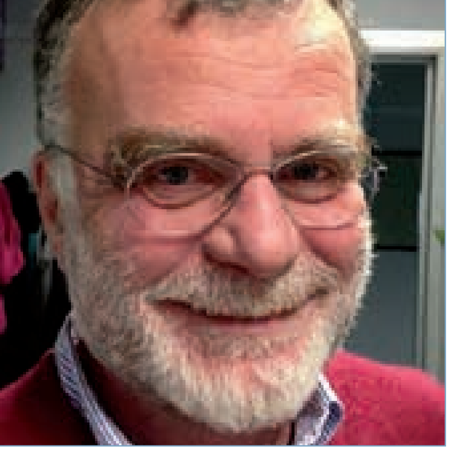


Chair:
Prof. Luigi Vigevano

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 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.

DOCTORAL PROGRAM BOARD		
Prof Airoldi Alessandro	Prof Dozio Lorenzo	Prof Masarati Pierangelo
Prof Anghileri Marco	Prof Frezzotti Aldo	Prof Morandini Marco
Prof Astori Paolo	Prof Galfetti Luciano	Prof Quadrio Maurizio
Prof Bernelli Zazzera Franco	Prof Ghiringhelli Gian Luca	Prof Quaranta Giuseppe
Prof Bisagni Chiara	Prof Gibertini Giuseppe	Prof Quartapelle Procopio Luigi
Prof Bottasso Carlo	Prof Guardone Alberto	Prof Ricci Sergio
Prof Consolati Giovanni	Prof Lavagna Michèle	Prof Sala Giuseppe
Prof Di Landro Luca	Prof Mantegazza Paolo	

ADVISORY BOARD	
Giorgio Brazzelli, AgustaWestland & Distretto Aerospaziale Lombardo	Marco Molina, SELEX Galileo
Matteo Casazza, Leitwind	Fabio Nannoni, AgustaWestland
Massimo Lucchesini, AleniaAermacchi	Franco Ongaro, Estec

SCHOLARSHIP SPONSORS
Agusta-Westland
ASI
Tecnospazio

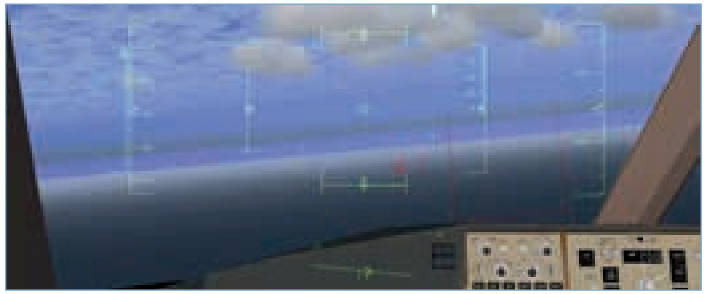
PILOT IN THE LOOP AEROSERVOELASTIC SIMULATION IN SUPPORT TO THE CONCEPTUAL DESIGN OF A FLY BY WIRE AIRPLANE

Fabio Bocola - Supervisor: **Prof. Pierangelo Masarati**

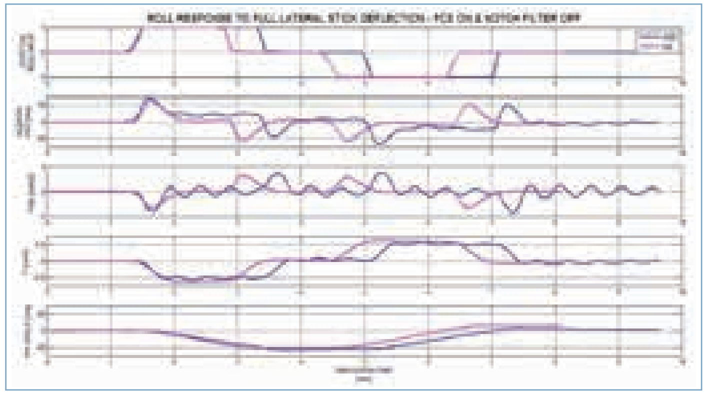
The objective of this thesis is the development of an interdisciplinary simulation environment to support the design and optimization of new generation aircraft with Fly-By-Wire (FBW) control systems technology. This study deals with the shift from the Classic to the Integrated design approach of aircraft preliminary design, since the increasing application of FBW technology has introduced new and possibly unforeseen aeroservoelastic problems that require a reassessment of the traditional approach.
In this integrated design process, to take advantages from Fly-By-Wire Control System performances, the following involved disciplines

- Flight Mechanics
- Structural Dynamics and Aeroelasticity
- Control Theory

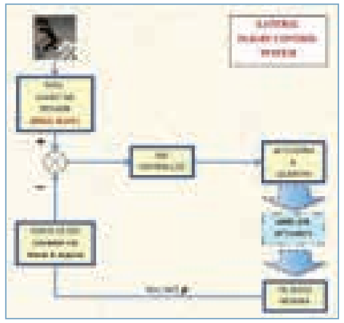
Certification Requirements and Handling Qualities are captured in a concurrent design environment, in order to explore and eventually exploit their mutual interactions, thus introducing structural elasticity from the very beginning of FCS control laws design.
An essential part of this process is the development of an Aeroservoelastic Static Flight Simulator for pilot-in-the-loop flight tests. This very useful tool is aimed to provide the design Team with early evaluation of FCS control laws, predictions of handling qualities and Aircraft-Pilot Coupling behaviors, still at the design stage. These valuable information can then be fed back in the conceptual design loop, with the final target to reduce time to market and development costs of a new aircraft.
The proposed concept is an even simpler, desktop-level tool, consisting of a personal computer and a joystick, where all the aspects of the mentioned disciplines are combined, providing the project engineer with a preliminary global insight of the airplane's dynamic behavior.
Attention has been primarily dedicated to minimizing the cost of the tool, using off-the-shelf desktop computers, widely diffused commercial and open-source software (Figure 1). At the same time, the flexibility and the versatility has been a main driver, to give the designer the possibility to easily address both airplane modeling and flight simulation.
Two aircraft models have been realized. They essentially differ in the detail of the flight dynamics module: the Aeroservoelastic (ASE) model, and the Rigid Body (RB) one. Among other aspects of the pilot-vehicle interaction, the flight test campaign primarily aimed at verifying the existence of a Control Spillover or Pilot Induced Oscillation (PIO), and determining whether the Aeroservoelastic model influences the piloting technique: both aspects have been successfully investigated.
The flight simulation of the aeroservoelastic (ASE) airplane model with a Fly-By-Wire FCS, has evidenced a Roll Spillover at 2.05 Hz, due to the interaction between the rigid body roll mode and the first structural antisymmetric wing bending (AWB) mode (Figure 2).
At this stage of the project, since the airplane is still totally virtual, engineers can proceed by either acting on the wing structure or providing the FCS with Notch Filter: because this FE model was already the result of an optimization process (NeoCASS), the latter solution has been adopted (Figure 3)
The aggressiveness of pilot's inputs on the inceptor (Aggression) has been introduced as a quantitative parameter to evaluate the pilot workload while performing high gain tasks: this method has proven to be valid by the comparison of the same task performed by two pilots with a significantly difference in flying experience.
Pilot-in-the-loop flight tests have evidenced that the Aeroservoelastic airplane (ASE), when compared to the Rigid Body (RB) one, is more responsive to pilot's inputs, due to the response of higher frequency unsteady aerodynamic modes triggered by Roll FCS mode: this airplane behavior affects the flying technique, by addressing the pilot to adapt roll inputs in order to reduce the aggressiveness on roll control inceptor.
The effects of Turbulence and Time Delay of the FCS on aggressiveness has also been evaluated, showing that Time Delay does not have a significant effect on ASE Aggression due to the ability of the pilot to compensate (it only increases the workload), but Turbulence do have some effects. A specific task has been designed, showing that Lateral Turbulence produces an increase of the roll ASE Aggression to values even significantly greater than the RB ones, because the unsteady aerodynamic response can also be triggered by the Turbulence itself, forcing the pilot to increase the inputs to the inceptor to perform the assigned task. This increased sensibility of the ASE airplane to lateral turbulence may suggest the implementation of an active gust alleviator device.
According to piloted flight simulation results, Figure 4 reports the quantitative and qualitative average ratings of the adopted evaluation metrics.



1. Visual Obstacles for pilot-in-the-loop maneuvers



2. Roll Control Spillover – Notch Filter OFF



3. FBW Roll Control Law Architecture

FLIGHT TEST CONDITIONS: DESCENT AT [illegible] KEAS @ [illegible]
FLIGHT CONTROL SYSTEM ON NOTCH FILTER ON

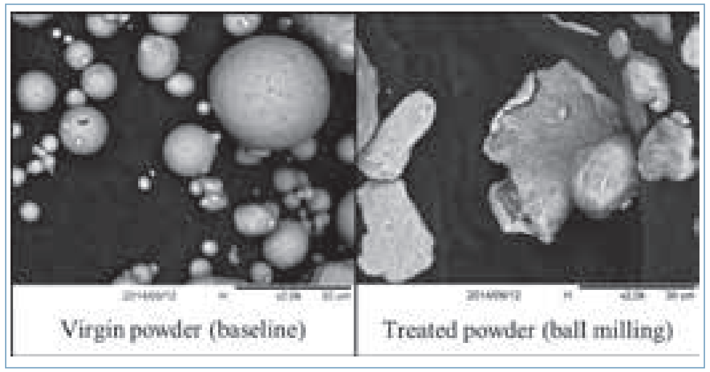
TASK	TURBULENCE	FCS ROLL TIME DELAY	AVERAGE RATINGS			
			ROLL AGGRESSION	PITCH AGGRESSION	COOPER-HARPER	BEDFORD WORKLOAD
SLALOM	0	0	AEROELASTIC [illegible]	AEROELASTIC [illegible]	[illegible]	[illegible]
			RIGID [illegible]	RIGID [illegible]	[illegible]	[illegible]
SLALOM	0	[illegible] ms	AEROELASTIC [illegible]	AEROELASTIC [illegible]	[illegible]	[illegible]
			RIGID [illegible]	RIGID [illegible]	[illegible]	[illegible]
VISUAL PATH	LATERAL LOW to MOD	0	AEROELASTIC [illegible]	AEROELASTIC [illegible]	[illegible]	[illegible]
			RIGID [illegible]	RIGID [illegible]	[illegible]	[illegible]

4. PILOT 1 – Roll & Pitch Aggression Average Ratings

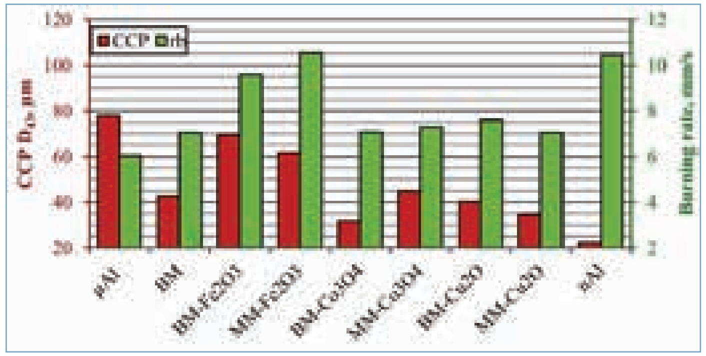
MECHANICALLY ACTIVATED AL FUELS FOR HIGH PERFORMANCE SOLID PROPELLANTS

Stefano Dossi - Advisor: **Prof. L.T. De Luca** - Co-Advisor: **Dr. Filippo Maggi**

Metal fuels are widely used in space propulsion to increase solid rocket motor (SRM) performance. The intrinsic properties of micrometric aluminum (μAl), like stability, low toxicity, low cost, and high metal content (about 99.5%, depending on size), make this powder one of the favorite materials employed for industrial production of solid rocket propellants (SP). During the combustion, the low reactivity of μAl causes the formation of condensed combustion products (CCPs) lowering the theoretical performance enhancement granted by the metal. The reduction of Al powder size down to the nanometric scale (nano-sized Aluminum, nAl) allows a consistent reactivity enhancement, confirmed by the reduction of the ignition temperature (T_{ign}), by the faster SP burning rate (r_b) and by the decrement of CCP size. However, the low metal content (around 90%), the increment of SP slurry viscosity, as well as direct and indirect high cost (due to powder production, and to handling and health hazards), hinder the large scale use of nAl. A viable strategy to increase μAl reactivity, limiting problems related to the use of nAl, consists in treating the powder by mechanical processes with and without additives. In this work, two techniques for the mechanical activation (MA) of μAl (ball milling and mechanical mixing) were investigated and applied for the production of mechanically activated Al powders (ActAl). During the preliminary step, a rationale based on toxicity/generic hazards, cost and potential performance was carried out to support the choice of activation substances (Fe_2O_3, Co_3O_4, and Cu_2O). Similarly, the key parameters influencing MA were analyzed for the precise definition of the activation processes (3 ball milling and 1 mechanical mixing procedures). Fifteen ActAl powders were formulated and produced to guarantee a low toxicity, a good metal content, a good stability, and a higher reactivity than μAl. Each manufactured ingredient was analyzed "as it was" and as ingredient in AP/HTPB-based solid propellants. Experimental data were then crosschecked and compared to those obtained using a standard μAl and two nAl powders.
All the ingredients treated by ball milling exhibited strong morphological variations caused by the mechanical action of the spheres. Particles were characterized by a flake shape with the external surface crossed by cracks (Fig. 1). The additive, if used, was embedded inside particles with an effectiveness depending on the size and on the specific treatment. The particle shape of μAl (spherical or elongated with a regular surface) was kept using the mechanical mixing treatment. SEM images underlined that additives, when nanometric, were homogeneously dispersed on particle surface.
The powder behavior at low and high heating rate has been determined by thermogravimetry and ignition tests. Both the analyses evidenced an enhanced reactivity of ActAl, confirmed by a reduction of T_{ign} and by a total mass gain up to 33% (6% was the mass increment of the virgin powder). ActAl metal content was detected by a hydrolysis technique and was comprised between 93.5% and 97.5%, then higher with respect to nAl (86.6%-89.4% for the two tested powders), but lower than μAl (99.2% for the considered material).
Combustion tests were performed in a strand burner at 5, 10, 20, 30 and 40 bar to determine the effects of ActAl on propellant r_b and CCP size. Solid propellants loaded with ActAl exhibited an increment of the burning rate with respect to the baseline ranging from 17% to 74% at 40 bar, depending on both the treatment and the selected additive. Similarly SP pressure sensitivity showed a reduction up to 20% under the investigated conditions. With respect to ball milling treatments, mechanical mixing processes exhibited a higher efficiency in increasing propellant burning rate, but a lower capability in decreasing the pressure sensitivity. The substitution of μAl with ActAl brought to a consistent reduction of CCP mass weighted mean diameter D_{43} (up to 70% at 10 bar and up to 60% at 40 bar), thus confirming a reactivity enhancement.
As shown in Fig. 2, also D_{43} variation exhibited a strong dependence on the additive and only a minor relation with the specific activation procedure.
An investigation of particle morphology influence on T_{ign} of Al powder was performed modelling the evolution of a single isothermal particle positioned in an ambient filled with O_2 and subjected to a slow heating rate (up to 50 K/s). The concept was based on an energy balance and includes both regular and irregular particles. Three geometrical families have been considered for analyses: spheres, prolate spheroids, and oblate spheroids. Irregular particles, characterized by a higher external surface, exhibited a lower T_{ign} than regular ones, confirming the key role played by the shape in the reactivity enhancement of ActAl.
The analyses of experimental results evidence that MA is a good strategy to obtain versatile and easily handling ingredients. ActAl exhibited a higher reactivity than μAl, a good metal content and safety characteristics similar to micrometric powders. When used as ingredients in SP, ActAl shows a good capability in reducing the size of CCP and offers the possibility to tailor the propellant burning rate, by controlling the activation parameters.



1. Particle morphology variation due to mechanical milling. ActAl particles assumed a typical flake conformation independently on the presence of an additive. SEM, magnification 2000X.



2. CCP mass weighted mean diameter and burning rate at 40 bar for a series of solid propellants loaded with μAl, nAl and different ActAl. The activated powders were processed by ball milling (BM) and by mechanical mixing (MM). The figure shows the possibility to decrease propellant CCP size and to tailor the propellant burning rate, by using ActAl. Nanometric aluminum guaranteed a stronger CCP size reduction, but also a higher burning rate enhancement.

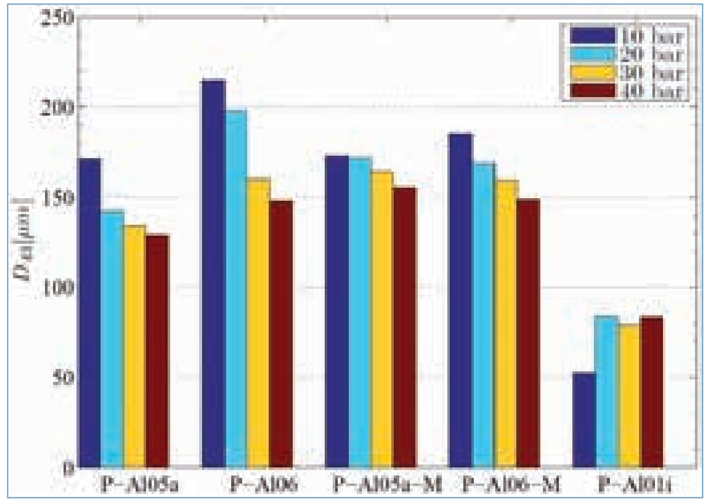
EFFECT OF AL PARTICLE SHAPE ON SOLID ROCKET PROPELLANTS

Marco Fassina - Supervisor: **Prof. Luigi T. De Luca**

Nowadays access to space is no more a dream but a necessity. Satellites orbit insertion is still a tough issue, which presents several technical and managerial aspects to be optimized in the mission project phase.
Solid propellant rocket motors offer a good solution to some questions concerning the payload launch phase.
These propulsive systems guarantee high performance, readiness and reliability in addition to relatively low costs; on the other hand, liquid propulsion systems, that are their direct competitors, provide higher performance and lower environment impact at larger cost and complexity.
This work is addressed to the evaluation of Al particle shape influence on propellant properties, such as viscosity, burning rate and agglomeration, through the analysis of the condensed products. In order to obtain more information about this aspect that in the past was never rigorously faced, four different micrometric powders have been tested and compared. The powders are the following: Al05a, a typical Al powder used for space applications, with approximately spherical shape; Al06, a commercial powder with irregular flaky shape, which does not find applications in rocket propulsive systems; Al05a-M and Al06-M, which are the previous two powders modified by a ball milling process to enhance particle irregularity. In addition to this set of micrometric powders, also a nanometric powder (Al01i) has been introduced in the comparison. This inclusion was made to settle where the increment of specific surface, due to particle irregularity, can be placedbetween a micrometric and a nanometric powder. To compare the different powders, the following characteristics have been analyzed: granulometry, performed with a laser granulometer; active metal content, by water bath, and morphology, which required the development of an ad hoc technique based on optical microscopy. To classify particle morphology four dimensionless parameters has been used: 1) form factor (FF);2) aspect ratio (AR);3) roundness (R); and 4) compactness (C).
From the results obtained it is possible to assert that Al05a is the finest powder with the highest metal content and geometrically can be seen as composed by particles similar to spheres. For irregular powders, also through SEM images, it can be stated that particles which compose Al06 powder can be compared to prolate spheroids while the milling process leads to the formation of oblate spheroids.
Since the interest of this work is addressed to analyze the effect of Al particle shape on solid rocket propellant features, the corresponding propellants have been manufactured.
The manufacture has been done using a resonant acoustic mixer, developing a dedicated procedure for propellant production. Resonant acoustic mixers offer some advantages with respect to mechanical mixers, such as, for instance, continuous vacuum mixing and reduced contaminations.
The composition used for propellant production is 68% of Ammonium Perchlorate, 18% of Al and 14% of binder.
The propellant characteristics analyzed are: burning rate, agglomeration process, through the analyses of condensed combustion products (CCPs), and uncured propellant viscosity.
Burning rate has been evaluated using the windowed strand burner technique and expressing results in the form of the standard Vieille's law.
A significant improvement to the technique used to collect and analyze condensed combustion products has been done during the prosecution of this work.
The analyses carried out on condensed combustion residuals were addressed to determine their particle size distributions and their chemical compositions.
Burning rate tests show that the propellant P-Al05a has the lowest performance in terms of burning rate and ballistic exponent, which expresses the pressure sensitivity to pressure changes.
The most interesting results have been shown by the propellant P-Al06, which evidences the lowest ballistic exponent.
Concerning the propellants loaded with micrometric Al powders, CCPs mean volumetric diameters decrease with pressure, while for the propellant loaded with nanometric powder CCPs mean size shows pressure insensitivity (over 10 bar), as can be seen from the results shown in Figure 1.
Chemical analyses (XRD and EDX) showed that the principal species identified in CCPs are aluminum, oxygen and carbon, and the crystalline phases are Al^0, α-alumina, γ-aluminaand δ*-alumina.
Combustion efficiency grows with pressure and is systematically higher for propellants produced with milled powders, while decreases with pressure for the propellant loaded with nano-aluminum.
Once the CCPs chemical composition is known, it is possible to estimate the refractive index in order to obtain finer results from the granulometric analyses.
Numerical simulations were carried out to evaluate two-phase flow losses, which represent the most important source of loss for solid rocket motors.
The code developed at SPLab is able to track particle evolution inside the combustion chamber and the nozzle, simulating different interaction between gas and particles as well as between particles. The phenomena simulated include combustion, fragmentation and collision.

ID	D_{43} [μm]	FF	AR	R	C	Metal content [%]
Al05a	42.7±0.5	0.88±0.02	1.28±0.04	0.84±0.02	0.90±0.02	99.5±0.3
Al06	66.4±0.7	0.70±0.02	1.74±0.08	0.63±0.02	0.79±0.02	98.0±0.4
Al05a-M	65.0±0.6	0.78±0.02	1.58±0.08	0.68±0.02	0.82±0.02	97.6±0.8
Al06-M	69.9±0.8	0.80±0.02	1.69±0.08	0.64±0.02	0.79±0.02	95.2±0.8
Al01i	0.141±0.001	-	-	-	-	88.7±0.2

Table 1 - Al particle characterization results. Shape factors analyses were not applicable to Al01i.



1. CCPs mean volumetric diameters versus pressure. Particles have been analyzed with a laser granulometer, adopting the Fraunhofer approximation.

AEROSERVOELASTIC MODELING AND CONTROL IN PRESENCE OF FREEPLAY

Sebastiano Fichera - Advisor: **Prof. Sergio Ricci**

Freeplay is one of the most important nonlinearities that affect the control surfaces of the aircrafts; it can induce flutter phenomena and limit the performances of the same airplane. To investigate the effect of control surface freeplay, an aeroelastic wind tunnel model of a T-tail was developed. A variable amplitude freeplay was introduced in the control chain by a specifically designed linkage. The numerical models were built, according to the modern aeroelastic approach, describing the dynamics of the tail by a state space system with a lumped nonlinearity.

Introduction

The research on nonlinear aeroelasticity and, in particular, on control surface freeplay, is motivated by the significant number of cases known in the literature of aircrafts that have experienced Limit Cycle Oscillations (LCO) caused by it. In fact, freeplay in the control chains may arise as consequence of many factors, including wear of the parts during the aircrafts life. In order to perform numerical and experimental investigations, a wind tunnel model of a T-tail equipped with the rudder and the control system was designed and manufactured.

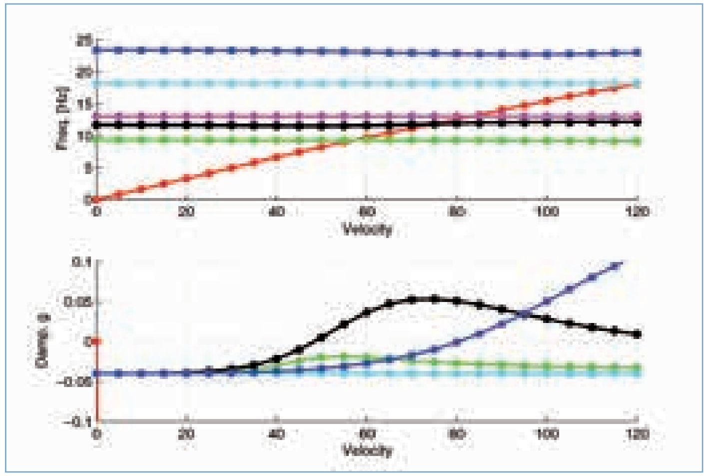
Experimental rig

The T-tail unit considered in this work is the one of the X-DIA, an aeroelastic model representative of a nonconventional three surfaces regional jet (called Target Aircraft), intensively investigated in the last few years at the Department of Aerospace Science and Technology of Politecnico di Milano.
The model is composed by dynamically scaled aluminium alloy spars, which are inserted in a series of aerodynamic sectors made by styrofoam covered with a carbon fiber skins. In order to have a variable amplitude freeplay, a mechanism was introduced in the control chain between the actuator and the rudder; it is composed by a rigid linkage connected with the rudder and that ends with a pin that is slipped into a fork connected with the gear of the electric motor used to actuate the movable surface.

1. T-tail aeroelastically scaled wind tunnel model.

Numerical models

The T-tail State Space (SS) matrices are built using the structural Finite Element model and the aerodynamic DLM, both developed in MSC.Nastran.
The SS model is a Reduced Order Model (ROM) with the basis made by the free surface rigid mode plus the significant elastic modes. The frequency domain aerodynamic matrix is transformed into a finite state space realization by using Roger's algorithm.
The linear aeroelastic behaviour of the model is shown in the numerical V-g/V-f flutter diagrams (see figure 2) computed with the free surface. The first (11.63 Hz) and the second (23.22 Hz) fin bending modes cross the zero damping line respectively at 47 m/s and 78 m/s.
The direct integrated (time marching) model was designed by assembling the structural and the aerodynamic state space systems. The nonlinearity was introduced as a lumped element in the feedback loop by using a penalty function approach.
The model is time-varying velocity in order to be able to reproduce the effect of an increase (or decrease) of the free stream speed during the simulation.
A High Order Harmonic Balance (HOHB) was developed as well. The method approximates the response of a given nonlinear system, which is undergoing LCOs, with a Fourier series leading to a set of nonlinear algebraic equations that can be solved by an iterative method.
Once the numerical models were validated, an alternative control algorithm for vibration reduction was developed.



2. V-g V-f diagrams.

Experimental tests

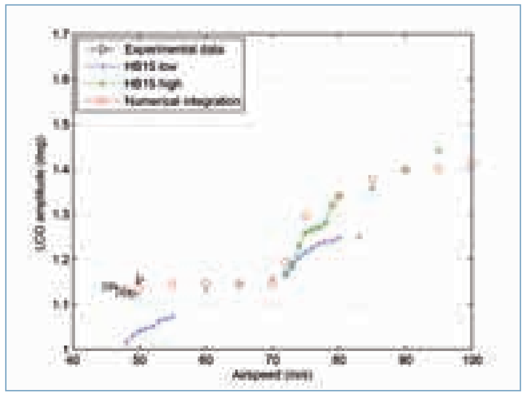
Wind tunnel tests were conducted on the experimental rig in order to tune the FE model and to validate both the numerical models. The acquisition and control of the system was handled by a hard real-time tool called RTAI.

Results

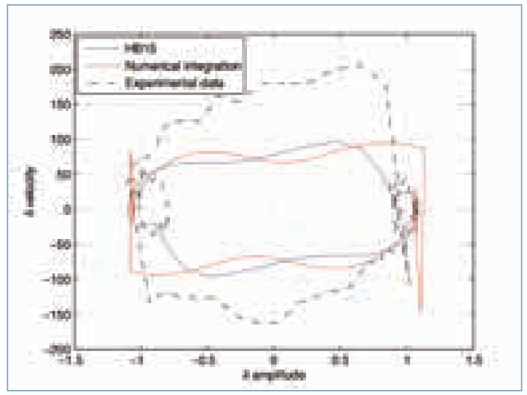
The experimental results, as well as the numerical, show the typical trends for a nonlinear aeroelastic model.
Figure 3 shows the LCO amplitude trend increasing the airspeed. The HOHB, as the numerical integrated model and the experimental data, depicts two regions: the first is the consequence of the flutter of the first bending mode, while the second is a combination of the first and the second mode flutters.
The portraits comparisons are shown in figure 4. It is possible to see a good agreement of the trends even if the HOHB is not completely able to catch the peaks due to the foldings of freeplay stiffness.

Conclusion

This work presented different methods for the study of nonlinear systems. The results of a numerical integrated model and a HOHB procedure are compared with experimental data for a T-tail in presence of freeplay nonlinearity in the rudder's control chain. The methods shown to be able to catch the correct solution for the nonlinear system.



3. LCO amplitude, NI - Experimental - HOHB comparison ±1°.



4. LCO portraits at 50 m/s, NI - Experimental - HOHB comparison ±1°.

VIBRATION ANALYSIS OF LAMINATED COMPOSITE PLATES AND SHELLS USING A SPECTRAL METHOD

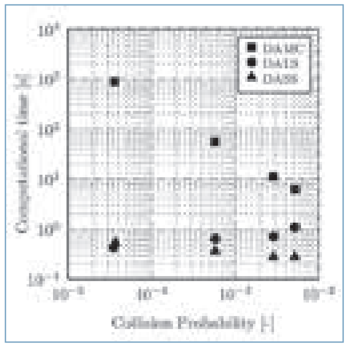
Amir Hossein Mohazzab - Supervisor: **Lorenzo Dozio**

Accurate yet efficient modeling and solution of plate and shell structures can be considered a classical problem in structural mechanics. Over the last fifty years, researchers proposed many different approaches to face this problem, urged by the increasing adoption of flat and curved panels as structural elements in a large variety of engineering applications. For example, rectangular, skew, annular, cylindrical and spherical panels are important components of built-up aircraft and spacecraft structures. Plate and shell structures are also widely applied in automotive, marine and civil engineering disciplines. In the last three decades, the design of plate and shell structures has known new exciting opportunities by the usage of composite materials. Composite laminated plate and shells offer higher stiffness/ strength to weight ratios than most metallic constructions and today they are fairly common in advanced engineering applications such as aerospace systems.
In service, laminated panels are typically subjected to various dynamic loads, and it is crucial that their dynamic response is well predicted from the design stage onwards in order to assure their integrity and stability. The accuracy of free vibration analysis of laminated plates and shells mainly relies on two aspects. The first issue is related to the assumptions and simplifications adopted in the mathematical model of the structural component. The second aspect involves the method selected to solve the governing equations of the problem.
Models of flat and curved panels based upon the three dimensional (3-D) theory of elasticity can be considered as the most accurate, since no overly simplified assumptions are introduced in describing the kinematics of deformations. As such, 3-D models are suitable for plates and shells of any thickness ratio and any shallowness ratio, ranging from thin and shallow to thick and deep shells vibrating at low to high frequency. However, a full 3-D dynamic analysis, especially for composite plates and shells, is rather complicated and time consuming. Therefore, so-called plate theories aimed at reducing the problem from three to two dimensions have been introduced by employing appropriate assumptions on the displacement behavior in the thickness direction.
Many different displacement-based two-dimensional (2-D) theories for laminated panels are available. Generally speaking, we can distinguish between equivalent single-layer (ESL) and layerwise (LW) theories, including or not shear deformation, rotary inertia and thickness stretching factors. ESL approaches assume a proper overall kinematic field throughout the thickness of the laminated structure, whereas an independent displacement field is postulated for each layer in a LW framework and appropriate continuity conditions are imposed at each layer interface. Typically, both ESL and LW kinematic fields are expressed as complete polynomial series expansion of the thickness coordinate and the highest power of the assumed polynomial set is generally referred to as the order of the theory. Owing to their intrinsic simplifications, 2-D theories provide reliable models for a limited range of thickness ratios, frequency values and through-the-thickness variation of material properties. The accuracy usually degrades as the wavelength of the vibration mode is of the order of magnitude of the panel thickness and as the variation of mechanical properties through the thickness direction increases like the case of sandwich panels. This loss of accuracy can be successfully compensated by using theories of higher order and/or relying on a LW approach, with the price of increasing the complexity and computational cost of the resulting models. Frequently, the knowledge in advance of the correct shell theory balancing the accuracy and computational burden for the specific problem under investigation can be a hard task. A unified modeling framework capable of tailoring the order and typology of the shell theory without the need of a new modeling effort each time would be highly desirable.
The other important aspect related to the computation of natural frequencies of laminated panels is the method adopted to solve the equations governing the dynamic problem. Again, many different approaches are available in the literature. Exact solutions satisfying both the differential equations and the boundary conditions are possible only for a limited set of plate and shell geometries, boundary conditions and lamination sequences. In most practical situations, one must rely on approximate methods. The most common and traditional approaches include the Ritz method and the finite element method (FEM). For simple structures, the Ritz method shows better convergence and less computational need than FEM. However, the FEM overcomes the limitations of the Ritz method in dealing with complicated boundary conditions and complex shapes. More recently, new emerging meshless methods are increasingly applied to the analysis of plate and shell problems with the aim of eliminating some difficulties existing in FEM such as mesh distortion and remeshing.
The scope of this thesis is to present an advanced modeling and solution framework for the free vibration analysis of both thin and thick, deep and shallow laminated panels with different combinations of boundary conditions. The range of applicability of the resulting tool is similar to a fully 3-D analysis, with also the possibility of using economical low-order theories when more refined models are not required. Therefore, the balance between accuracy and computational savings can be tailored on the specific application under study. The modeling aspect exploits the power and versatility of the Carrera's unified formulation, which provides a smart way of handling arbitrary refinements of classical plate theories. The discretization of the problem to obtain an approximate solution of the natural frequencies is performed by the spectral collocation method, which is capable of providing relatively light discretized models to be profitably used in extensive optimization and parametric studies.
The spectral collocation method used here, also known as Chebyshev collocation method or pseudospectral method, can be considered to be a global spectral method that performs a collocation process, i.e., weighting functions are delta functions centered at special grid points called collocation points. Since the mathematical formulation is simple and powerful enough to produce approximate solutions close to exact values, this method has been largely adopted with success in solving partial differential equations governing many physical phenomena such as fluid dynamics and wave motion. It was also used in some applications for the solution of structural mechanics problems. The thesis discusses many different plate and shell structures, ranging from rectangular to skew and circular sector plates, including cylindrical, spherical and conical shells. For all cases, the analysis is performed for various combinations of free, simply-supported and clamped boundary conditions. Some studies are also provided for structures involving elastically restrained edges. Both single-layer isotropic and multi-layered orthotropic plates and shells are considered. It is shown, through a huge number of comparisons with fully 3-D analyses and other references based on 2-D approaches, that the present computational framework is efficient, versatile and accurate. In particular, it is observed that stringent requirements on the accuracy of the computed frequency values can be satisfied only by 2-D high-order layerwise models, in particular when thick and deep anisotropic curved panels are considered. However, the present approach can also allow building less costly low-order equivalent single-layer models when a more refined analysis is not required for the specific case under investigation.

HIGH ORDER METHODS FOR SPACE SITUATIONAL AWARENESS

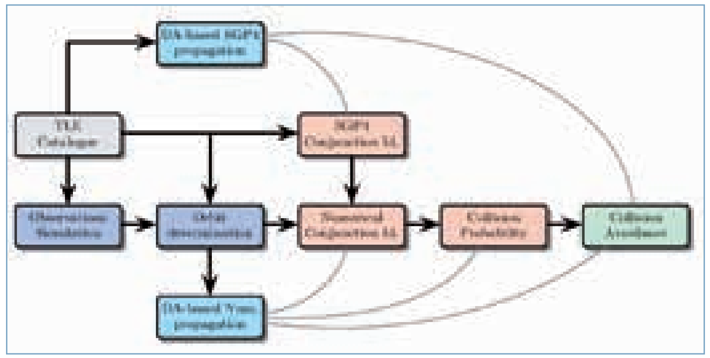
Alessandro Morselli - Supervisor: **Franco Bernelli Zazzera**

The era of space exploration started in 1957 with the launch of the first manmade object, the soviet satellite Sputnik I. Since then a large number of manmade objects was launched into space, and many of them are still orbiting the Earth.
The large majority of objects currently orbiting the Earth is a result of fragmentations, mostly caused by collisions and explosions. These events can have catastrophic effects on the near-Earth environment: they increase the number of objects and, thus, the probability of further collisions, potentially leading to a collisional cascade. This scenario is named Kessler's syndrome after the name of the scientist that first analysed the effects of the increasing density of resident space objects.
Mitigation guidelines have been published by various organisations such as the Inter-Agency Space Debris Coordination Committee (IADC) and the United Nations (UN). The general aim of space debris mitigation is to reduce the growth of space debris by ensuring that space systems are designed, operated, and disposed of in a manner that prevents them from generating debris throughout their orbital lifetime. In parallel specific space programs were started to build the expertise required to manage the challenges posed by the space traffic control problem.
The thesis deals with the development of new methods for the Space Surveillance and Tracking of the near-Earth environment. All the relevant aspects of the problem are addressed: orbit propagation, orbit determination, conjunction identification, collision probability estimation, and collision avoidance manoeuvre design. The main goal was to implement innovative methods to propagate uncertainties in an efficient and accurate way, which is a major problem when dealing with a large amount of data.



1. Research activity: workflow and interconnections between developed algorithms.

In this framework, differential algebraic techniques are used to perform nonlinear propagation of uncertainties on the orbital state and to speed-up computational demanding simulations, such as Monte Carlo methods. An introduction to Differential Algebra (DA) and its tools, as well as a description of the high-order DA-based propagators developed, is given in the first part of the work. In particular, the first ever high-accuracy DA-based numerical propagator is developed, using some of the most recent models for Earth gravitational field and atmosphere density.
Then, the problem of orbit determination is addressed. A novel algorithm based on batch least square fit that can process measurements from a bistatic radar with a multibeaming receiver is analysed. The algorithm is capable of estimating, with a single measurement, the whole set of six orbital parameters, with a good accuracy on the orbital position. By adding optical measurements the estimate gets closer to the reference state and the ballistic coefficient can be estimated as well.
Two algorithms for the conjunction identification are proposed: the first is based on the DA-version of the analytical propagator SGP4/SDP4 and the rigorous global optimizer COSY-GO. The choice of the objective function is such that all stationary points of the relative distance between the two objects can be computed in the time window of interest with a computational time that ranges from a few to tens of seconds. The second algorithm uses the procedure for the DA expansion of the time and distance of closest approach. The advantage of this approach is that it provides the polynomial approximation of the distance of closest approach with respect to the uncertain initial states of both objects, that can be used to efficiently compute collision probabilities.
The three methods for the collision probability computation exploit the availability of the DA expansion of the distance of closest approach to perform fast Monte Carlo simulations. The numerical simulations to compute the minimum relative distance for each sample of the simulation are replaced by fast polynomial evaluations. A DA-based standard Monte Carlo method and two advanced Monte Carlo techniques, Line Sampling and Subset Simulation, are used. These advanced techniques limit the number of samples required to compute sufficiently accurate estimates of the collision probability, which is usually well below 10^{-3}. Since they are based on polynomial evaluations, the methods allow for large computational time savings. As an example when 1000 samples are required the computation time can be reduce by two order of magnitude. Besides enabling the collision probability computation in a Monte Carlo fashion, without any assumption on relative dynamics as in the classical algorithms, the developed methods can be used with any statistics, such as uniform distribution or Gaussian mixtures.
The design of collision avoidance manoeuvres is tackled as a multi-objective optimization problem, using a particle swarm optimizer. Two approaches are analysed, the first is based on SGP4/SDP4 and the corresponding method for conjunction identification, whereas the other uses the DA-based numerical propagator and the expansion of the distance of closest approach with respect to the execution time and the manoeuvre velocity vector. The optimization returns a set of fuel-efficient manoeuvres that can raise the miss-distance and decrease collision probability besides being compliant with mission constraints.
Overall, the proposed algorithms can be combined in comprehensive DA-based Space Surveillance and Tracking tool. The tool would be able to manage the uncertainties by considering the nonlinearities arising from orbit determination and orbit propagation and could produce accurate estimations of the collision probability to rank close conjunctions. More in general, the tool would support in the management of space traffic, re-entry, and observation scheduling. In the scope of the mitigation guidelines, any improvement in handling such operations will have beneficial effects on space debris population control and the future exploitation of space.



2. Computational time of DAMC, DALS, and DASS vs. collision probability.

VIBRATION-BASED DAMAGE IDENTIFICATION TECHNIQUES

Kamal Rezvani - Supervisor: **Prof. Sergio Ricci**

Higher operational loads, greater complexity of design and longer lifetime periods imposed in civil, mechanical and aerospace structures, make it increasingly important to monitor the health of these structures.

A wide variety of highly effective non-destructive methods, such as acoustic or ultrasonic methods, magnet field methods, penetrating liquids, eddy-current methods or thermal field methods, and so on, are currently available for the detection of defects. Unfortunately, they are all localized techniques, implying long and expensive inspection time; often, structural components are not inspected just because of their inaccessibility and damage can propagate to critical levels between the inspection intervals. The drawbacks of current inspection techniques have led engineers to investigate new methods for continuous monitoring and global condition assessment of structures. That is the case for methods based on vibration responses that allow one to obtain meaningful time and/or frequency domain data and calculate changes in the structural and modal properties, such as resonance frequencies, modal damping and mode shapes, FRF based methods, and use them with the objective of developing reliable techniques to detect, locate and quantify damage.

The fundamental idea of the vibration methods for damage detection is that modal parameters (natural frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping, and stiffness). Therefore, changes in the physical properties will cause detectable changes in the modal properties. So, this process involves the observation of a structure/system over time using periodical measurements. In other words, most vibration-based damage detection methods can be considered as some form of the pattern recognition problem as they look for the discrimination between two or more signal categories, e.g. before and after a structure is damaged or differences in the damage levels or locations.

The work here presented addresses the subjects of damage detection, localization and quantification in structures. The reported examples show the implementation and comparison of a number of various damage detection and localization methods based on vibration responses changes.

The objective of such a study is to ascertain the possibility of using various damage detection and localization methods with and without the need for modal identification. In recent years, the authors have developed some simple methods and tools based upon the use of mode shapes and frequency response functions (FRFs), which seem promising and have given good results in some practical applications. The advantage of using such methods, which is based on mode shapes, is that only measured mode shapes are required in damage identification, without having to know the complete stiffness and mass matrices of the structure.

To use of directly measured FRFs data, which provide an abundance of information, is further beneficial as the execution of experimental modal analysis is not needed, thus greatly reducing human induced errors. Here, all methods are first tested on data of a simple steel beam structure (see Figure 1) to assess their feasibility and performance. Then all proposed methods are applied to a more complicated structure, a typical aircraft stiffened panel, for extension and validation purposes.

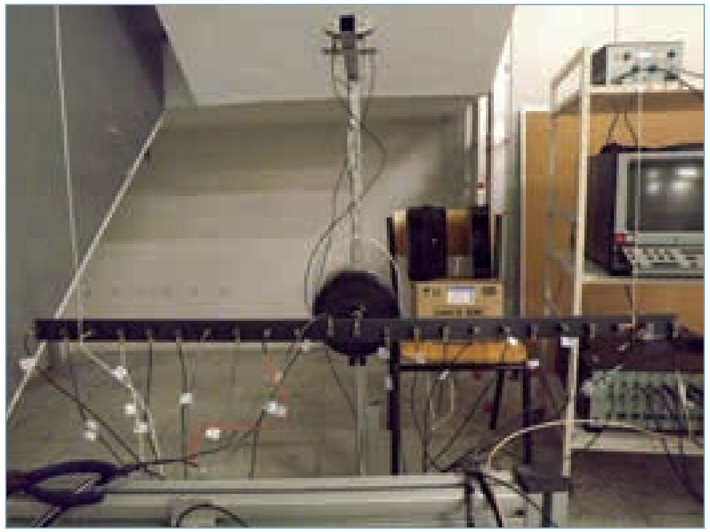
All developed methodologies are verified by numerical simulations and laboratory testing for both structure. As defects, notch type damage of different severity are investigated for the beam structure.

For the panel structure four different types of structural change are studied. i.e. remove some screw for disconnecting the stiffener from the panel and create a saw cut along the all the depth of the height of second stiffener. FRFs of panel in each state are recorded by two measurement systems (see Figure 2, LMS Hammer Testing and PSV-Laser Scanner Vibrometer) and for each scenarios the related mode shapes are extracted by PolyMAX algorithm of LMS Testlab software.

In addition, numerical simulated examples, after correlation with the real experimental one, of both mentioned structures will be used, as well as an experimental test cases, where damage is inflicted in a free-free condition. To simulate noise disturbances experienced during the experimental testing, for the numerical simulations of example beam, measurement data generated by MSC/Nastran are polluted with 3% of random noise level.

The study shows the potential of the proposed methods for simple and rapid detection, accurate and reliable localization and monitoring of damage in structures.

The reported examples also show that some proposed methods (i.e. PCA based, Transmissibility based) are highly capable for damage detection and localization and structural health monitoring even in the noise polluted data.



1. Experimental test setup of steel beam

a) LMS Hammer Testing

b) PSV-Laser Scanner Vibrometer

2. Experimental test setups of typical aircraft aluminum stiffened panel.

MODEL IDENTIFICATION AND CONTROL OF VARIABLE PITCH QUADROTOR UAVS

Fabio Riccardi - Advisor: **Prof. Marco Lovera -** Co-Advisor: **Prof. Carlo Luigi Bottasso**

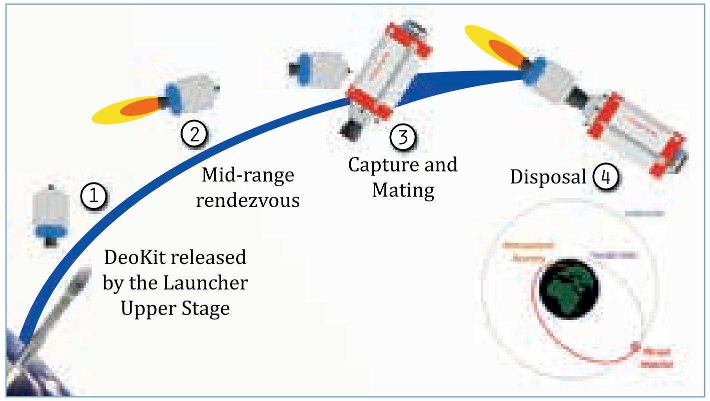
The interest in quadrotors as platforms for both research and commercial Unmanned Aerial Vehicle (UAV) applications is steadily increasing. In particular, some of the envisaged applications for quadrotors lead to tight performance requirements on the attitude control system, so wide bandwidth controllers must be designed. This, in turn, calls for increasingly accurate dynamics models of the vehicle's response to which advanced controller synthesis approaches can be applied. In view of these considerations the main goal of this thesis work was the development of an integrated, highly automated procedure, and relative tool chain, aimed at a fast and reliable deployment of the attitude control system for variable pitch quadrotors, encompassing identification of linear control-oriented model for the attitude response and optimization-based tuning for the parameters of the on-board controller structure. The research activities were carried out exploiting the collaboration with AERMATICA SpA: a quadrotor prototype, with relative ground systems and laboratory bench test have been made available from company, together with all necessary vehicle data.
Proper identification experiments of the pitch attitude dynamics in hovering were designed, adopting a PRBS excitation command, and conducted on a quadrotor prototype, in both on laboratory bench test and in flight conditions. The gathered data was used to feed a number of different identification methods, exploring both black-box and grey-box approaches, to obtain LTI control-oriented models. From an exhaustive comparison of the obtained pitch attitude dynamics models performance in replicating the experimental data, the black-box PBSID subspace method appears to be the best candidate for the identification part of the procedure: it is able to dealing with data generated in closed-loop and it is computationally efficient. Moreover PBSID identified models demonstrate that operating the quadrotor constrained on single DoF test-bed is representative of the actual attitude hovering dynamics in flight: the ν-gap analysis between the two different conditions models assures that the controller synthesis using the on test-bed model will guarantee acceptable performance also when applied on in flight one.
Concerning the control synthesis part of the tool chain, it was preferred to maintain the preexisting attitude controller scheme (cascade PID loops) adopted on-board of considered quadrotor, in order to work in continuity and accelerating the implementation process. Therefore the robust control design approach selected was the structured H_∞: optimal tuning of the PIDs parameters was determined assigning desired closed-loop stability and performance requirements, aimed to improve the vehicle wind gust rejection capability compared to previous tuning, obtained with a manual trial and error process executed directly on the vehicle, and replicate its set point tracking performance considered already adequate. The structured H_∞ synthesis was applied on both on test-bed and in flight identified PBSID models of attitude pitch dynamics in hovering: the results obtained in simulation demonstrate the requirements fulfillment and above all the optimal tuning obtained with the test-bed model in the loop can be applied also in flight with a non-significant loss in control performance, hence the attitude controller tuning can be achieved using models obtained in safe (and more repeatable) identification experiments executed indoor on the test-bed, avoiding a risky and time-consuming in flight identification test campaign.
The performance in terms of set point tracking, for the optimal tuning obtained with on test-bed model, was evaluated experimentally on the quadrotor in bench test condition: results confirm the behavior expected from simulations. Moreover the robustness assessment of obtained optimal tuning set respect to identified models uncertainties (evaluated through a bootstrap based technique) was achieved, performing a Monte Carlo simulations campaign.
In conclusion the entire control design process, specifically addressed to near hovering condition (quadrotors mainly operate in this flying regime during typical missions), was developed and successfully applied to the real case of considered quadrotor pitch attitude DoF (with results applicable also for roll considering the geometrical symmetry of the vehicle). In order to obtain a final validation of the procedure, optimal tuning parameters (in both cases, using on test-bed and in flight models) will be applied on-board, testing the considered vehicle control performance in flight, also in presence of wind gust. To complete the tool chain the work will be naturally extended to the yaw DoF. The use of the developed approach represents a valid and faster alternative to the manual empirical process for attitude controller tuning and would be included in AERMATICA control design and development process in the near future. As future work extension, a similar integrated procedure may be developed for the translational quadrotor DoFs, clearly without the possibility to perform identification experiments on bench test.
The secondary topic addressed in this thesis was the development of an emergency maneuver to safely recover a one rotor fault occurrence for a variable pitch quadrotor. The capability of dealing with faults is crucial for UAVs, especially when the vehicle has to operate in critical missions, e.g., flying above populated areas or in proximity of industrial plants sensitive facilities, where the ability to safely conclude the flight without hurting people or causing damages could be mandatory. Moreover strict safety requirements are expected to be imposed by forthcoming regulations about the use of small-medium size UAV for civil applications. The vehicle dynamics modeling with three working rotors was discussed: a single DoF model for the yaw was developed, characterizing the vehicle spin dynamics and validated through a test campaign on a proper bench test. Hence the vertical DoF dynamics was added to yaw, adopting a proper model for the rotor inflow in descent operating states where the momentum theory in invalid (Vortex Ring State and Turbulent Wake State). The reliability of adopted rotor aerodynamics model was demonstrated through a wind tunnel test campaign conducted on isolated rotor. Concerning the roll/pitch attitude control strategy to perform the proposed emergency maneuver, the problem of maintaining the pitch (or roll) angular set-point when one of the two opposite rotor of longitudinal (or lateral) quadrotor axis goes into fault (avoiding the vehicle turn over at the thrust loss instant) was tackled, exploiting the capability to generate negative rotor thrust, peculiar feature of variable pitch architecture in comparison with the most common variable RPM implementation. An experimental campaign operating the vehicle on the single pitch (or roll) DoF was carried out, replicating a rotor fault commanding a power-off: the results demonstrate that the implemented strategy is able to avoid vehicle "flip".
In order to complete the validation of the proposed one rotor fault recovery automatic maneuver, with the aim of implement the feature on AERMATICA vehicles, incremental complexity future activities are planned before the final test in flight. The next step will be the testing of roll and pitch control with a faulty rotor when the spin about yaw axis is present, safely operating the quadrotor on a proper 3 DoFs test-bed constraining only the vehicle translations and freeing concurrently the three rotations. A further work will be the development of a complete simulation environment, to conduct a comprehensive validation of the emergency maneuver, considering also the vertical and longitudinal/lateral dynamics.

HYBRID ROCKET PROPULSION FOR ACTIVE REMOVAL OF LARGE ABANDONED OBJECTS

Pietro Tadini - Relatore: **Luigi. T. De Luca**

During the last 40 years, the mass of orbital artificial objects increased quite steadily leading to a total of about 6670 metric tons. Most of the cross-sectional area and mass (97% in low Earth orbit, LEO) is concentrated in about 4500 intact objects, i.e. abandoned spacecraft (S/C) and rocket bodies (R/Bs), plus a further 1000 operational S/C. According to NASA results, the active yearly removal of 5 large abandoned intact objects would be sufficient to stabilize the debris growth in LEO, together with the worldwide application of mitigation measures. However, besides legal and political issues, Active Debris Removal (ADR) is strongly hampered by high costs involved. In this research, hybrid rocket propulsion is proposed as a valuable option for ADR missions. This technology has advantageous features: non-toxic propellants that, besides their lower price, reduce the complexity of handling, storability and load operations, decreasing the connected costs and avoiding the need of a special staff; throttleability which could favor the rendezvous phase and allows for soft initial accelerations to weak S/C targets; reignition capability for multi-burns operations. For an ADR mission the propellant couple HTPB+H_2O_2 might represent an ideal solution. In fact, HTPB boast of high mechanical and aging properties and isotropic combustion, whereas the hot gases generated by the catalytic decomposition of H_2O_2, at high concentration (90%), can be exploited for the HTPB ignition and reignition, as well as for a Reaction Control System (RCS), spilling from the same main tank. Moreover, this propellant couple theoretically causes a lower nozzle throat erosion with respect to HTPB with pure oxygen oxidizer. However, hybrid propulsion has not been tested in orbital environment yet (low TRL). Concerning the ADR mission two targets are considered: Envisat (7.8t) and Cosmos-3M 2nd stage (1.4t). The first is characterized by the highest removal priority, the second is a good candidate for multi-removal and demonstrative missions, due to its large number in LEO (~300); the same developed technology might be used to remove larger abandoned R/Bs, such as the Zenit 2nd stage (8.9t). Controlled reentry is the preferred solution for the disposal of large objects; a single boost maneuver is assumed to lower the perigee below 60 km with a FPA< -1.5° at an interface of 120 km. A ΔV of 200 m/s is required starting from an orbit of about 770 km. The mission is performed by a de-orbiting kit (DeoKit) made by a Hybrid Propulsion Module (HPM) and an ADR platform, which loads all the systems for mission control, object capture and RCS. In order to evaluate hybrid propulsion for ADR, a design tool for overall internal ballistics analysis and preliminary sizing was implemented, based on the same approach recently suggested by Funami and Shimada (Japan Aerospace Exploration Agency). The code uses moderately complex models and allows to estimate the fuel regression rate for the couple HTPB+H_2O_2, for which no data are presently available in literature. The flow field is described by the Q1D compressible non viscous Euler equations with a conservation equation for the mixture fraction. The calculation domain consists of the combustion chamber and a nozzle. The solid fuel has a single circular perforation. The mass addition from the solid fuel surface is considered as a source term, in which the fuel mass flux is evaluated with the Marxman model, assuming pure convective regime. The code considers only the gaseous phase for both the fuel and oxidizer. Chemical equilibrium is applied for the combustion considering 9 chemical species to simulate both HTPB+O_2 and HTPB+H_2O_2. The domain is

discretized by finite elements, using MUSCL+Limiter method for high order accuracy in space solution. AUSMDV is used for numerical flux evaluation. The time integration is performed by a two-stage Runge-Kutta method. The time evolution of the chamber conditions is achieved by compiling the convergence results, providing a quasi-static description of the regression rate during combustion. For validation purpose, the regression rate r_f estimated with Marxman model was compared with experimental results for HTPB+O_2, obtaining an underestimates of about 16% at high mass flux (G_{ox}) and up to 50% at low G_{ox}. This lack can lay at both the effects of injection geometry, which, in the real case, can produce significant differences from Marxman's theory, and the use of a pure convective heat transfer (soot particles cause an important radiation contribute). However, the computed r_f range is assumed acceptable for the conservative preliminary design and propellant mass budget of a HPM. The ideal motor performance evaluated for pure H_2O_2 is reduced considering the oxidizer dilution (90%), the Bray approximation for nozzle expansion, and the nozzle multi-dimensional losses, by means of a correction factors



1. ADR mission profile description. The DeoKit is assumed to be released by a launcher upper stage on the same orbital plane of the selected target. Rocket bodies, such as Cosmos-3M 2nd stage, reveal two possible connection points: nozzle or payload adapter.

database estimated with NASA CEA. Throat erosion is introduced through the numerical simulation results of Bianchi and Nasuti (La Sapienza, Rome). The motor design aims at minimizing the size and masses, keeping low combustion times (<100 s) since HPM nozzle is not cooled to avoid the need of an expensive system. From the design analysis, the highest performance (I_s) is achieved with a length-to-diameter ratios (L/D) of about 12 for the solid grain, resulting in a long and thin motors, and relatively low oxidizer mass flow rates. Single-burn maneuvers can be used for low ΔV budgets, while higher ΔV's require a multi-burn strategy to satisfy the burn time constraint. Finally, the HPMs for the selected targets assumes a ΔV of 240 m/s. The Cosmos-3M might be removed by an HPM of 258 kg (DeoKit 566.8 kg), with a single-boost maneuver. Vega can load 2 DeoKits, while the Soyuz Launcher up to 6, allowing for multi-removal scenario. For Envisat removal a two-burns disposal is preferred to reduce the HPM mass and size, combustion times and accelerations. In case of S/C, the stresses to the structure must be limited to avoid the breaking risk of external appendages (i.e. solar panels, etc.). The acceleration achieved are below 0.14g. Envisat might be removed by an HPM of 1260 kg (DeoKit 1771 kg). Soyuz can load two DeoKits. Hybrid propulsion might represent a key choice for ADR applications. To overcome the lack of on-orbit demonstration, a possible approach could be to equip new satellites with small hybrid motors able to perform their post-mission disposal.

PARAFFIN-BASED SOLID FUELS: A LOW COST AND GREEN SOLUTION FOR THE COMPETITIVENESS OF HYBRID ROCKET PROPULSION SYSTEMS

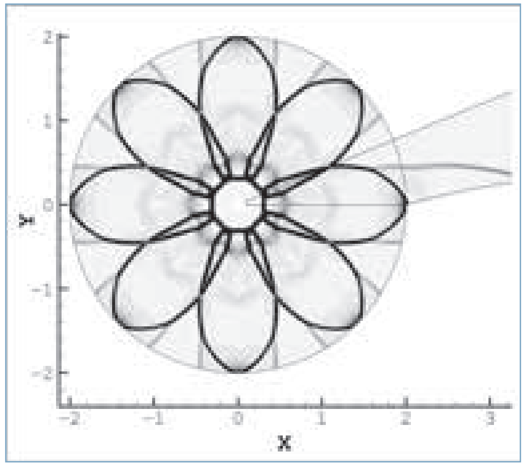
Elena Toson - Supervisor: **Prof. Luigi T. De Luca**

Due to their potential for high performance, inherent safety, throttling and restart capability and low development costs, hybrid rocket engines are believed to be good candidates for launcher boosters, suborbital launchers and landers and in particular for in-space propulsion applications. In order to be competitive with the other chemical rocket propulsion systems, i.e. liquid rocket engines and solid rocket motors, hybrid rocket engines should maintain high performance while preserving their features. Moreover even if the environmental impact is not directly affecting the system performance, it is of fundamental importance in light of present regulatory requirements and its effect on society, so the possibility to select low cost and non-toxic fuels makes this technology even more interesting.
In order to perform a comprehensive analysis of hybrid rocket engine design trends and demonstrate their potential, a design/optimization tool for in-space, single stage hybrid rocket propulsion system is developed. Hydrogen peroxide/paraffin-based propellant combination and a lunar mission are selected as the reference case. Spacecraft gross mass (defined as the sum of the payload mass - everything except the propulsion system -, the propulsion system structural mass and the propellant mass) to payload mass ratio is minimized over key propulsion variables such as the chamber pressure, oxidizer to fuel ratio *O/F*, nozzle area ratio and burning time. Sensitivity analyses on geometrical constraints, fuel regression rate, *O/F* shift, nozzle erosion rate, were performed. Major findings show that: the fuel regression rate has the highest influence on the engine size and gross mass, but it should be underlined that the minimum cost function value is not reached for the highest considered regression rate; the nozzle erosion rate also has a high influence on the performance due to the decreasing nozzle expansion ratio during the engine burn, resulting in a lower delivered specific impulse; the *O/F* shift, caused by the variability of the fuel mass flow during combustion, does not have a strong effect on the system performance. Calculations were also carried out with the hydrogen peroxide/hydroxyl terminated polybutadiene (HTPB) propellant combination. For this slow burning fuel, both single port and multiport geometries were considered. The comparison points out that for this fuel, the single port configuration results in really high mass ratio based cost function and too long combustion chamber. The multiport configuration can help in terms of decreasing *L/D* of the engine, but the cost function still remains much higher if compared to the fast burning paraffin fuel baseline case. Inevitably, the hybrid system in a multiport design configuration does not preserve its intrinsic simplicity. The appealing design is consequently identified with a single circular port solution with a fast burning fuel as paraffin, which also preserves the low cost and non-toxicity requirements.
In order to be used as fuel, a paraffin-based mixture should fulfill a number of requirements, as the ease of manufacturing, good mechanical properties while preserving high regression rates and a good thermal stability. These requirements are related to thermal, rheological, viscosimetric, ballistic and physical properties of the paraffin-based mixtures. Starting from the selection of six different paraffin waxes, both macro and micro crystalline, combined analyses were performed in their pure form and related mixtures that are likely to be used as solid fuels in hybrid rocket engines. Results obtained by ballistic experiments performed on a radial micro combustor at SPLab in Politecnico di Milano, demonstrate that the regression rates of paraffin waxes mixed with stearic acid and graphite which shows liquid droplets entrainment, are up to three times higher with respect to the baseline HTPB. Among these paraffin-based fuels, the one based on micro paraffin wax shows a lower enhancement. Experimentally it was shown that the lower is the viscosity of the paraffin-based mixture at 120 °C, by tests performed at the Space Propulsion Institute of DLR, the higher is the measured regression rate. The results are well in agreement with the current literature theoretical combustion model for liquefying fuels, for which, the less viscous is the fuel liquid layer the higher is the fuel regression rate.
If on one hand the micro paraffin shows lower regression rates, on the other hand rheological tests reveal its mechanical resistance to higher external temperatures. It was even experimentally demonstrated that improvements on the softening point, up to 51 °C, are achievable by mixing a microcrystalline wax with a synthetic wax characterized by a higher nominal melting temperature even without compromising the regression rate. But uniaxial tensile tests reveal that higher maximum stresses and good elasticity are reached with the macro paraffin waxes. For example one of them, showing really high regression rates, reaches ductile rupture at a maximum tensile stress of 3 MPa.
Concerns in the use of paraffin-based mixtures are also caused by the repeatability of the manufacturing process and the good homogeneity of the solid grain. To better control the grain manufacturing process, an experimental facility was set up and a repeatable procedure was implemented to measure waxes density in softening and melting intervals. To improve the fuel grain homogeneity, the substitution of graphite, commonly used as additive to give a black color for increase the mixture absorptivity, with a black dye results to be successful and negligible mean regression rate losses in the considered oxidizer mass flux range were observed.
To sum up, all collected data establish a unique and useful database for the identification and measurement of the fundamental properties for liquefying fuels applicability in hybrid rocket engines. Thanks to this database, useful advices were identified: generally the micro paraffin based mixtures should be preferred for applications with large storage and operations temperature intervals, macro paraffin based mixtures should be preferred when really high regression rates are demanded and external loads are severe. For the studied application, one macro and one microcrystalline paraffin waxes were identified to be good candidates.
Finally, the proposed hybrid rocket design solution was compared in terms of gross mass with other existing chemical rockets for in-space applications having the same total impulse. Another comparison was performed in terms of ideal thermochemistry with different fuel/oxidizer couples. The obtained results and the preservation of all the features that are making these systems more and more studied and tested among the scientific community underline and support their real competitiveness.

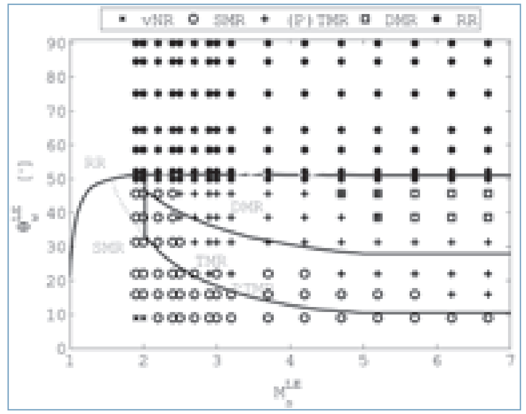
DYNAMICS OF CYLINDRICAL CONVERGING SHOCK WAVES INTERACTING WITH CIRCULAR-ARC OBSTACLES

Federica Vignati - Advisor: **Prof. A. Guardone**

Cylindrical and spherical converging shock waves can be used to attain high energy concentration at the focus point, thus making them interesting for applications where high temperature and pressure are required, e.g. in Inertial Confinement Fusion. Unfortunately, converging shock waves suffer from corrugation instabilities which hamper the front regularity and reduce the shock intensity with respect to the axisymmetrical case.
The stabilization of the converging shock wave may be obtained by means of the so-called "shock reshaping" i.e. by changing the shock shape into a more stable one. Literature points to the use of suitable shock-solid body interactions to reshape the converging cylindrical waves into stable prismatic ones.
The dynamics of the interaction between cylindrical shock waves converging in air and circular-arc obstacles is investigated here. Diverse geometric configurations (the obstacle number, thickness-to-chord ratio and leading edge radius), operating conditions (the pressure ratio across the discontinuity used to generate the shock wave and the gas conditions) and thermodynamic models (ideal and van der Waals gas thermal equations and polytropic and harmonic constant-volume specific heat) are devised from the reference configuration in which symmetric lenticular obstacles are introduced to reduce the shock-obstacle losses.
Numerical simulations are performed using the FlowMesh code, a Finite-Volume solvers for Euler equations. To reduce the simulations computational cost, a multi-domain approach is developed. The global domain is split into three, the Far Field- , the Obstacle- and the Focus-Region, dedicated respectively to the simulation of the cylindrical shock generation, of the reshaping and of the focusing. A technique which exploits the symmetry of the reshaping is developed for reducing the azimuthal extensions of the three regions (from a 360°-spanning domain to a (360°/N)-spanning one, that is the elementary domain), and for reconstructing a-posteriori the solution outside of the boundaries (fig. 1).
A novel method to trace the shock position during the time is also developed. It applies to solutions computed by means of numerical schemes which describe the pressure across the shock wave as a continuous ramp, and it accounts for the very complex shock-induced flow field. This criterion applies both to the evaluation of the shock position at a given time and to the determination of the time associated to the shock passage by a given radius.
The solution computed using these two new tools provides the same accuracy provided by full two-dimensional simulations and a reduction of the computational time of more than one order of magnitude.
Numerical results concern mainly two phenomena: one is the local shock-obstacle interaction, and the other the one is the complete reshaping and focusing of the shock wave.
The first phenomenon, i.e. the leading edge reflections, is studied here for the first time in the case of cylindrical shock waves interacting with cylindrical obstacles.
Diverse reflection types are observed and classified in accordance to pseudo-steady reflections criteria, highlighting the onset of similar patterns but for different configurations (fig. 2).
An analytic model is proposed for the description of the Regular Reflection unsteady evolution, which agrees fairly well with the numerical results.
The conditions for the Regular-Mach Reflection transition along the obstacle are determined.
The influence of the obstacle geometry is observed on the so-called "absolute" wedge angle, whereas it is absent on the "perceived" wedge angle; for both angles, M presents a null or negligible effect.



1. Numerical Schlieren of the 2D-2D domains overlapping zone



2. Leading edge reflection types, depending on the diverse values of M and N.

The trajectory of the Triple Point is traced for genuine Mach Reflections. The independence on the shock intensity and a pseudo-homothetic behavior of the trajectories with respect to the leading edge radius are observed. Due to theoretical considerations, a second order fitting is derived only on data sampled along the first half-chord, showing good accordance with data. Considerations on the offset of the trajectories from the reflecting surface suggest that the definition of Inverse Mach Reflection in presence of cylindrical converging shock waves is more complex than for planar shocks.
The second phenomenon is the reshaping of the shock. N is included among the investigated factors. Contrary to the behavior of leading edge patterns, which do not exhibit any dependence on M, the values of pressure P and temperature T attained at the focus point depend mostly on it. N is found to be rather influential, especially on P. The leading edge radius produces a weaker effect than other factors and, in addition, does not exhibit a particular trend. In all the configuration, larger thickness-to-chord ratios cause more relevant losses, and therefore, lower values of P and T. The configuration producing the highest temperature peak at the focus point consists of 16 obstacles with the lowest thickness-to-chord ratio and leading edge radius of 14cm, associated to a shock produced by an initial pressure ratio of 27.
Different shock patterns are observed after the leading edge reflection, including reflections over the upper symmetry boundary, post-trailing edge patterns and the "nozzle effect". Depending on the configuration and, therefore, on the resulting patterns, polygonal shock waves are observed with a time-dependent number of edges, switching among N, 2N, 3N and 4N configurations.
A general decreasing of the focusing effectiveness is highlighted by the study of the effects of the adopted thermodynamic model, if the van der Waals model is considered.
The applicability of the self-similarity assumption of the shock propagation is empirically tested in conditions for which theoretical models are not available. Pseudo-self-similarity exponents are computed for four diverse thermodynamic models, highlighting a trend between N and the self-similarity exponent.
The unsteady shock wave convergence is traced in the pressure-specific volume plane. One-dimensional results show an excellent accordance with Hugoniot adiabat. On the contrary, a departure of numerical data concerning two-dimensional shock waves from analytic curves is observed, due to fast but intense transient phenomena in correspondence of the shock reflections.