal (nano-sized Aluminum) and metal hydride (Magnesium hydride, MgH_2).

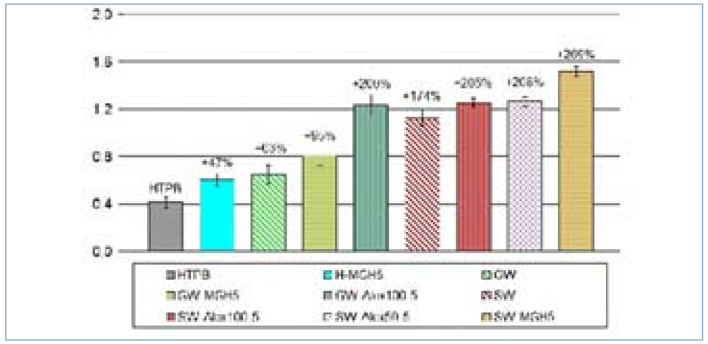
Results discussion

Using single slab configuration, no performance increase is obtained with respect to pure HTPB. This can be explained taking into account the effect of the upper cold wall, leading to a lower temperature distribution in the chamber, which in turns inhibits metal particles oxidation and consequently the binder combustion. Using double slab configuration, a slight performance increase is obtained with respect to pure HTPB, due to the enhanced heat feedback to the fuel surface.
The best results are obtained with the finest metal powder (Alex50, shortest combustion time) and with metal hydride (MgH_2, higher reactivity). The results suggest that double slab configuration is effective in enhancing r_f for all the tested formulations.

Figure 2 shows a comparison among the average r_f values obtained for the tested fuel formulations. The reference oxygen mass flux value chosen is 120 kg/m²s.
The obtained results, using paraffin-based fuels doped with nanoAl and MgH_2, show a r_f increase with respect to the pure HTPB baseline formulation up to +270% at the reference oxygen mass flux.
Both GW- and SW-based fuels give higher regression rate than HTPB- or mixed-based fuels. SW-based fuels (which show the highest entrainment tendency due to their low viscosity and surface tension) give higher r_f than GW-based fuels, thus suggesting that entrainment effect is the main variable for the regression rate enhancement. MgH_2 addition give the best results in SW-based fuels, while Alex addition give the best results in GW-based fuels, thus suggesting that hydride reactivity is more effective than particle size in enhancing r_f under high entrainment conditions.



1. Scheme of the interchangeable sample holders designed for this work.



2. Regression rate comparison for the different fuel formulations tested. Oxygen mass flux: 120 kg/m2s.

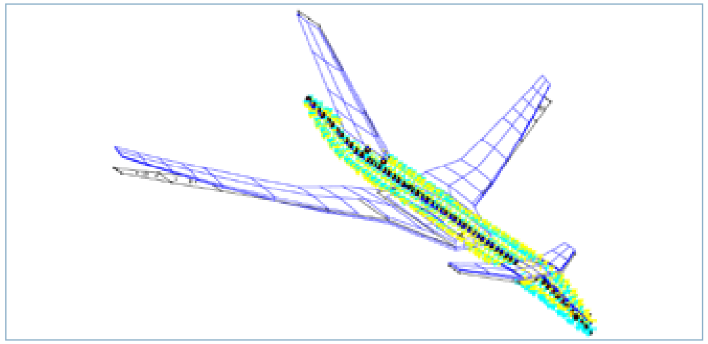
Concluding remarks

Further investigation is needed in order to establish the contribution to overall regression rate performance of different scale, different fuel formulation and different sample geometry. The problem of the scale factor prevents from expressing the results obtained in absolute terms, because they depend on several variables. Nevertheless, a relative comparison shows regression rate enhancements up to +500% at the highest oxygen mass fluxes tested (about 350 kg/m²s). The best results were obtained with SW-based fuels filled with MgH_2. Using GW-based fuels, regression rate enhancements up to +95% (for GW filled with MgH_2) and up to +200% (for GW filled with nano-Al) with respect to pure HTPB are obtained at the highest oxidizer mass flux tested.
The results reported in this work allow a direct comparison among different fuel formulations, clearly indicating the best average regression rate is obtained with fuel formulations having high entrainment tendency.
Moreover, the main problem limiting the use of paraffins as solid fuels, i.e. their poor mechanical properties, was overcome using a strengthening structure.

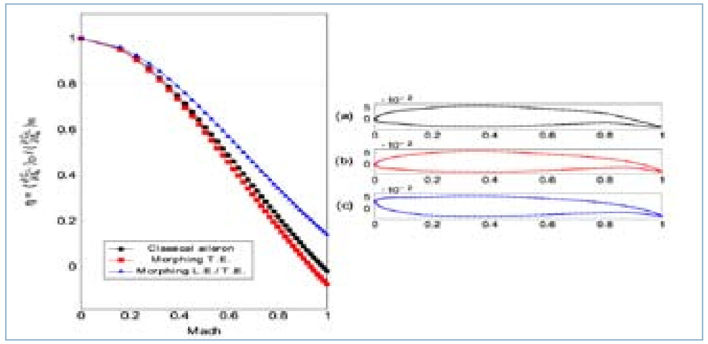
METHODS AND TOOLS FOR THE CONCEPTUAL ANALYSIS OF ADAPTIVE AIRCRAFT CONFIGURATIONS

Luca Riccobene

The present work deals with morphing at conceptual design level. Nowadays, material and actuator technologies are mature enough to enable large scale shape variation but finding a trade-off between weight penalties, mechanisms complication, actuation power and performances is still crucial. The problem intertwines different disciplines, like structures, control theory, aerodynamics and materials; like in aeroelasticity domain, treating separately each aspect ends with many design changes at later stages.
A multi-disciplinary approach is thus needed to cope with adaptive structures, and to span the design space in acceptable time it's necessary to take a step back from detailed solution: an high level approach is preferable, since it avoids time-consuming simulations but at the same time provides reliable trade-off studies. The conceptual design phase becomes attractive and the possibility to have an integrated environment, where the different disciplines interact sharing information in an easy way, must be sought. The aim of the European funded SimSAC project was to build such an environment and, during this project, the Aerospace Department of Politecnico di Milano developed a structural module, called NeoCASS, which allows fast aero-structural analysis as well as MDO optimization. The author worked on NeoCASS, in particular on the W&B module and developing an ad hoc equivalent plate model in view to study adaptive configuration.
The procedure - called SMARTCAD+ - herein presented is a collection of tools which aims to help the designer in introducing morphing at conceptual level: specifically, the active camber concept is the benchmark for the procedure. Looking at state--of--the--art morphing applications, the "root" of morphing lies in nature, but its principles should be declined in a different manner since biological materials can't cope with forces scaling with cube or square law. Smart materials and smart structures are thus investigated and can be tailored to improve adaptability, although sometimes is sufficient a smart design.
Morphing is basically mission-driven: efficient meeting of different and often opposite requirements that calls for an adaptive solution. To fully understand benefits and drawbacks, is mandatory a "high level" multi-disciplinary study starting from preliminary or even conceptual design phase.
To study unconventional or adaptive configuration it's necessary to overcome semi-analytical or empirical structural weight estimate: the structure should exists, if only a reduced order model, to grasp aero-structural interactions.
At this first requirement, a realistic airframe weight estimate, two more adds: bringing aeroelastic analysis at conceptual design stage and, further on, introducing adaptivity.
The NeoCASS module has two of the mentioned requirements. The first gross weight estimate of W&B is refined in GUESS and subsequently in SMARTCAD, if resorting to multi-disciplinary optimization. As a test-case of weight prediction capability on an unconventional configuration, the TCR (Transonic Cruiser) was chosen, and results were in good agreement with SAAB estimate; using SMARTCAD solver, some practical consideration based on maneuver loads were made, critically assessing the configuration airframe, see Fig.1.
Relying on a parametrical description of aircraft layout, NeoCASS outputs automatically structural and aerodynamic meshes, which can be quickly and easily updated occurring a design change.
On this purpose two structural models are available: a beam model, adapted to MATLAB environment from previous work, and an equivalent plate model. The study of low aspect ratio wing and/or single components like winglets is well-suited for equivalent plate models, because they imply a two-dimensional domain; moreover in morphing studies many solutions impose deformable sections, thus violating classical beam assumption of rigid rotation about the elastic axis. The model developed, while having a simpler displacement formulation if compared to literature, has interesting features, like mean axis formulation and hybrid modeling capability (the two models are combined through Guyan reduction): the aircraft is not reduced to its wing. Its major drawback is related to matrix ill-conditioning, however it was demonstrated that acceptable results, at least for conceptual design, can be achieved; a validation with detailed finite element model of an aluminium fighter wing was conducted, showing good agreement even though using a coarse approximation.
SMARTCAD+ is an extension of SMARTCAD which introduces adaptivity at conceptual design level; it's a procedure based on three main tools: SMARTCAD itself, which gives the structural and aerodynamic meshes, a compact airfoil geometry description (CST) and a linear approximation technique, which determines parametrically the deformed shape starting from the base shape.
Having aileron efficiency as aircraft global index, two different active camber concepts were compared to classical aileron: conformal trailing edge and leading/trailing edge combined deflection. Being the aircraft rigid, the former is about 65% more efficient in roll compared to classical, but introducing aeroelastic effects it decreases efficiency; the latter achieves better results for all Mach numbers, because leading edge counteracts the twisting moment induced by pressure distribution shift toward trailing edge (see Fig. 2).



1. TCR hybrid model deformed shape at cruise (Ma=0.65, z=0)



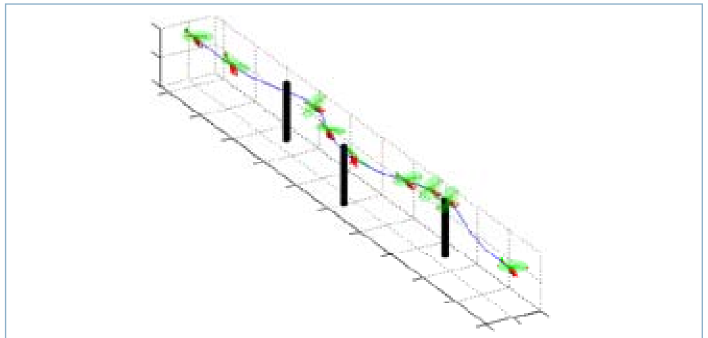
2. Aileron effectiveness: comparison between classical and morphing solutions; (a) classical control surface, (b) morphing trailing edge, (c) morphing leading an trailing edge with a gear ratio of 1

OPTIMAL DESIGN OF HELICOPTER MANUEVERS INCLUDING HUMAN FACTORS

Francesco Scorcelletti

In this work advanced trajectory optimization techniques are applied to first-principle models in rotorcraft flight mechanics. The capability to simulate aggressive maneuvers at the boundary of flight envelope is a powerful tool not only for the estimation of the maximum performance achieved by a given aircraft configuration, but also for preliminary design, trajectory planning, analysis of innovative configuration, envelope expansion studies, definition of new piloting procedures, etc. To answer these needs, trajectory optimization codes implement appropriate numerical strategies, which interacting with third-party flight simulators, allow to compute the controls which fly the vehicle model in an optimal and constraint-satisfycing way. Trajectory optimization procedures lie in a upper level respect to physical modeling and the two worlds, procedures and modeling, are conceptually separated and communicate each other only through specific interfaces.

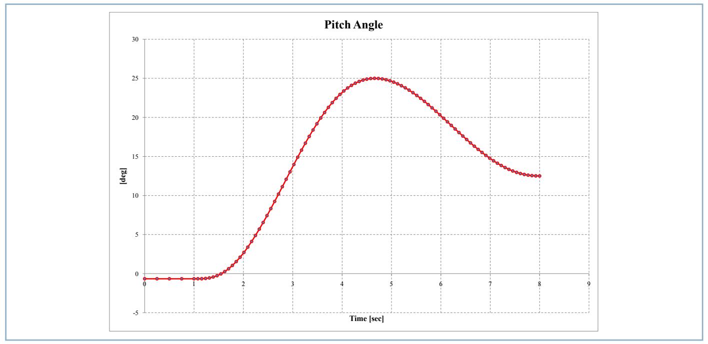
The mathematical definition of a maneuver is formulated in the context of the optimal control theory and direct methods, such as the direct transcription and multiple shooting, are used for its solution. A general purpose code for trajectory optimization implementing multistrategies solution techniques is developed and tested, being conceptually designed to be coupled with whatever third-party black-box flight simulator tool, since very simple assumptions are required for the communicating interfaces.
The flight dynamics code is here represented by the commercial software FLIGHTLAB, a multibody tool specifically tailored for rotorcraft simulation, offering the ability to create hierarchical models of varying fidelity levels for each aircraft component.
A compilation of a library of complex maneuvers related to the simulation of the ADS-33 Mission Task Elements (MTEs), for the handling qualities analysis of a given helicopter configuration, rather than to the analysis of Emergency Procedures, namely fly-away recoveries after partial loss of power available and safe landings in fully power-off conditions, is developed.



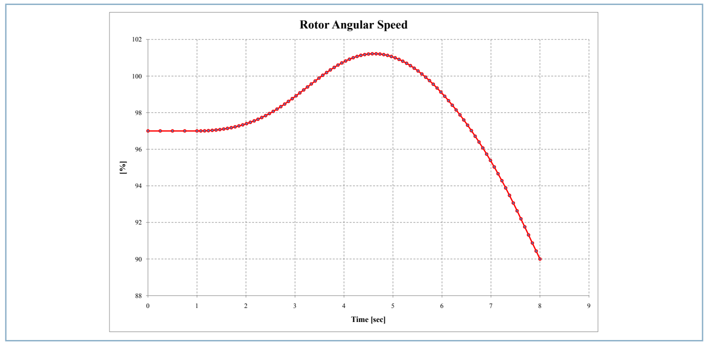
1. Slalom MTE. Snapshots

An example of MTE analysis, namely the Slalom maneuver, is depicted in Figure 1 in terms of snapshots of the vehicle motion during the trajectory. In this case the helicopter should initiate the maneuver in steady forward flight, lined up with the centerline of the test course and is required to perform a series of smooth turns at 500-ft intervals. These turns must be at least 50 ft from the centerline, with a maximum lateral error of 50 ft. The exit condition is steady forward flight. A minimum time maneuver has been evaluated with the trajectory optimization code in order to estimate the maximum performance achievable.

An interesting Emergency Procedure analysis is represented by the Engine-Off Landing maneuver starting from a steady autorotation flight in proximity of ground.
The emergency landings in fully power-off conditions are very critical maneuvers and statistically 50 % of cases result in fatal accidents. The Engine-Off Landing approach is here evaluated with the goal of minimizing the touch-down kinetic energy of the vehicle, while considering specific constraints to guarantee the safety of the overall procedure.



2. Engine-Off Landing. Pitch Angle



3. Engine-Off Landing. Rotor Angular Speed

Figure 2 shows the time history of vehicle pitch angle, which is characterized by a maximum representing the so-called 'flare'; this high angle is used to increase the inflow through the rotor, thus the rotor kinetic energy, as shown in Figure 3. The rotational energy of the rotor is used, at the very end of the maneuver, to reduce the vertical speed through a collective step, in order to guarantee a safe touchdown.

The maneuvers contained in the aforementioned library are obtained considering just the aero-mechanics components, without introducing the human pilot limitations, thus probably overestimating the maximum achievable performance.
In this thesis, probably for the first time in literature, novel formulations for introducing human factors into the trajectory optimization framework are presented. Initially just the effect of the neuromuscular actuation delay is investigated, while a formulation to include state-of-the-art path controller pilots is presented through the introduction of additional constraints in the maneuver optimal control problem.

DISTRIBUTED CONTROL OF MULTI-AGENT SYSTEMS ON A GRAPH

Stefania Tonetti

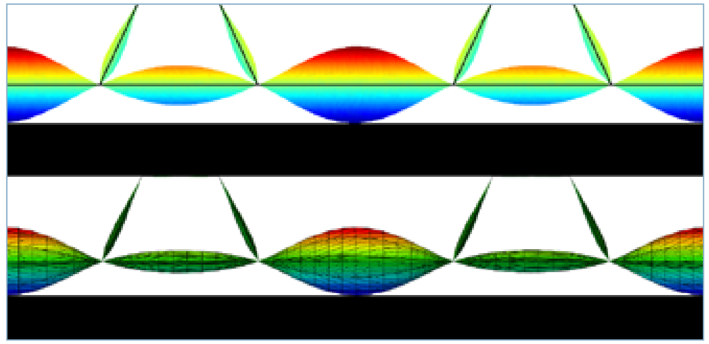
In numerous mission scenarios, the concept of a group of agents cooperating to achieve a determined goal is very attractive when compared with the solution of one single vehicle.
In this class of systems, even if the agents are dynamically decoupled, they are coupled through the common task they have to achieve.
When the number of agents grows, centralized control is no longer feasible and distributed control techniques become attractive. Applications of coordinated control of multiple vehicles can be found in many fields, including microsatellite clusters, formation flying of unmanned aerial vehicles, air traffic control,automated highway systems and mobile robotics.
This thesis concerns distributed control of interconnected multi-agent systems with linear dynamics where the interconnection topology is modeled as a graph, in which the single agents are represented by a node, while the interaction links are the arcs. The dynamics is first considered homogeneous among the agents and then a more general scenario of non-homogeneous dynamics is studied. The contribution of this work is to show a general method to derive the transfer functions between any pair of agents, where the interconnection topology is described by arbitrary directed graphs and the leader-follower architecture is only a particular case. The task of this dissertation is not to present a formula that simplifies the complexity of computing sensitivity matrix, but to give insight into its structure, in order to better understand the role that topology plays.
Mechanisms that rule the behavior of a multi-agent system are analyzed and intrinsic limits on the controller design due to the topology are shown. Modern control theory is studied starting from classical control theory by means of graph theory.
The first part of this work explores the tradeoffs and limits of performance in feedback control of homogeneous interconnected multi-agent systems, focused on the network sensitivity functions.
The sensitivity transfer functions between every pair of agents, arbitrarily connected, can be derived using a version of the Mason's Direct Rule. Explicit forms for special types of graphs are presented. An analysis of the role of cycles points out that these structures influence and limit considerably the low frequency behavior of the system. The more the cycles are equally distributed among the formation, the better performance the system can achieve, but they are always worse than the single agent case. Our analysis demonstrates that the presence of cycles in the interaction topology degenerates the system's performances. If there are cycles in the graph, the disturbance entering on an agent passes through its neighbors and comes back making more difficult to attenuate it. So a leader-follower topology seems to be the best choice, but this is not entirely true. If the graph is not strongly connected, the network sensitivity transfer matrix is not full. There is no disturbance propagation between two agents, but the multi-agent system is blind to commands entering some agents. Even if the presence of cycles appears to be bad, they are needed to keep the formation strongly connected and to ensure complete observability of the system. The networked version of Bode's integral formula is also proved, showing that it still holds for multi-agent systems.
The framework developed allows to correlate the Laplacian eigenvalues to structural properties of the underlying graph.
The practical feasibility and the advantages of a distributed control strategy is then shown for a linear end-fire antenna array formation with unmanned aerial vehicles. The antenna array design is given and each vehicle's position is controlled using a feedback law with the input consisting of the vehicle's individual state plus any available states of the neighbors. An improvement in antenna array directivity can be achieved applying a station keeping distributed control, instead of a decentralized one, to formation of quadrocopters. Starting from results obtained on limits in performance for multi-agent systems, different interconnection topologies are studied and the ETH Zurich Flying Machine Arena (FMA) is used as a test case. We propose a simplified method to evaluate array performance that well predicts the formation behavior even in presence of uncorrelated disturbances like wind gusts.
Even if distributed control always ensures the higher directivity, we can in general conclude that a complete graph topology is suggested if the elements forming the antenna array are limited to a small number, while a decentralized control is indicated for a high number of agents. In the middle the choice has to be led by trade-off between loss in directivity caused by decentralized control and communication and computational effort needed from the distributed strategy. The second part of the thesis explores stability and performance of non-homogeneous systems, extending results obtained for homogeneous systems. A class of multi-agent systems is presented for which a separation principle is possible, in order to relate formation stability to interaction topology.
Cycles and paths are still involved in the network sensitivity functions, but if the agent dynamics are different, topology is not the only player in determining system's performance. The low frequency behavior is also influenced by zero frequency gain and poles at the origin of the open loop transfer function of each agent. If every single agent has the same number of poles, the larger the low frequency gain, the better the formation disturbance rejection. If an agent has a higher number of poles with respect to the others, it will behave like a single agent in the formation. There are fundamental limitations to what can be achieved by distributed control of non-homogeneous systems. If the behavior of one agent improves, the behavior of the others get worse. Control design is a redistribution of disturbances at low frequency among agents.

ANALYTICAL FORMULATION FOR BUCKLING AND POST-BUCKLING ANALYSIS AND OPTIMIZATION OF COMPOSITE STIFFENED PANELS

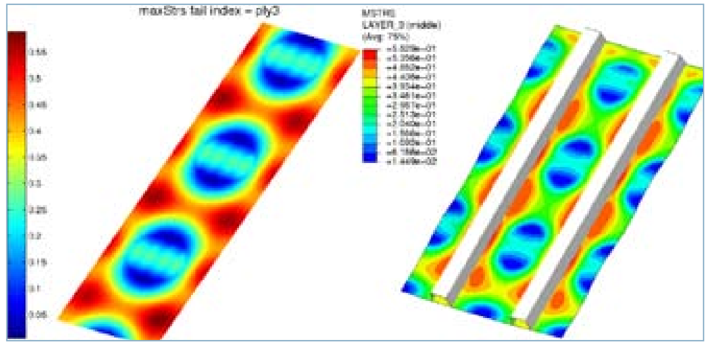
Riccardo Vescovini

Stiffened panels are structural elements characterized by high strength to weight ratio and are commonly employed in load bearing components such as fuselage panels.
They are often required to operate under compressive and shearing loads, and can be susceptible to buckling phenomena. However, composite panels can carry considerable loads beyond the buckling load, and can operate in the post-buckling range.
Today, the common design practice mainly relies on numerical analyses and physical tests. Unfortunately, the finite element analyses are often time-consuming, so computationally efficient simulation tools are required to improve the design process.
The thesis work regards the development of analytical and semi-analytical formulations for the fast buckling and the post-buckling analysis and optimization of composite stiffened panels. In the first part of the work, closed-form solutions are derived under the assumptions of flat panels, orthotropic lay-ups and compression loads.
In the second part, semi-analytical models are developed to make possible the study of flat and curved panels, combined loading conditions of compression and shear, and symmetric and balanced lay-ups.

A closed-form solution for the global buckling is obtained referring to the smeared theory, based on the idea of distributing the stiffness provided by the stiffeners on an equivalent layer of material. The formulation is derived adopting a mixed approach, where the compatibility and the equilibrium equations are solved with the method of Galerkin. Comparisons are preformed between the analytical solution and finite element eigenvalue analyses, obtaining differences on the buckling load below 10%.
A second analytical formulation is presented for the study of panels undergoing local buckling modes.
The structural model is based on the representation of the skin between the stiffeners, considering elastically restrained longitudinal edges to account for the restraining effect provided by the stiffeners.
Closed-form solutions are derived to evaluate the buckling load, the out of plane displacement at different load levels and the initial post-buckling stiffness.
Results are compared with finite element analyses and the difference between numerical and analytical buckling loads is below 4%. The post-buckling behaviour is compared in terms of post-buckling stiffness and out of plane displacements, and satisfactory agreement is observed.
The nondimensional development of the formulation allows to trace design curves representing the buckling and the post-buckling for a wide class of laminates through the definition of few lamination parameters.
Semi-analytical formulations are discussed in the second part of the work. They are based on energy approaches solved together with the method of Ritz. Governing equations are derived analytically, while solutions are found numerically.
The first semi-analytical formulation is focused on the study of the global buckling mode and adopts a beam representation to model the stiffener. Percent differences below the 10% are obtained for the buckling loads of flat and curved panels loaded in compression and shear. The formulation is also able to represent the buckling modes with a good degree of accuracy, as shown by comparison with finite elements.
The second semi-analytical method is developed to study the local buckling response of blade, J, T and omega stiffened panels. The formulation is based on a plate representation of the section where both the skin and the stiffeners are modeled as plate elements.
A refined representation of the skin/stiffener interaction is so obtained and local stiffener instabilities can be accounted for. The analytical/numerical comparison reveals percent differences below 6%. The comparison between semi-analytical and numerical buckling modes is shown in Figure 1 for an omega stiffened panel loaded in shear.
The third semi-analytical formulation is developed for the local post-buckling analysis. The panel is modeled considering the skin between the stiffeners and assuming elastically restrained longitudinal edges. The numerical solution of the nonlinear problem is performed with an arc-length procedure with capabilities to cross critical points and to capture snap-backs or snap-throughs. Comparisons with finite element results show the ability of the formulation to predict load displacement curves, post-buckled shape as well as stress and failure index distribution over the skin, as shown in Figure 2.
The last part of the work regards the implementation of a genetic algorithm that is coupled with the analytical formulations to obtain a fast tool for the preliminary optimization.
Examples are presented for the stacking sequence optimization of stiffened panels to maximize the buckling load or to minimize the structural weight. Linear and nonlinear constraints are introduced regarding the buckling load, the pre-buckling stiffness and the post-buckling response.
The proposed approach has the advantage of reduced computational time, resulting in a much faster time than an equivalent procedure based on conventional finite element analysis.
The idea of coupling analytical and semi-analytical formulations with genetic algorithms seems an effective strategy to enable the designers to consider buckling and post-buckling requirements in the preliminary design phases when detailed information regarding the structure are not yet available and the design space is too large to consider the use of finite element analysis in a convenient time.



1. Comparison between semi-analytical and Abaqus buckling modes for an omega stiffened panel loaded in shear



2. Comparison between semi-analytical and Abaqus maximum stress failure index in the post-buckling range