MECHANICAL ENGINEERING | PHYSICS | PRESERVATION OF THE ARCHITECTURAL HERITAGE | SPATIAL PLANNING AND URBAN DEVELOPMENT | STRUCTURAL, SEISMIC AND GEOTECHNICAL ENGINEERING | URBAN PLANNING, DESIGN AND POLICY | **AEROSPACE ENGINEERING** | ARCHITECTURAL COMPOSITION | ARCHITECTURE, BUILT ENVIRONMENT AND CONSTRUCTION ENGINEERING | ARCHITECTURE, URBAN DESIGN, CONSERVATION OF HOUSING AND LANDSCAPE | ARCHITECTURAL, URBAN AND INTERIOR DESIGN | BIOENGINEERING | DESIGN | ELECTRICAL ENGINEERING | ENERGY AND NUCLEAR SCIENCE AND TECHNOLOGY | ENVIRONMENTAL AND INFRASTRUCTURE ENGINEERING | INDUSTRIAL CHEMISTRY AND CHEMICAL ENGINEERING | INFORMATION TECHNOLOGY | INTERIOR ARCHITECTURE AND EXHIBITION DESIGN | MANAGEMENT ENGINEERING | MATERIALS ENGINEERING | MATHEMATICAL MODELS AND METHODS IN ENGINEERING

PhD Yearbook | 2018

DOCTORAL PROGRAM IN AEROSPACE ENGINEERING

Chair:
Prof. Luigi Vigevano

The aim of the course is the acquisition of the high level competence required to carry out innovative research and/or state of the art advanced applications in industries, public or private research centers, Universities or public and service companies in the area of aerospace engineering, including all the fields associated to it. The level of the course allows the graduates to compete in a European and international environment.
The course is three years long, requiring 180 credit points (ECTS), including possible study-abroad periods and internships in private or public institutions. The program and credits are divided in three main educational areas:

1) Main courses (30 credits), during the first year: courses examining fundamental subjects (problems, theories and methods) of the scientific research in the disciplinary areas involved;
2) Elective courses and training on specific themes (30 credits), gained in the second year: specific and personalized educational programs aimed at a more deep overall knowledge and to master the techniques adequate for the subsequent development of the doctoral thesis, plus seminars focused on specific and advanced methods;
3) Development of the Doctoral Thesis (120 credits): the thesis is developed within the Department or, in some cases, in other institutions, in close contact with the Department. The thesis is started immediately (20 credits in the first year), and developed in the second (40 credits) and third year (60 credits) of the doctoral program.

If the candidate has a background curriculum lacking some introductory knowledge required for the Doctorate, the Faculty will ask to recover such knowledge, with the assistance of the tutor.
The same Faculty will verify afterward the overcoming of whatever was lacking during the annual meeting of admission to the second year of the course.
The course program related to point 1 does not follow a rigid scheme. So, besides widening the basic scientific culture of the candidate, it will take into consideration also the objectives and the core topics of the candidate's thesis. Again the program outlined at points 2 and 3 will try to consider general cultural requirements as well as what is deemed to be more specifically related to thesis subject, as agreed between the candidate and the Faculty. For the activities of type 2 and 3 a study period in a foreign country is allowed, even strongly suggested perhaps. Its duration should range from a few weeks up to one and a half years. The related activities should be carried out in well known and qualified scientific institutions (universities, research centers, etc.), and well contribute to the cultural and scientific achievements of the research.
Due to the amplitude and interdisciplinarity of the aerospace sector, the professional skills achievable will span a wide area and not cover just a specific topic.
The educational goals will create high level specialists in the domains of: helicopters and rotary winged vehicles, fixed winged vehicles and space vehicles.
In this context, a more specific competence can be gained either in a single or in the integration of special subjects such as: dynamics and control, fluid mechanics, systems and equipment, flight mechanics, passive structural safety, intelligent and automated systems, structures and materials.
In this respect, some examples of professional skills achieved in the course of the past 24 years of doctoral program are here reported:

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

Since its foundation, 24 years ago, the doctoral course on Aerospace Engineering graduated more than 70 PhDs.

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ACTIVE DISK BRAKING CONTROL SYSTEMS ANALYSIS AND DESIGN FOR AIRCRAFT

Mohammadali Aghakhani Lonbani – Supervisor: Gianluca Ghiringhelli

The main objective of an Active Braking System (ABS) is to control the wheel slip to maximize the friction coefficient between the wheel and the run-way, irrespective of the runway surface condition. The introduction of new braking system for aircraft such as the hydro- or even electro-mechanical brakes used in brake-by-wire (BBW) system, which has a more continuous braking operation with a high level of accuracy, necessitates the continual review and improvement of the active braking system. From the control point of view, therefore, more refinement of the ABS operation could be also achieved with the improved hardware components.
Here are current research objectives and motivations:

- Reviewing different controller strategies among the available control systems and also among the control systems concepts to design newer control strategies for the aircraft application in case of rigid and flexible Landing Gears (LG).
- Gear-walk instability due to flexible struts of landing gears may cause excessive wear of the aircraft components and lead to the catastrophic accidents. It also affects the fatigue life of the aircraft structure, comfort of the passengers and cargo safety. The research tries to figure out how a designed controller for a conventional (rigid strut) landing gear model in an active braking when it is implemented on a landing gear with a flexible strut, and also to compare the results with a controller designed specifically for the flexible strut landing gear model.
- Investigating how different strategies act when they deal with much complicated models of a full aircraft with fuselage body effect, flexible landing gear strut and dynamic tire ground interaction under aerodynamic forces such as lift force.
- Studying the sensitivity closed-loop system performance with uncertain systems parameters values and investigate effects of an interface system (i.e. actuator dynamics).
-

To answer the above questions and reach the objectives, a new Multi-Phase Scheme Control (MPSC) is designed to fulfill stability criterion of this time-varying system. Unlike the previous designs in the literature, an estimated value of the slip rate in combination with measured angular acceleration of the landing gear wheel are used. The simulation results showed the success in the stability of close-loop system to brake actively around a desired value of the wheel slip in a scenario for a single and rigid strut wheel-tire system with half of fuselage vertical forces on it. Another question to answer is that if a new controller for a newer model (LG with flexible strut) is necessary or the previously designed controller MPSC is adequate for active braking. To answer the question, the Second-Order Sliding Mode Controller (SOSMC) is designed which is compatible with the flexible model states and dynamics. The controllers have been tested to actively brake on the same flexible model then their performance shows the SOSMC is much suitable in smooth braking than the MPSC braking. So the promising results justify the importance of having relative

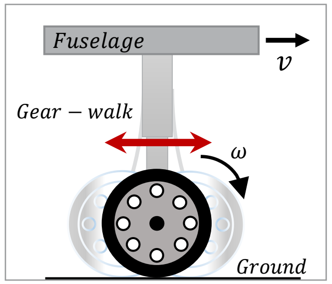

Fig. 1 - Landing gear system with a flexible strut

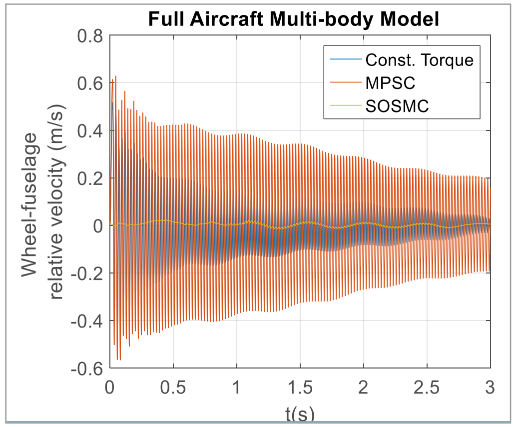

Fig. 2 - Gear-walk damping of active and passive controllers

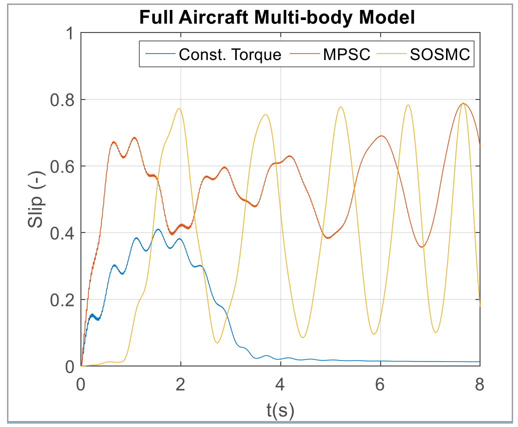

Fig. 3 - Slip rate regulation at 0.5

motion information into account.
In a much sophisticated full aircraft model with/without flexible strut on MLGs, both active control approaches have been implemented and performances are tested. It is quite important to emphasize that the path of control systems design has been started from simplified models written by ODEs. The behavior in single and flexible LG models are also repeated in the models (Simple aircraft and aircraft with flexible strut LG models) in MBDyn multi-body code.
The only difference in behavior in amplitude and frequency of oscillations can be justified by the difference in friction models used in two software, but general behavior is following the same way not only in constant braking but also in active braking by both above controllers' approaches. The added value of this study is presenting this possibility that how new terms of dynamics such as fuselage pitch degree of freedom and also lift force could affect the braking response and consequently the gear-walk damping performance. The presence of lift shows an increasing trend in braking torque in all the simulations to regulate a constant slip rate reference.
The success of SOSMC in keeping the wheel gear-walk oscillation low can give a room to tune the controller and modify its dynamics to become even faster in torque response while the amplitude of oscillations is still inside an acceptable range. This can also show a different performance efficiency in active braking.

TRAJECTORY OPIMIZATION OF LIMITED CONTROL AUTHORITY SPACECRAFT IN HIGH-FIDELITY MODELS

Diogene Alessandro Dei Tos - Supervisor: Francesco Topputo

Gravity pulls are normally treated as undesired perturbation actions, and thus zeroed by a control system. In this work, gravity is rather leveraged to achieve space mission objectives with ever more stringent requirements on costs, time, and robustness. This work focuses on methods for harnessing gravity in favor of space mission designs. Attention is placed in the exploitation of high-fidelity modeling, the realm in which low-energy low-cost transfers exist. Flying in highly nonlinear gravity fields is appealing due to the unique features that can be achieved if these models are properly exploited. Lagrange point orbits, ballistic captures, low-energy transfers, invariant manifolds, etc., are mere examples of what can be done by using the natural motion of a spacecraft subject to two (or more) gravitational attractions that are comparable. Beside generating orbits that cannot be designed in the classic two-body problem, multi-body models may enable considerable propellant savings, launch window widening, and overall safety increase. This is achieved by a wise exploitation of the high sensitivity in initial conditions (i.c.), allowing spacecraft characterized by very limited control authority to accomplish such transfers.

A hierarchy is established for several astrodynamics models of increasing complexity and a way is proposed to unify the description of different gravitational models with 13 time-dependent coefficients. A novel methodology is proposed to compute ballistic captures in the planar elliptic three-body problem (ERTBP) for small eccentricities. The nonlinear nature of the gravitational dynamics is exploited to generate quasi-periodic motion in a solar system model. The output set of quasi-halos is used as baseline for the mission analysis of low-resources spacecraft. The Earth–Moon system is analyzed as a dynamical laboratory to perform test on General Relativity. The Sun–Earth saddle point (SP) is characterized and many optimal trajectories that fly through this region are found with a series of impulsive maneuvers, later translated into finite burn arcs with a direct pseudo-rendezvous optimization technique. The contributions to the field of this PhD dissertation can be divided into three parts: (1) Exploitation of the chaotic natural dynamics to compute ballistic capture solutions with a novel approach, (2) Challenges and solutions to design a robust trajectory for low authority platforms, and (3) Enabling the Earth–Moon system as a dynamical laboratory for exploration.

Ballistic captures in the Sun–Mars case

A novel methodology is proposed to compute ballistic capture trajectories in the ERTBP. Periodic motion of the circular problem is used as a generator to trigger ballistic capture mechanisms in the Sun–Mars case, where the capture ratio improves by two orders of magnitude when compared to existing works. States are mapped from the circular to the elliptic problem with a single-parameter transformation and the initial true anomaly of the P_1–P_2 system is parameterized. A large-scale survey is completed using 3 families of periodic orbits (POs and generating 37.2 million ballistic captures that are evaluated and classified for potential use. This methodology shows that ballistic captures originating from low osculating eccentricities and performing many revolutions around P_2 exist in abundance. A sample of a persistent trajectory is shown where P_3 stays near Mars, in a weakly captured state, for more than 90 years. Feasibility in the continuation process of weak capture solutions towards a more realistic solar system environment is demonstrated. A sample solution generating from a g_2 family is shown in Fig. 1b together with its altitude and energetic trends (Fig. 1c). Fig. 1a shows the complete topographic map generated from an i.c. belonging to the g_2 family of Mars-circulating periodic orbits.

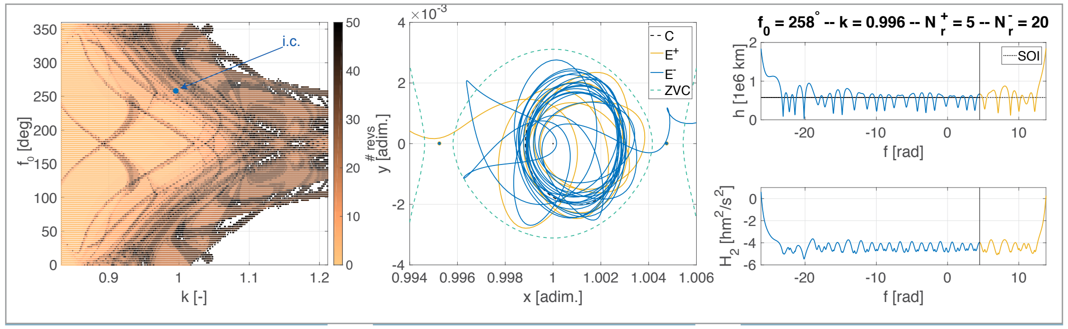

Fig. 1a - g_2 stable solutions.

Fig. 1b - Capture orbit sample

Fig. 1c - Altitude (top), energy.

Fig. 1 - Samples of ballistic captures generating from simple periodic orbits in the Sun-Mars system

Astrodynamics for a CubeSat: challenges and solutions

The Lunar Meteoroid Impacts Observer (LUMIO) mission is proposed to (1) Advance the understanding of how meteoroids evolve in the cislunar space by observing the flashes produced by their impacts on the Moon, and (2) Characterize meteoroids flux impacting the lunar surface. A trade-off analysis is done on the selection of LUMIO orbit. Transfer and station-keeping (S/K) costs and geometrical stability are traded for a set of operative orbits computed in the roto-pulsating restricted *n*-body problem (RPRnBP): a tested and validated high-fidelity solar system model. Sample solutions are shown in Fig. 2.

The S/K cost is estimated by employing the Target Points Method. A Monte-Carlo simulation is performed with 10,000 samples, considering the impact of the injection, tracking, and maneuver execution processes on the nominal orbit. The transfer cost is computed by means of a direct optimization technique that patches positions along the parking orbit and the target quasi-halo stable manifold in forward/backward times.

The Earth–Moon system as a dynamical laboratory

Evidence is mounting on the importance of the gravitational SP. These are locations where the net gravitational accelerations balance. Regions about the SP present clean, close-to-zero background acceleration environments where possible tests of the General Relativity can be conducted. Among the SP in the solar system, the Sun–Earth one seems appealing due to its relatively easy accessibility: it is located at approximately 258,800 km from the Earth, along the Sun–Earth line, between the Sun and the Earth. Although they are remarkable locations in the solar system, SP are still unexplored. Their location and non-equilibrium nature suggest that flying by the SP can be done using highly nonlinear, under-actuated orbits as opportunistic mission extension of spacecraft already about the Lagrange points.

The Sun–Earth SP is fully characterized in terms of geometrical and dynamical properties. A parametric analysis is performed to consider spacecraft initially on several Lagrange point orbits having different out-of-plane amplitudes. Orbits are designed in the RPRnBP, the focus is on solutions with low Δv budget achievable with ultra-low thrust propulsion and that experience one or multiple passage through the SP.

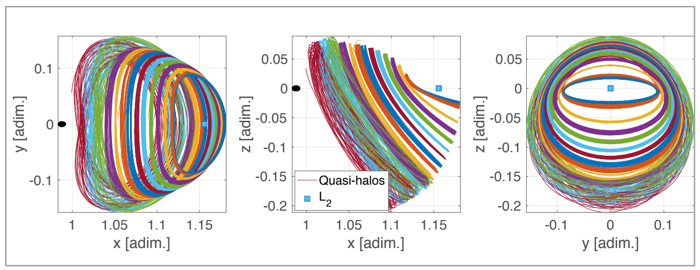

Fig. 2 - Earth–Moon L2 quasi-halos in the roto-pulsating frame

DESIGN AND VALIDATION OF ACTIVE GUST LOAD ALLEVIATION SYSTEMS FOR AIRCRAFT

Federico Fonte - Supervisor: Sergio Ricci

Co-Supervisor: Paolo Mantegazza

Since the beginning of the aviation, great attention has been paid to the effect of atmospheric gust and turbulence on the aircraft structure, in order to evaluate and possibly limit their effect on the ride qualities and on the structural loads. This attention has become even larger in the recent years due to the development of digital control systems, the improvements of the actuation systems and the increase in flexibility of the airframes. In the future a even larger attention will be paid to the gust and turbulence encounter since the slender, lightweight and very flexible structures that are designed to increase the aircraft efficiency are also very sensitive to gust and turbulence excitation.
A large number of theoretical studies on the phenomenon have been performed with some applications to experimental aircraft, but there are few experimental validations of the performances of the control systems, that are complicate by the necessity of reproducing the structural flexibility of the aircraft, the flight condition, the actuation system and the atmospheric turbulence. This thesis work focused on a complete evaluation of the application of active control systems for gust load alleviation, considering the numerical modelling of the aeroelastic system, the design of the control system and presenting the results from a wind tunnel test campaign devoted to the validation of such systems. The possibility to develop dedicated control surfaces for load alleviation purposes was also investigated, analysing the possibility to combine the gust load alleviation system with a span increase.
The numerical model of the aeroelastic system was generated with the use of the capabilities already implemented in the NeoCASS tool, a tool developed at Politecnico di Milano for the aeroelastic analysis of aircraft at the conceptual design phase. In this thesis work an extension of the capabilities of NeoCASS was introduces, regarding the representation of the system in state-space form. The state-space form for the definition of the aeroelastic system is the best suited for the design and analysis of control systems, but need to be generated through an approximation process starting from the more traditional frequency-domain representation. The capability to perform and control this approximation procedure was introduced in NeoCASS along with the possibility to analyse the stability and the response of the aeroelastic system. A bridge between the aeroelastic analysis and the flight dynamic analysis of the response was also introduced by allowing the reformulation of the state-space aeroelastic system to the flight dynamic standard, allowing the use of a single model for the design of structural control system and flight control systems.
Based on the numerical state-space model of the aeroelastic system the gust load alleviation control systems were designed, considering two different strategies for the design of the controller:
A Static Output Feedback (SOF) controller, which is an optimal controller constrained to have an algebraic structure. It has the advantage of a simple implementation allowing high controller frequencies, in addition it is easily schedulable for the operation at different flight conditions.
A Recurrent Neural Network (RNN) controller, based on the use of two different recursive neural networks, one identification network used for the identification of the system and the second one used for the computation of the optimal control input. The two networks are trained online during the operation of the controller thus obtaining an adaptive control system.
Both control strategies are quite flexible and allows for the design of a multiple-input multiple-output controller, for both of them two different structures were considered.
A feedback strategy based on the use of accelerometric signals on the aircraft wing and fuselage.
A feed-forward strategy based on the direct measurement of the gust by means of an angle of attack vane placed at the aircraft nose. The direct gust measurement allowed to avoid the delays associated with the dynamic of the structural response, thus the controller can operate in advance to alleviate the gust input.
Numerical results show the effectiveness of both control strategies, for the SOF controller a similar level of load alleviation was obtained with the feed-forward and the feedback controllers.
For the RNN controller, however, better results were obtained with the feed-forward scheme, thanks to the higher correlation between the measured signal and the wing loads.
The SOF control law was also evaluated experimentally in a series of wind tunnel tests performed within the GLAMOUR project, part of the Clean Sky research program. The project consisted in the realization of an aeroelastic wind tunnel model of a regional aircraft equipped with three movable control surfaces: inner and outer aileron and elevator. Since only symmetric conditions were examined only the left half of the aircraft was generated, placing it on the floor of the test chamber and allowing the rigid pitch rotation and plunge displacements. The gust was generated using a series of vanes placed at the inlet section of the test chamber and rotated around their quarter-chord axis. Strain gauges and accelerometers were used to measure the structural response of the model, while instead of using the angle of attack sensor, a virtual measurement of the gust was used based on measurements taken in characterization tests for the gust generator.

Fig. 1 - GLAMOUR model in wind tunnel.

NONLINEAR H∞ FILTERING FOR ATTITUDE ESTIMATION PROBLEMS IN AIRCRAFT AND SPACECRAFT CONTROL

Muhammad Farooq Haydar - Supervisor: Prof. Marco Lovera

Nonlinear control theory has a long history of developments which use matrix Lie groups to solve control and estimation problems. These nonlinear control and estimation problems on the Lie groups have traditionally been formulated as optimization problems. This work seeks to investigate the suitability of Lie groups (namely, the unit circle (S1) and SO(3)) for use in H∞ sub-optimal filtering problem through satisfaction of a sufficient condition. Although it has been noted by Krener (1997) that the worst-case estimator (i.e., H∞ filter) can be thought of as a generalization of minimum energy estimation of Mortensen (1968), in this work this notion has been made concrete on the unit circle and SO(3) by deriving the conditions for nonlinear H∞ filtering and comparing it with the recently proposed minimum energy filter formulations.
The interest in this problem is motivated by several applications, especially the potential application to multi-rotor flight vehicles operating in different modes and diverse operating conditions.
In this work, attitude estimation problems in aircrafts and spacecrafts have been considered and addressed using nonlinear estimation techniques. The primary problem considered in this thesis was to develop nonlinear H∞ filtering algorithms directly on the unit circle and SO(3) which respect a given upper bound on the energy gain from initial estimation error and the disturbances to a scalar performance index which should be chosen to be a function of the estimation error. The solutions on the unit circle and on SO(3) have been worked out starting from the dissipation inequality, by taking the normalized Euclidean distance on unit circle and SO(3) as the generalized estimation error. By assuming a positive semi-definite storage function and applying the extreme conditions for the disturbances, the Riccati-type inequalities have been obtained which give sufficient conditions on the evolution of the filter gain solving the sub-optimal H∞ filtering problem and thus guaranteeing a given upper bound on the error gain. The proposed solutions have been compared with the extended Kalman filters and the minimum energy filters through numerical examples and the results suggest that the performance of the proposed filters is encouraging. The fact the proposed filters admit a positive definite (and symmetric for the matrix case on SO(3)) solution at all times and that their performance is relatively less affected by the initial conditions and the variation in noise intensities, indicates the robustness and suitability of this approach to filtering especially for cases such as miniature UAVs.
Optimal filters such as the minimum energy filter and the Multiplicative Extended Kalman Filter (MEKF) were found to be performing better than the proposed H∞ filter when the filters are perfectly tuned using the true knowledge of the noise/disturbance levels. However, for the more practical case of uncertain variations in the noise levels, the proposed H∞ filter was found to be performing better than the minimum energy filter and the Kalman filter. The measurement and estimation errors averaged over 300 Monte-Carlo runs with random initial conditions and 50% variation in process and measurement noise standard deviation are reported in Figure 1. The minimum energy filter was found to be prone to numerical instabilities when initialized with a large initial gain but low initial estimation error, therefore after repeated numerical blow-ups it was observed that a reasonable value of initial gain for any random initial estimation error is 0.1 × I3x3, which is used here. The rest of filters are, however, initialized with a higher initial gain (i.e., 10 × I3x3). The proposed H∞ filter seems to perform very well in transients as well as at the steady state, while it was never found to encounter any instabilities in all these cases contrary to the case of the minimum energy filter.
The second main problem was to workout practical sensor fusion solutions for high accuracy attitude determination problem for line-of-sight steering of a spacecraft. An unconventional magneto-hydrodynamic sensor (ARS) was selected to complement the traditional sensors at frequencies higher than the bandwidth of gyroscopic and star-tracking sensors. Parametric models of the ARS and their noise spectral densities were obtained, and their uncertainties, along with the temperature and hardware effects, were modelled. These detailed models were implemented in Simulink to construct a high-fidelity simulation software, while the parametric models were used to develop online and offline filters. Initially, a local (linear) filtering problem was solved using a multi-rate filter which was adapted to extrapolate the star tracker output to compensate for the inherent delay (100~150 ms) in the star tracker output. This local filtering problem was extensively tested in the simulation environment developed in the Simulink and demonstrated favourable performance. This local filtering problem was later extended to semi-global problem and was addressed using the MEKF, the minimum energy filter and the nonlinear H∞ filter proposed earlier in this work. Two types of solutions were considered, firstly a solution based only on the ARS and the star tracker was developed and eventually a more complete solution based on the ARS, rate gyro and the star tracker was proposed. In order to mitigate the effects of measurement delay, the measurement of star tracker was extrapolated in both of these solutions using an output predictor designed on the SO(3). The results from the simulations suggested that MEKF offers better overall trade-off between convergence and the steady state tracking error, while geometric filters (i.e., the minimum energy filter and the H∞ filter designed on SO(3)) appeared to lose their edge over the MEKF for this case.
Finally, the relative attitude estimation problem for the case of uncooperative objects orbiting in space was tackled by reformulation and adaptation of different potentially promising filtering algorithms. Different cases for Monte-Carlo simulations were considered, which covered the effects of variations in initial conditions, noise intensities, the angular velocity and the inertia matrix of the object. Extensive Monte-Carlo simulations showed that the minimum energy filter can yield slightly better performance than the MEKF if the order of the angular velocity of the object is known and is used in the filter tuning. The second order minimum energy filter performs remarkably well and tends to approach the performance levels demonstrated by the filters which have access to the angular velocity of the uncooperative case. However, if the inertia matrix of the uncooperative object is not known or if there is large uncertainty associated with the knowledge of the inertia matrix, a proposed variant of the second-order filter, named second-order minimum energy filter (without dynamics), outperforms the second-order minimum energy filter.
The results presented in this thesis can be extended in several directions, and the obvious extension of the H∞ filter on SO(3) to the vector measurements case is already underway. The proposed H∞ filter can also be extended to the Special Euclidean Group (SE(3)) and to other Lie groups.

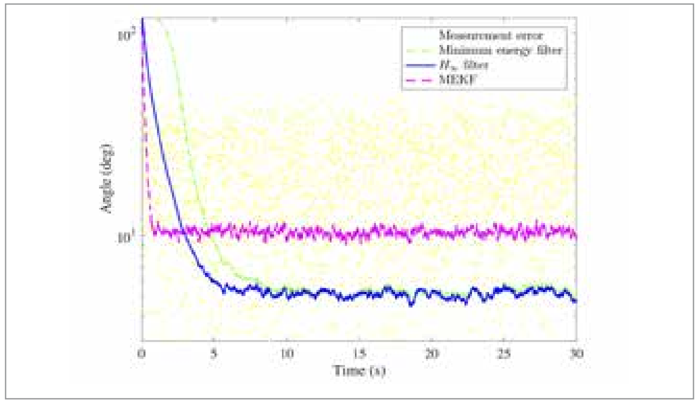

Fig. 1 - Measurement and estimation errors of the attitude filters.

GEOMETRIC TRACKING CONTROL OF UNDERACTUATED AND THRUST VECTORING UAVs

Davide Invernizzi - Supervisor: Prof. Marco Lovera

Multirotor Unmanned Aerial Vehicles (UAVs) gained lots of attention in the last decade thanks to the broad field of applications in which they can be employed.
In the standard configuration, the propulsive system consists of direct-drive fixed pitch propellers which are installed in a co-planar fashion and pairwise to cancel the net aerodynamic reaction torque, in hover, with counter rotating rotors. This mechanical simplicity has established their success both in commercial and research applications. Nevertheless, these vehicles are inherently underactuated platforms as the propulsive system can deliver a force only along a fixed direction of the aircraft frame. As a result, this design limits the vehicle maneuverability and interaction capability: position and attitude tracking requirements cannot be fully decoupled and it is not possible to exert a net force in any direction of the space.
The increasing demand of complex and challenging applications involving aerial vehicles has led to the design of novel configurations to overcome the intrinsic maneuverability limitation of underactuated platforms. By designing an actuation mechanism that can change the direction of the thrust with respect to the aircraft frame, a net force can be produced in the three dimensional space.
This thesis focuses on the modeling and control of multirotor UAVs with thrust vectoring capabilities (Figure [1]). In the first part, a multi-body model of a general aerial vehicle with tiltable arms is developed within the framework of geometric mechanics. A simulation platform based on a modular design is implemented with the Modelica modeling language. This object-oriented approach allows to build articulated systems by assembling the constitutive components and to easily include models of increasing complexity when available. Based on an approximated model of the multibody system, the full pose trajectory tracking problem is addressed in the second part of the work. Different degrees of actuation are considered, starting from the assumption of full actuation. A solution based on geometric control theory and a quasi time optimal approach is devised. Then, a reduced tracking control problem, compatible with the co-planar platform underactuation, is tackled. This is instrumental in the design of the control strategy for platforms with limited thrust vectoring capabilities, which is the main contribution of the thesis. The most relevant cases of thrust vectoring limitations are reviewed according to a classification proposed in the literature. For these cases, only a partial decoupling of position and attitude tasks may be realized: the full pose (position and attitude) tracking problem is not solvable under thrust vectoring limitations (Figure [2]).
Much literature is devoted to the trajectory tracking problem for the standard co-planar rotors configuration but a few works address thrust vectoring platforms. We propose a novel technique to deal with the thrust vectoring limitations. First of all, we show that the complete (position and orientation) tracking of a desired trajectory in SE(3) is not feasible if the thrust can be delivered only in a finite region around the vertical body axis of the vehicles. However, by relaxing the attitude tracking requirements, position tracking can be achieved. Indeed, ensuring position tracking is mandatory in most application involving UAVs in order to guarantee safe operations.
With respect to the solutions proposed in the literature, our approach introduces the concept of the attitude planner, a dynamical system that is in charge of prioritizing the control objectives. Specifically, it modifies the desired reference attitude to guarantee that the platform can deliver, according to the specific actuation mechanism, the control force required by the position tracking objective. We prove that under a specific condition, also the desired attitude motion can be exactly tracked. Then, we study the stability of the corresponding non-autonomous system, with the attitude planner in the loop. The proposed control law guarantees global asymptotic tracking for the position subsystem under mild assumption on the reference trajectory. When the attitude reference is trackable, global tracking for the attitude subsystem can also be easily concluded by exploiting existing control laws.
All the control designs have been tested on the simulation platform to assess their robustness against unmodeled dynamics and external disturbances.
The final goal of the thesis was to implement and validate the control laws on a co-planar quadrotor and on a quadcopter tiltrotor (Figure [3]) that was developed in our research Laboratory (ASCL). Several experiments have been conducted indoor by exploiting a camera motion system to recover information about the state of the aerial vehicles. We have considered several maneuvers to assess the performance and robustness of our control designs in different scenarios.

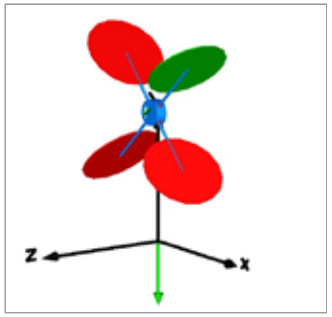

Fig. 1

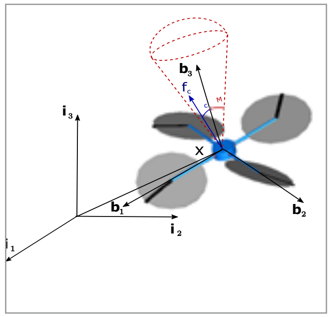

Fig. 2

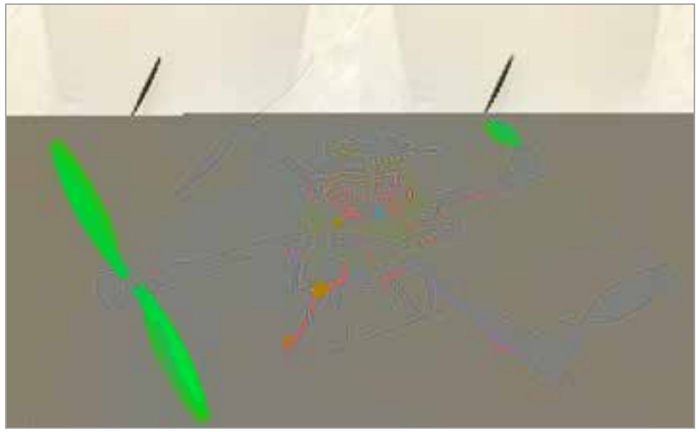

Fig. 3

NON-IDEAL COMPRESSIBLE FLUID THERMODYNAMICS OF MIXTURES: MEASUREMENTS AND MODELING

Luuc Keulen - Supervisor: Prof. Alberto Guardone
Co-Supervisors: Prof. Andrea Spinelli, Dr. E. Mansfield

Many processes operate with working fluids made of multiple components in multiple phases (e.g. chemical reactions, distillation, thermodynamic power cycles, refrigeration cycles and heat pump cycles). To improve the design of process equipment and increase the uptake of environmentally friendly fluids, a solid understanding of mixture properties is necessary. The choice of the working fluid is driven by different requirements arising from the specific application. A great variety of substances, with different thermo-physical properties, are used in industry for various applications. These fluids range from simple fluids to heavy fluids formed by complex molecules. Among the fields where mixtures can possibly increase the efficiency are power cycles for sustainable energy conversion, an example is the organic Rankin cycle (ORC). Many of these power cycles for sustainable energy conversion operate in the non-ideal thermodynamic region, close to the liquid-vapor saturation curve and the critical point, where the actual thermodynamic behavior of gases can deviate significantly from that predicted by the ideal gas law. The understanding of non-ideal compressible fluid thermodynamics of mixtures will enable to improve existing industrial processes and machinery for ORCs. The scientific interest is not only limited to ORCs or other power cycles operating with organic substances. The scientific interest extends to a wide range of application where fluids and mixtures operate in the non-ideal thermodynamic region.

This work presents original research in the field of non-ideal compressible fluid thermodynamics of mixtures. The study is focused on mixtures of fluids with high molecular complexity, these are complex siloxanes currently used as heat transfer fluids and in ORCs and perfluorocarbons. The presented work is concentrated in three directions and aims to (i) gain more knowledge of the non-ideal thermodynamic behavior of mixtures composed of molecular complex fluids in the non-ideal gas region, (ii) the development of accurate thermodynamic models for mixtures of linear siloxanes, (iii) and determine the thermal stability and decomposition products of linear siloxanes. A better understanding of these aspects can improve the study of gas dynamic phenomena and the use of mixtures in experiments and industrial applications.
In the first part of the research a fundamental research on the speed of sound behavior for binary mixtures of molecular complex fluids (e.g. linear siloxanes and perfluorocarbons) in the non-ideal thermodynamic region is conducted. The speed of sound behavior is qualitatively investigated using the polytropic van der Waals model and verified using the Helmholtz energy equation of state. Non-monotonic behavior of the speed of sound is observed upon varying the composition of the mixture. The non-monotonic behavior of the speed of sound is more evident if the molecular complexity of each pure components of the mixture differs. This non-monotonic behavior is caused by the interaction between the different components in the mixture.
In the second part measurements are performed to determine the bubble-point pressures for three binary mixtures of linear siloxanes, Hexamethyldisiloxane (MM) with Octamethyltrisiloxane (MDM), Decamethyltetrasiloxane (MD_2M), and Dodecamethylpentasiloxane (MD_3M). Large uncertainties are observed for the lowest temperatures, an extensive analysis of the uncertainties is conducted and concludes that these large uncertainties are mostly caused by the effect of impurities of non-condensable gases. For each binary mixture new binary interaction parameters are fitted for the multi-fluid Helmholtz energy model using the obtained bubble-point pressure data.

To conclude, an experimental test-rig is designed and commissioned for the determination of the thermal stability limit and decomposition products of pure fluids and mixtures. An expected feature of mixtures of siloxanes is that they exhibit a higher thermal stability limit than their pure components, due to the redistribution process occurring at high temperature, where more complex molecules decompose into simpler molecules, which then recombine again into the more complex molecule. This redistribution and therefore the possible increase of the thermal stability temperature can enhance the use of complex molecular fluids for experimental and industrial applications. Results are obtained for the pure fluids of MM and MDM. For both fluids minimal decomposition products are observed using chemical analysis of the liquid and vapor phase. Though formation of other linear and cyclic siloxanes as decomposition products are observed as well as volatile gases in the vapor phase.

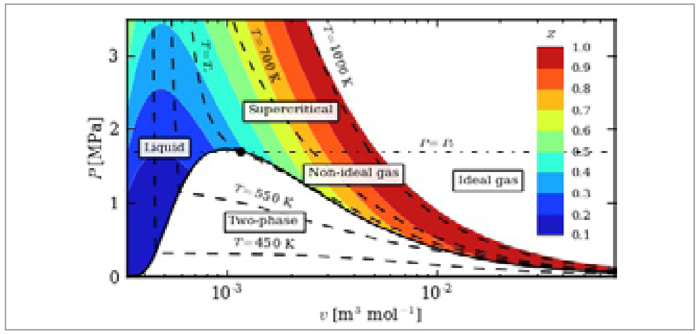

Fig. 1

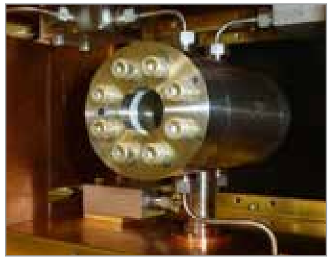

Fig. 2

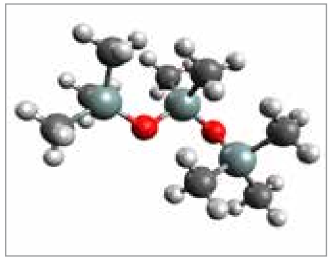

Fig. 3

METHDOS AND TECHNOLOGIES FOR ACTIVE CONTROL OF DYNAMIC LOADS ON HIGH PERFORMANCE AIRCRAFT

Sheharyar Malik - Supervisor: Sergio Ricci

A series of controllers ranging from static output feedback to dynamic output feedback are presented to attenuate the buffet loads on the wing of the high performance aircraft. The application of controllers is presented for two aircrafts, i.e. Aluminum Fighter Aircraft (AFA) and X-DIA commercial aircraft. Experimental validation is also performed for X-DIA aeroelastic wing at De-Ponte wind tunnel, Politecnico di Milano. The research presents a multidisciplinary approach starting from numerical analysis of Aeroelastic structure on MSC/NASTRAN to the experimental validation of the developed control laws in MATLAB. Inhouse software, MASSA is used to extract the state space model that captures the true dynamics of the aeroelastic structure.
High performance aircraft performing maneuvers at high turn rate and flying at high angle of attack causes the upstream flow to get separated from the leading-edge extensions and engine nacelles. The separated unsteady and swirling flow moves downstream and it immerses the wing and the vertical tail of the aircraft in the disturbed flow. The flow has sufficient amount of energy in a frequency bandwidth that excited the structural modes of the wing and vertical tail of the aircraft. The phenomenon is more evident and common in advance high performance aircraft as they compromise on structural stiffness.
In the early days, structural augmentation was used to address the issues posed by aeroelasticity. However, with the advent of advanced control techniques and instrumentation, it became possible to alleviate the aeroelasticity issues by active control schemes. The solution to the aeroelastic problem is provided by active control schemes that are named as collocated, Identical location of accelerations and forces, LQG and LQR methods. In the presented research, static output feedback controller based on newly developed second order quadratic formulation is applied to alleviate the buffet loads on the wings of the aircraft. Coupled Lyapunov equations are used along with heuristic optimization techniques that are devotedly developed for the optimization of feedback gain. Active aeroelastic technique based on robust control is seldom used although it is mature field analytically but practically the stringent requirements posed by reduced state space order while capturing the true dynamics of the aeroelastic system, time delay associated during real time operation and performance specifications to meet the actuator bandwidth puts constraints on the performance of the system guarded by robust controllers. In this dissertation, robust control based on h-infinity method is also applied to quantify the robustness of the system under uncertainties.
Two active control schemes are proposed for Aluminum Fighter Aircraft (AFA) based on static output feedback control. First technique is related to unconstrained movement of actuators while the second technique is optimizing the actuator movement for active control of buffet loads. The results demonstrated the significant attenuation, 82% reduction in the first bending and 45% reduction in the first torsion mode for the first technique. The attenuation is decreased to 75% and 35% for the first bending and torsion modes, respectively when the active controller also provided the optimized actuator movement. The variance decrease of actuator movement is reduced by 5 times (1.8179mm) as compared to unconstrained actuator movement.
Six active aeroelastic control schemes are developed for X-DIA commercial aircraft. The schemes are named as Buffet load Mitigations Systems (BLMS). The dedicated wind tunnel aeroelastic model of X-DIA wing is used as a benchmark to validate all the developed controllers. The first scheme developed is based on modal control provided by static output feedback control. The developed control law (BLMS I) attenuated the first bending and first torsion mode along with additional damping added to these modes. The results demonstrated the attenuation of 18dB and 10dB for the first bending and first torsion modes. Aspect of suitable actuator/sensor configuration for modal attenuation is dealt in BLMS II. Frequency response, power consumption, effectiveness and Hankel singular values are used experimentally to rank the performance of actuators in specific mode of interest. Trailing edge outboard outperformed other control surfaces for bending mode attenuation, trailing edge inboard is characterized as the most suitable surface for torsion mode attenuation.
To make trailing edge outboard as the single most efficient control surface, novel aspect of adding filters to the output feedback for participating frequency is analyzed in BLMS III. The state space system of notch and peak filters is selected as such to not disturb the overall dynamics of the system while showing enhancement in the attenuation. The results showed improvement of 1dB in the torsional mode when operated by trailing edge outboard alone.
BLMS IV is dedicated towards the robustness of optimization algorithm and subsequently for the robustness of the complete X-DIA aeroelastic system. The numerical procedure followed for parametric uncertainties in the actuators and sensors showed robustness as the same initiation point and termination criteria is held during all the cases. However, the numerical procedure predicted the decrement of 2 to 2.5dB for uncertainty of 20 % in the instrumentation.
BLMS V opted the advanced robust stability and robust performance criteria derived from Mu synthesis for the existing static output feedback controller. As a consistent procedure, the reduction of the order of aeroelastic system is achieved by balanced stochastic truncation method, model reduction exhibited significance simplification without loss of accuracy. Model reduction is followed by the 20% uncertainties in the system, to be accounted for the robust performance and robust stability of the system. The stability margin of 1.420 – 1.492 is achieved with structured values less than one for the frequencies in range of interest.
BLMSVI is dedicated towards achieving globally robust control for the aeroelastic system, in this context H-infinity and Mu Synthesis controllers are devised for the aeroelastic system.
The aspect of model reduction procedure is successfully applied by decomposing the flexible body modes of the aeroelastic system. The reduced model retained its natural linear time invariant (LTI) system behavior over the range of frequencies in interest. On the basis of BLMS II, the MIMO system is changed to SISO system. The system attenuated the bending modes with additional damping and predicted the robust performance and stability of the reduced order aeroelastic system under uncertainties. Mu-Controller proved to be more prone to sensitivity and noises.

OPTIMIZATION OF PLASMA ACTUATORS FOR FLOW CONTROL

Federico Messanelli - Supervisor: Marco Belan

Plasma actuators are a rather innovative active flow control technique, with many appealing characteristics, including a low weight, an extreme simplicity of realization, the possibility to be retrofitted on already existing surfaces, a fast time response and the absence of moving mechanical parts. On the other hand, they have also some drawbacks, including ozone production, low efficiency and low control authority for high speed flows. To overcome these limitations, they need additional research work to be applied on industrial scale. The objective of this experimental work was to increase plasma actuators performances for separation control.

Plasma actuators are mainly of two types, corona and dielectric barrier discharge (DBD), depending on the relative positioning of the electrodes. Both these devices exploit the high electric fields applied between two electrodes opportunely located on a dielectric surface to generate a weakly ionized plasma, responsible for the creation of a body force acting on the air and the induction of an ionic wind of some meters per second. However, corona actuators are unstable, with frequent transitions to the electric arc regime, characterized by high currents and dangerous for the integrity of the device. For this reason, they were almost entirely abandoned by the research world.

Some studies about the optimization of the many geometrical and electrical parameters that influence the actuators performances are available in literature: an interesting development for DBD is the serrated edge geometry, which means periodical triangular tips on the active electrode. By introducing an additional free geometrical parameter, namely the inter-tips distance, we generalized this configuration (multi-tip geometry). We decided to further investigate this shape, introducing it also on corona for the first time, by performing a parametrical study on the geometry both at the bench and in the wind tunnel with the actuators at the leading edge of a NACA0015 airfoil. Such a study was not available in the relevant literature before this thesis.

Tips locally increase the electric field, as testified by the brighter luminosity of the plasma, and, only for DBD, couples of counter-rotating vortices are generated between two adjacent tips, which can be exploited for flow control.

In the first experiment, 30 multi-tip plasma actuators (15 corona and 15 DBD, including straight traditional devices), characterized by different tips sharpness (ratio between tips length and width) and density (tips number per unit span), were compared at the bench, in initially quiet air, on the basis of the maximum induced velocity, the massflow and the electro-mechanical efficiency.

We found that corona stability, quantified as the mean time between two consecutive sparks, grows with tip sharpness, as well as the induced velocity and the massflow. Furthermore a low tips density is beneficial for inducing higher velocities, also for DBD, but more tips imply a better homogeneity in the span direction and larger massflows. The induced velocity maxima are closer to the wall for DBD than for corona, which is better for boundary layer control, but corona are on the whole more efficient than DBD thanks to their lower power consumption. Multi-tip devices greatly overperform traditional straight actuators.

In the second experiment, the same actuators were compared on the basis of their separation control performances on the airfoil, i.e. lift increase and drag reduction in light and deep stall, measured by means of a purposely built balance. The investigated Reynolds numbers range was between 80k and 330k. Both traditional steady actuation (DC high voltage for corona, continuous sinusoidal voltage for DBD) and unsteady mode (burst modulated sinusoid, with different reduced frequencies and duty cycles) were analyzed. This last operation mode was introduced for the first time for corona actuators, that were found once again to be more efficient than DBD. Generally speaking, multi-tip devices give better performances than traditional configurations, at the price of a larger power consumption for equal applied voltage: however, for many applications it is desirable to keep a lower voltage and obtain at the same time better performances, since this reduces the risks of arcing towards near metallic components and of perforating the dielectric surface on which the electrodes are located. For corona, high tips sharpness and density are beneficial for separation control, which is linked with high massflow generation. For DBD, an optimal inter-tips spacing is found, depending on the discharge length, which is connected to optimal (streamwise) vortex generation. Steady actuation gives the largest lift increments in light stall, while unsteady actuation is better in deep stall, with reduced frequency around 1 and low duty cycles for lift increase and larger reduced frequencies (at least 4) and duty cycles for drag reduction. Unsteady actuation promotes the generation of spanwise vortical structures at the burst modulation frequency, that favor the mixing between the bulk flow and the boundary layer. Large power savings can be also obtained, since the power scales linearly with the duty cycle. Moreover, this operation mode further enhances corona stability. The superposition of unsteady actuation and multi-tip geometry is not beneficial for multi-tip DBD, due to the complicated and not constructive interactions between the spanwise vortices caused by burst modulation and the streamwise structures favored by multi-tip shape.

A third experimental characterization was performed during my visiting period at the University of Poitiers, on one multi-tip corona and one DBD, selected on the basis of the previous results. Power measurements at the bench confirmed the higher power consumption of DBD. Fittings for the power trend versus the voltage (and frequency) were suggested for the two devices. Optical characterization of the discharge, by means of iCCD photos, gave interesting insights about the discharge regimes, depending on the polarity, and analogies between DBD and corona were found. Balance measurements with the actuators at the leading edge of a NACA0015 in the wind tunnel substantially confirmed the results already collected at Politecnico, with steady and unsteady actuation superiority for light and deep stall respectively. A time-resolved PIV (particle image velocimetry) analysis confirmed that unsteady actuation is responsible for the creation of spanwise vortical structures released in the flow at the burst modulation frequency. The time-resolved reattachment process following the actuator ignition was analyzed for the first time with multi-tip geometry. Furthermore, significant differences were observed for DBD on image planes aligned with tips or roots of the active electrode, confirming the three-dimensionality of the flow induced by this kind of device. We also found evidences that the above mentioned vortices can increase the lift, even without promoting a large reattachment of the flow, as it happens for dynamic stall on oscillating airfoils.

In conclusion, plasma actuators performances for flow control can be increased by multi-tip geometry and an opportune use of steady or unsteady actuation. Plasma actuators are almost mature for industrial applications, at least for low speed flow control. Maybe they will never be used on commercial airplanes, but they can be effectively exploited for ground vehicles, light aircraft and wind turbines.

DATA-DRIVEN CONTROL SYSTEM DESIGN FOR MULTIROTOR SYSTEMS

Pietro Panizza - Supervisor: Prof. Marco Lovera

One of the main objectives of control theory is to design a specific controller that drives the output of a plant to track a defined setpoint signal or to satisfy a design target.
In the model-based approach a mathematical model of the plant is required in order to obtain the specific controller. Modelling the plant is necessary for this type of methods and it represents one of the most delicate and difficult steps in model-based methods. Model identification can be adopted to obtain the plant model exploiting measured data from experimental tests on the true system. Different identification techniques can be use to get the model of the plant: in the black-box framework the model is obtained directly and solely from the measured input-output data, whereas exploiting grey-box algorithms a physically-motivated model is first derived from first principle considerations and then the model parameters are calibrated with the measured experimental data.
However, even if the most advanced identification method is employed, the model always represents an approximation of the real system and some errors are inevitable. Consequently, since the model-based approach is based on the assumption that the plant model represents the true system, these methods are inherently less safe and less robust due to the unmodeled dynamics. Furthermore, even if the model is accurate but the assumptions on the system are not correct, the results on the stability and robustness of the closed-loop system are not always valuable. Usually, trying to characterize difficult effects produces a complex model that cannot be used for controller design. Indeed, a model with an high order or a high level of nonlinearity leads to controllers with high order and high nonlinearity. Thus, a controller reduction procedure is inevitable since controllers that are too complex could be difficult or costly to design, use and maintain. This step is generally problematic since any stability guarantees that were formulated for the full-order controller may not transfer to the reduced-order controller. Furthermore, whilst the optimality of the full-order controller can be guaranteed, that is not the case for the reduced-controller.
In many applications the structure of the controller is predetermined. Many industrial processes, for example, use predefined PID controllers and the procedure is limited to tuning the PID gains. Tuning only the controller gains starting from a full-order controller is far from trivial. For this reason, the full-order controller cannot be employed and structured model-based control techniques have been developed.
In order to overcome all these limitations, the data-driven control approach emerges as a valuable solution to obtain the specific controller. Since the main feature of these methods is the ability to obtain or tune a controller directly from experimental input-output plant data, they have been proposed to avoid the problem of under-modeling and to facilitate the design of fixed-order controllers.
Data-driven algorithms skip the modelling phase almost entirely and instead reformulate the controller identification procedure as a parameter optimization problem in which the optimization is carried out directly on the controller parameters.
Furthermore, the achieved performance of the controllers is not linked to the techniques used to model the plant or the order of the identified plant model.
It emerges that the main difference between model-based and data-driven approaches is whether the plant model is involved in the controller design. From this point of view, the data-driven class includes also methods that are not strictly related to the control community such as: neural network based control methods or fuzzy control methods.
Several data-driven control design algorithms have been recently proposed that are based on a rigorous mathematical analysis and under, certain reasonable assumptions, they can guarantee also the stability of the closed-loop system.
The data-driven algorithms considered in this work are also computational efficient: this allows a fast re-tuning of the controller when the plant performance is reduced (e.g. components ageing) or when the operating conditions change (e.g different payload or environment).
As other control strategies, data-driven methods are not omnipotent. Certain assumptions must be made before applying these algorithms and, considering the data-driven methods employed in this work, some of these assumptions involve the system to control (such as, e.g. achievable closed-loop bandwidth, dominant dynamics, presence of time-delays). Without this information, obtaining a satisfactory tuning can be challenging, as the choice of an unattainable closed-loop reference model can lead to poor performance (not unlike erroneous structure selection in model identification problems)
The reader must not be surprised by this statement. Indeed, the amount of required plant information is less than in the model-based framework and, as will be explained in the next section and in the following chapters, this information is usually available from the plant manufacturer or can be obtained with simple open-loop or closed-loop tests.
Furthermore, some new definitions must be coined for these methods such as robustness. Indeed, since these algorithms do not involve directly the plant model and neither the unmodeled dynamics, the traditional definition of robustness is no longer valid.
At this point where the data-driven framework is introduced, the reader could ask if data-driven methods perform better than model-based methods. If the evaluation criterion is the variance of the controller parameters then the model-based approach achieves better results since it has been shown that an approach based on two optimisation steps is statistically efficient.
Nevertheless, the previous criterion represents only an intermediate step toward the evaluation of the methods. If the control cost achieved by the designed controller is taken into account, the following considerations are valid:
if the model structure is perfectly known and the model order is low, the model-based approach is theoretically always the best approach.
If the model structure is not completely known and/or a high order model is identified, the data-driven approach can statistically outperform the model-based solution in terms of the control cost, even if the variance of the parameters remains larger.
Because in the real world the model structure is never perfectly known and under-modeling can not be avoided with a low-order model, the data-driven approach may give better results in many real applications.
Furthermore, in order to achieve a statistically efficient estimate, the model-based approach requires both the system and the noise model to be correctly parameterized.
Finally, the data-driven approach requires a convex optimization problem if the controller is linearly parameterized whereas the model-based approach requires that both the controller and the plant model are linearly parameterized.
The applicability of data-driven methods to the tuning of control laws for multirotor UAVs has been verified with reference to three different platforms which cover a wide range of Take-off Weights corresponding to:
a large platform (5 kg Take-off weight), representative of a multirotor for professional industrial applications (see, e.g. the DJI Matrice 200 platform);
a medium platform (1.5 kg Take-off Weight), representative of a multirotor for recreational personal use (see, e.g. the DJI Phantom 4 platform);
a small platform (200 g Take-off Weight), representative of the class of "harmless" multirotors according to the Federal Aviation Authority (< 250 grams) or the Ente Nazionale per l'Aviazione Civile - ENAC (<300 grams).

STRUCTURED FLIGHT CONTROL LAW DESIGN FOR HELICOPTERS AND TILTROTORS

Simone Panza - Supervisor: Prof. Marco Lovera

Rotorcraft control design represents a challenging problem, due to the presence of many competing design requirements. Inherent instability, inter-axis coupling, and poor bare airframe handling qualities impose the need for an automatic flight control system, in order to relieve pilot workload. The flight control system has the potential to dramatically increase the performance of the vehicle, by augmenting the system with additional modes which can help the pilot in the task of controlling the vehicle.

In order to achieve the high performance required, it is necessary to take into account accurate mathematical models of the vehicle, which are capable of capturing the dynamics of interest. The properties of stability and performance shall be achieved by the flight control system not only in nominal conditions, but also in face of uncertainty of the model. Moreover, the control design procedure must be oriented to clearance: the system shall meet the requirements stated in standard documents, with practical implementability of the designed control laws being a key point. In this perspective, the flight control system architecture should be kept as simple as possible.

The objective of this thesis is to set-up a methodology for control law analysis and design, which can be systematically applied and easily adapted to different rotorcraft configurations (*e.g.*, helicopter, tilt-rotor, tilt-wing, ...), by considering a set of state-of-the-art tools which can be effective in the practical design of rotorcraft flight control laws. These tools shall cover the following aspects of the design procedure:

- modeling: on the basis of high-order models, tools for model order reduction, uncertainty description, and "control-oriented pre-processing" are developed to obtain a simplified - yet representative - model which can be effectively used in control law design;
- requirement definition: tools for definition of control requirements, both from standard specification documents and from the literature, are set-up; such requirements encode the desired behaviour of the closed-loop system, *i.e.*, of the controlled aircraft.
- analysis: tools are needed to study the stability and performance properties of the closed-loop system (with respect to the requirements); these tools allow to carry out analysis both in nominal and in perturbed conditions (thus assessing the property of robustness to uncertainty);
- synthesis: by means of these tools it is possible to define the architecture of the flight control system, and to find optimal values of its tunable parameters so that the control requirements are achieved, even in presence of uncertainty.

Moreover, innovative concepts in flight control law design, enabled by the availability of measurements of the rotor blades motion and capable to improve performance and safety properties of the aircraft, are studied; the design of such innovative laws is carried out in the framework of the proposed control design methodology.

The flight control design problem is tackled in the framework of H-infinity control. In particular, a multi-objective optimization-based approach based on mixed-sensitivity is considered. The requirements are formalized in the form of frequency weighting functions, which are to be imposed on some pre-specified transfer functions of the closed-loop system. The idea behind mixed-sensitivity synthesis is to choose the controller parameters such that the shape of the frequency response of the closed-loop transfer functions follows a desired template, which is encoded in the form of the frequency weights, and in turn achieve the control requirements. The obtained solution will be optimal, according to a cost function based on the H-infinity norm operator.

The proposed approach is multi-objective in that each requirement is addressed by means of a different weighting function, which is associated to a closed-loop transfer function; each of these requirements can intuitively be given a graphical interpretation in terms of an upper bound on the frequency response magnitude. The requirements are enforced simultaneously.

A number of requirements representative of the rotorcraft control design problem can be addressed, taking inspiration from the helicopter standard specification ADS-33 and from the literature:

- stability;
- performance: the closed-loop system shall accurately track the pilot command;
- disturbance rejection: as a response to external disturbances (*e.g.*, wind gusts) the aircraft shall return to its equilibrium position;
- control action moderation: the control action generated by the control law shall be achievable by the actuators and not result in saturations;
- robustness: the aforementioned properties shall hold not only in the nominal condition, but also in perturbed conditions;
- safety: the control laws shall guarantee that the aircraft does not leave its safe operating envelope.

The structured version of the H-infinity problem is taken into account: this allows the designer to define the architecture of the control law and to choose which parameters are to be tuned; one possible application of this approach is the re-tuning of the parameters of existing flight control systems. The issue of robustness with respect to model uncertainty is tackled in the frequency-domain by means of non-parametric uncertainty description and of analysis and synthesis tools, based on the H-infinity framework and its extensions (*i.e.*, the structured singular value mu and the skewed structured singular value). Such tools allow to analyze the robustness of the closed-loop properties of an existing flight control system design, and to assess issues related to robustness, if any, providing useful information to modify the control design accordingly.

In particular, the structured mu approach represents an appealing technique, in that it allows to guarantee robust performance by design. The software tools available in the MATLAB Robust Control Toolbox are employed to solve the optimization problem.

The proposed methodology has been applied to several cases of rotorcraft configurations of industrial relevance, including manned (helicopter, tilt-rotor) and unmanned (quad-tilt-wing) aircraft. Examples of applications include:

- helicopter single-axis advanced control-oriented modeling;
- analysis of a helicopter multi-variable identified black-box model for control purposes;
- tilt-rotor multivariable control-oriented modeling, in nominal and perturbed conditions;
- quad-tilt-wing UAV modeling in the full operating envelope;
- tuning of quad-tilt-wing control laws with prescribed structure, achieving robust performance;
- analysis of closed-loop robust stability and performance with respect to actuator uncertainty;
- study of achievable tilt-rotor performance as a response to pilot command;
- analysis of stability and performance robustness for an existing tuning of a tilt-rotor flight control system, in nominal and perturbed conditions;
- analysis of quad-tilt-wing UAV performance limitations determined by the flight control system architecture;
- closed-loop robust performance analysis of quad-tilt-wing UAV;
- tuning of helicopter attitude control laws with rotor state feedback to improve performance;
- tuning of tilt-rotor attitude control laws with rotor state feedback to improve safety.

CHARACTERIZATION OF PARAFFIN-BASED HYBRID ROCKET MOTORS FUELS

Anastasia Petrova - Supervisor: Prof. Luciano Galfetti

Paraffin waxes represent an important class of solid fuels for hybrid rocket propulsion because of the sensitive increase in regression rate which is possible to obtain compared with traditional fuels. The melting of these fuels forms a thin, hydrodynamically unstable liquid layer on the surface and the entrainment of droplets from the liquid–gas interface increases the rate of fuel mass transfer. Due to the well-known unsuitable mechanical properties, typical of pure paraffin waxes, an increase of elasticity and toughness is mandatory in order to use paraffin waxes as solid fuels for hybrid rockets.
This research project, performed at the Aerospace Science and Technology Department of Politecnico di Milano, is focused on the development of innovative solid fuels for hybrid rocket propulsion in order to reach a good trade-off between mechanical and ballistic properties. The investigation of fuels characterized by a low melting temperature, such as paraffin-based solid fuels is performed using different approaches.
The first one involves the investigation of different paraffinic material i.e. macro- and microcrystalline waxes. Paraffin is an easily available inexpensive material, while it is soft and brittle. However, the mechanical properties of paraffin-based fuels need to be improved: paraffin itself is too brittle compared to rubbers as polymerized HTPB especially at low storage temperatures in deep Space.
The second one is based on the mixing of paraffin-based fuels, with strengthening materials (polymers: SEBS, PE, SIS, EVA) in order to improve mechanical properties of the paraffin.
The third approach, involves investigation of compositions with metal hydrides (i.e. Magnesium hydride (MgH_2) or Lithium Aluminum hydride ($LiAlH_4$)) in order to enhance the regression rate.
Viscoelastic, mechanical, thermal (DSC), and ballistic (regression rate measurement) tests are carried out in order to obtain information about this new family of fuels.
As it was shown in current research, the investigated properties of paraffin based fuels significantly depend on the nature of the wax used as a compound. So, knowing the properties of the particular commercial paraffin and additives such as polymers and metal powders, it is possible to match some specific requirements, depending on the selected hybrid engine purpose.
The nature of the wax and polymer concentration determines changes in the viscoelastic behavior. With increasing of polymer concentration, viscosity increases. SASOL showed higher viscosity at the same rates. It is connected with its higher melting temperature and molecular weight and branched structure.
Rheological investigations for all formulations were performed: it was obtained that the addition of polymers increases the storage modulus value. The storage modulus for all investigated paraffin-based materials decreases with increasing the temperature. The addition of polymers to paraffin causes the increasing of melting temperature.
The temperature up to which the material gives rheological response is important because it is linked with the material's tendency to entrainment. The tendency to entrainment and regression rate is higher with lower maximum temperature at which a rheological response is obtained and lower viscosity. Despite the fact that polymers addition increases melting temperature of the sample, it was obtained to be lower than that for HTPB which is higher than 60°C.
The overlaying with DSC thermographs allows see the softening and melting behavior.
SASOL wax is able to keep its elastic energy until 50 °C.
Comparing two different waxes, SASOL is 75 % more resistant to the stress than GW and has elastic behavior (can restore the shape) while GW has plastic behavior (can save the shape after the force). GW has a lower elastic region than SASOL and necking phase is present.
Also a natural paraffin (Ozokerit) was tested. It showed higher values of maximum stress and more elongation at break, so the strain. Comparing to pure paraffin ozokerite is more elastic and not so brittle, but it could be not useful for real propulsion in terms of availability.
As the polymer fraction increases the elongation at break increases with a not linear trend. SEBS increases plastic properties of pure microcrystalline SASOL: increasing of elongation in more than 5 times was obtained. Doped paraffin wax showed the amount of elasticity comparable with the rubber based fuels.
The effects of temperature and strain rate on the mechanical parameters are closely related to the changes of properties and the different fracture mechanisms for tested propellants at various temperatures and strain rates.
The obtained advantages of modifying paraffin with polymers are higher softening points, increased hardness, greater tensile strength, larger elastic modulus and larger percent elongation than pure paraffin wax based motors.
Another advantage of doped with polymer wax is the production of a more uniform wax. On the contrary, addition of $LiAlH_4$ decreases mechanical properties.
The thermal degradation characteristics were measured for pure paraffin and paraffin-based fuel. Macro paraffin wax which is GW shows one distinctive endothermic peak (solid-liquid transition) and another smaller peak which characterizes pre-melting solid-solid transition.
Microcrystalline SASOL shows two more or less distinctive endothermic peaks and a wider transition phase temperature interval. For GW melting heat absorption is 64,78 J/g, which is lower than 176,8 J/g (for SASOL). This showed that usage GW could reduce paraffin's melting heat absorption.
Considering the blend of SASOL with polymer there is almost no thermal shift of the main endothermic and exothermic peaks. There such a trend is described due to the amorphous nature of the polymer or to its very low grade of crystallinity.
In a blend between a paraffinic material and an amorphous material only the waxy material is detectable by DSC, which gives a signal directly proportional to the paraffin mass fraction. With decrease of paraffin content, the initial endothermic peak is reached in advance gradually, and the heat release increases continuously.
The knowledge of the fuel thermal behavior is vital for hybrid rocket applications as the formulation with higher temperature of solid-liquid transition has better resistance to storage and operative temperatures. Also the solidification process can be controlled better when the temperature intervals of the transition phases are lower. Finally, higher melting temperature means higher viscosity which decreases entrainment of the droplets so the regression rate is expected to be lower.
The fuel regression rate is an important parameter in the internal ballistics and overall performance of hybrid motors.
The time and average regression rate was calculated from the fuel mass loss and burning time.
The regression rate of the pure paraffins obtained in the current research was about 2 and 5 times higher for the macro-crystalline GW and micro-crystalline SASOL respectively than that of the classic polymeric hybrid fuels.
The average obtained values of the regression rate for the pure SASOL and the formulation with SASOL plus 20% of polymer are 4,35 and 1,85 mm/s respectively.
Comparison with previous results obtained for the pure GW and similar formulation with GW instead of SASOL showed that the regression rate of the sample with SASOL is higher, so it could be a good candidate for the usage as a hybrid fuel.
Considering the addition of the polymer to the pure GW it was obtained that GW with the lowest viscosity achieves the highest regression rate. The regression rate was decreased by 33 % with the addition of the polymer to the pure paraffin and by 43 and 58 % with addition of $LiAlH_4$ of 5 and 10 % respectively. Current research showed that the regression rate has greatly been affected by the fuel composition.

PRESSURE EFFECTS AND KINETICS INVESTIGATION FOR SOLID FUELS IN HYBRID PROPULSION

Dmitry Prokopyev - Supervisor: Prof. Luciano Galfetti

The goal of this research is to investigate pressure effects on solid fuel combustion and kinetics behavior in hybrid systems. In the paper the ballistic properties of HTPB-based hybrid fuel formulations and paraffin-based fuels burning in gaseous oxygen were investigated.
The experimental ballistic investigation has proved that there is no significant pressure influence on the regression rate for conventional hybrid fuels, as supported by G.A. Marxman and M. Gilbert. The experimental results have shown that fragmentation is increased by pressure enhancement. The tests carried out in SPlab demonstrated that the regression rate is higher than predicted by models, due to fragmentation effect. At the same time, Arisawa and Brill pointed out that the increase in applied pressure results into a slower pyrolysis of HTPB. Therefore, there is a possibility of no pressure dependence if these two phenomena are observed under nearly similar magnitude, as in the case of HTPB.
To investigate a pressure effect for paraffin based fuels, two waxes with different viscosities were observed. Two waxes contained mostly linear alkanes. Carlo Erba wax had lower viscosity then Sasol 1276 wax. Both paraffin-based fuels exhibit a weak dependence on chamber pressure. A higher regression rate is obtained for high pressures and this effect increases with decreased viscosity. An enhancement of the entrainment effect leads to the increase of the pressure effect.
The most promising materials for hybrid fuels are paraffin waxes that have regression rate 3 to 4 times higher than that of conventional fuels, such as HTPB. Following Karabeyoglu et al., the total regression rate for burning of paraffin-based fuels can be expressed as the sum of two terms: the evaporation regression rate, generated by the vaporization of the liquid into the gas stream and the regression rate due to the entrainment.

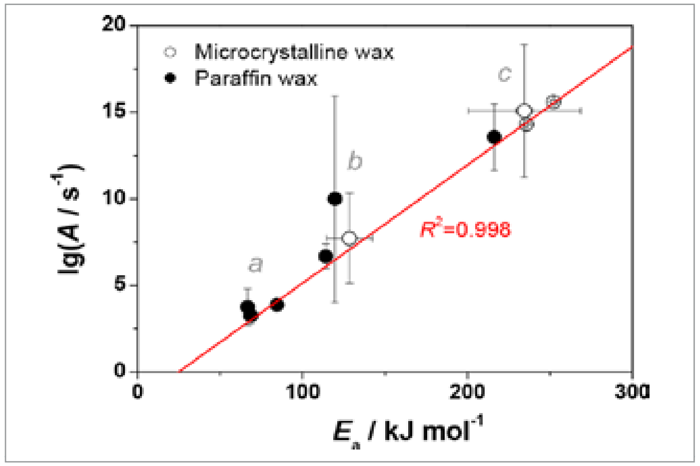

Fig. 1 - Points are the values from the obtained kinetic parameters for macro- and micro-crystalline paraffins.

Despite its practical importance, the kinetics of thermally-induced transformations in wax is not fully understood. The main focus of this work is to observe the vaporization process for paraffin-based fuels with pyrolysis study.
Paraffin waxes consist of mixtures of high molecular mass saturated hydrocarbons. Being heated from RT to 600°C under atmospheric pressure, paraffin wax undergoes three endothermic processes, i.e., melting, evaporation and thermal decomposition of molecules of different chain length to form smaller chains.
In the present study, the aim is to distinguish the paraffin wax thermal decomposition and obtain kinetic parameters of this process. To this end, thermal behavior of micro-crystalline SASOL 0907 paraffin wax was investigated by thermogravimetry (TGA) and high-pressure differential scanning calorimetry (HP-DSC) experiments at atmospheric pressure, as well as under nitrogen pressure of 1 and 5 MPa. The elevated pressure allows to suppress evaporation and observe the endothermic DSC-peak of the "pure" decomposition of paraffin SASOL 0907.
For the kinetic study, isoconversional and combined kinetic analysis were used. The current study shows that the variation of pressure conditions, accessible for the thermoanalytical experiments in combination with the comparative consideration of different wax samples, provides some insights into the process. This approach, i.e., the simultaneous consideration of the whole available kinetic information, seems to be the most promising in the kinetic analysis. By varying the operating conditions for the thermoanalytical experiments and conducting comparative analysis of two wax samples, the general descriptive scheme of their pyrolysis was suggested. Figure 1 graphically represents the kinetic information, obtained in the thesis.

After careful observation of Figure 1, the existence of three intervals of the activation energy values are suggested, i.e., around 70, 120 and 230 kJ mol⁻¹. The analysis of these kinetic parameters allows to propose the general descriptive model of the process of pyrolysis, which is presented in the thesis. Both studied materials contain two principal components: linear and branched hydrocarbons. Being heated, hydrocarbons evaporate when low confinement is applied, leading to the two corresponding mass loss steps.
The evaporation of the branched hydrocarbons is significant for micro-crystalline Sasol 0907 wax pyrolysis in atmospheric pressure and for macro-crystalline P-2 wax at elevated pressure. These two evaporation steps are denoted as "*a*" and "*b*" in Figure 1. When the confinement of the system becomes significant, the activation energy rises to 236 ±4 kJ mol⁻¹, and the reaction model follows the random-scission mechanism. This step, marked as "*c*" in Figure 1, is observed for both micro-crystalline and paraffin wax. At high pressures of the hydrocarbon vapor, the obtained activation energy values are in the range of 235-265 kJ mol⁻¹, agreeing well with our proposal for stage "*c*".
Thus, the evaporation of constituting hydrocarbons, decomposition in vapor, or its combinations were observed under different operating conditions. The overall process of the pyrolysis of micro-crystalline and paraffin wax is governed by competitive evaporation and decomposition. The overall kinetic scheme contains three main stages: the evaporation of the linear alkanes, the evaporation of the branched hydrocarbons, and thermal decomposition. The first process was analyzed in the frame of the Langmuir model, and its evaporation enthalpy was determined to be ΔH_{ev}(298 K) = 79 ± 7 kJ mol⁻¹. For the second stage the value of evaporation enthalpy for the branched hydrocarbons fraction from macro- and micro-crystalline waxes was determined as 114 ± 2 kJ mol⁻¹. Thermal decomposition becomes dominant at elevated environmental pressure, leading to the process with the barrier of 236 ± 4 kJ mol⁻¹, driven by the random-scission mechanism. The specific composition of the wax - the ratio of the linear and branched hydrocarbons and its distribution on the carbon numbers and the applied pressure - defines the vaporization kinetics.
For a performance evaluation of the rocket based on its total mass, the most important variable is the regression rate of the surface (how fast the fuel is burnt for a given configuration and fuel composition). For simulations the key parameters are the kinetics parameters that were obtained during this study. In addition, the results are believed to contribute to prediction of the thermal response during manufacturing process and, thus, can be incorporated in the modern models for the hybrid rocket propulsion engines.

FINITE ELEMENTS FOR ACTUATION OF COMPOSITE SHELL STRUCTURES THROUGH SHAPE MEMORY ALLOYS

Daniela Rigamonti - Supervisor: Giuseppe Sala

Shape memory alloys (SMA) represent an important class of multi-phase smart materials that have the ability to recover huge deformations. In aerospace field, most applications are based on the use of SMA as components in smart systems, especially for actuation purpose. The increasing number of SMA-based applications has motivated researchers to formulate constitutive models able to catch the complex thermo-mechanical behavior of these materials and to develop robust computational tools for advanced design purposes. However, such a research field is still under progress, especially in the prediction of several important effects characterizing SMA. One of these effects is the change in the transformation behavior with increasing number of cycles, named functional fatigue, causing the reduction of performance for an actuator. Another effect that is still an open issue in constitutive modeling research is the simulation of different thermal treatments. Both these two aspects originate from the microstructural conditions of the material. Motivated by the described framework, the thesis is dedicated to introduce microstructural changes resulting from functional fatigue or thermal treatments, into a design tool such as a finite element model. Concerning the constitutive modeling, the thesis proposes to start from an already robust model, whilst numerical implementation is going to be pursued using commercial software commonly used to design SMA actuators with the aim of being effective in exploiting the model for practical purposes. The constitutive and numerical modeling activities are completed by experimental characterization of NiTi SMA wires. Indeed, the design of SMA components is strictly related to the knowledge of their metallurgical aspects and the experimental characterization is not only devoted to model calibration, but is an indispensable means to understand the mechanisms driving the transformation and thus also determine the functional properties of the component that is under design. The work culminates in the simulation of the actuation effect of SMA wires on a morphing structures composed of corrugated laminates, both in the initial condition and after some cycles.

After a bibliographic research on the state of the art of SMA constitutive models, three interesting models were identified and analyzed. These apply to different categories of SMA constitutive models but have in common the ease of implementation and the computational efficiency, because to be an effective tool for the smart systems project, a model must also be "easy to handle". These models are calibrated and verified on the experimental results of a uniaxial tensile test. This analysis firstly is to meet the need to become accustomed to the modeling of SMA in general and to the numerous approaches developed in literature and secondly to determine which characteristic parameters of the various models can be used to represent the different microstructural conditions. The first option considered is an elaboration of the original model by Tanaka (1986). This is a basis for many phenomenological models consisting in a simple differential formulation easily integrable in Matlab. The second is the model by Boyd and Lagoudas (1996) derived from irreversible thermodynamics and currently implemented and made available in a Fortran code following the specifications for user-material subroutines by Abaqus. The last by Müller, Achenbach, Seelecke (2001) is a so-called free-energy model and its derivation is completely from thermodynamics basing on physical variables only. This makes it particularly interesting for a multiphysics software like Comsol. After this comparison, the third model (Müller, Achenbach, Seelecke, hereafter MAS) was the most promising to make changes including the effect of microstructure.

The analyzed version of the MAS model refers to a single–crystal model and the first idea was to introduce these changes in the definition of the energy potential. However, this implies considering the complex microstructural interactions in order to evaluate the energy contribute of interfaces, e.g. an interface energy due to grain boundaries or dislocations, to be added to the barrier energy needed for phase change. The introduction of a parametric version of the model made possible a second approach, based on the characterization of transformation energy as a function of the martensitic fraction. Instead of considering a set of physical single crystals within the representative elementary volume, each with a certain combination of barrier and interaction stress, the focus is only on the one single crystal that is always the next in sequence to undergo a phase transition, namely a representative single crystal (RSC). Once this physical crystal has transformed, the focus is switched to the one with the next higher barrier, and so forth. Therefore, the energy barrier for the transformation changes during the process as the physical elements undergo transformations: the RSC encounters a barrier that gradually increases as the volume of transformed martensite grows and likewise decreases if this drops. The major advantage is that the "mathematics" that needs to be solved is the same as in the perfect single crystal case, but with the barrier transformation stress no longer constant, but proportional to the fraction of transformed material, so that the transformation has been effectively parameterized by the phase fraction. This leads to the concept of an "effective" barrier–stress (σ_{EB}) driving the actual material response, which includes the externally applied stress (σe) and the internal interaction stress (σ_i). The effective barrier stress σ_{EB} can be determined analytically directly from an experiment performed at a low strain rate, i.e. assumed isothermal, interpreting the measured stress as the barrier stress itself (Heintze and Seelecke, 2008). Despite this giving reliable results for some types of materials in which the characteristic points (elastic field, nucleating point and propagation plateau) are easily identifiable, this is not equally true for the materials with different microstructural conditions object of the present work. For this reason, an experimental calibration of the barrier stress parameterized by the phase fraction is needed. To obtain it, an in situ X-Ray diffraction under uniaxial tensile stress is performed on sample with different microstructural conditions, both due to thermal treatments and cycling. The result of this analysis shows that these conditions can be well represented introducing as a variable the strain of the retained martensite ε^*_M, which can be calculated as the maximum transformation strain multiplied by the fraction of retained martensite $\varepsilon^*_M=\xi^*_M * \varepsilon_T$. Then, the residual strain observed in mechanical cycling can be assumed as the sum of this "retained martensite" strain and a certain amount of plastic strain.

Finally, the results of this characterization are used to simulate an aerospace application that consists in the use of SMA as actuators for an aerodynamic morphing skin based on corrugated shell geometries made by composite materials. This is simulated in two conditions of the wire one representing the properties at begin of life and the other after some cycles of shape modification, comparing the loss of performance. This demonstrates the possibility to use the parametrization of the barrier stress as a function of the martensitic fraction to foresee the performance of an actuator after some cycles. The barrier stress can be characterized and calibrated on the SMA element that has to be combined to the smart structure, by means of tensile isothermal tests after actuation fatigue cycling, and then the performance of the actuator can be predicted numerically.

STABILITY ANALYSIS OF WIND TURBINES THROUGH SYSTEM IDENTIFICATION TECHNIQUES

Riccardo Riva - Supervisor: Prof. Carlo Luigi Bottasso
Co-Supervisors: Prof. Alessandro Croce, Dr. Stefano Cacciola

The diameter and power of wind turbines have steadily increased during the last decades, and we expect that future wind turbines will reach even greater diameters and speeds. The highly flexible blades of a modern wind turbine are subject to an anisotropic wind that interacts with active and passive control systems, causing complex aero-servo-elastic phenomena. In this scenario, it is necessary to carefully evaluate the stability of the plant, and hence the stability analysis has assumed a central role in the design phase. Parked wind turbines often behave as linear time-invariant systems, but this approximation is no more appropriate when the wind turbine becomes operative. An in-operation wind turbine experiences a periodic variation of its aeroelastic characteristics. In fact, the gravity causes a periodic stiffening of each blade, while vertical and horizontal wind shears periodically change the direction and magnitude of the aerodynamic loads. Furthermore, even a steady wind causes harmonic components in the loads, known as *nP*. These phenomena can be captured by modeling the wind turbine as a linear time-periodic system, which implies that its stability must be evaluated with Floquet theory. For Floquet theory each mode is characterized by multiple frequencies and damping ratios, that manifest with more or less strength on different parts of the structure. This characteristic is often well visible in the measures and allows to identify the system correctly.
To perform the stability analysis of a wind turbine numerical model, it is possible to choose either model- or identification-based techniques. A model-based technique provides accurate results with little efforts from the user. However, modern wind turbine simulators are complicated to linearize, and each improvement to the mathematical model requires updating the linearization routine. This is not the case with an identification approach, since by its nature is model-independent, and this characteristic makes it particularly appealing to perform the stability analysis of a numerical model. Besides, to validate a numerical model it is often necessary to identify the system employing experimental measures. It is important to stress that each identification algorithm as its field of applicability, and therefore it is of paramount importance to select the best one for each case.
In this thesis, we have studied the stability of large wind turbines, by using and developing system identification algorithms that are fully compliant with the nature of the problem. We have chosen to concentrate on a few problems that we believe are particularly relevant for current and future wind turbines.
We have conducted all the stability analyses of this thesis, by following a rather general procedure. The first step of this procedure is to design an input that can excite the response of the desired modes. Typical inputs are forces and torques, having the trend of a doublet, or a band-limited noise. This input is then fed into the plant, which can be a wind turbine, a helicopter, or any other system since this procedure is entirely model-independent. For this work, we have always used multi-body models of wind turbines, characterized by a high fidelity. Some measures, in which the response of the modes is well visible, are then recorded. The measures are pre-processed, according to the needs of the identification routine, and then used to make the identification. The identification will directly provide the desired modal parameters or a reduced order model, that can be easily analyzed with the discrete-time Floquet theory.
We will now briefly review the topics covered in this work.
We first studied the stability of a wind turbine characterized by bend-twist coupled blades (BTC). The BTC is, in fact, a popular design solution for load reduction, but its implications on the stability are mostly unknown. For this study, we have selected the AVATAR wind turbine, a 10 MW wind turbine belonging to the class of low induction rotors. We have then applied the BTC by rotating the fibers of its spar caps, this way achieving a flap-twist to feather coupling. To perform the stability analysis of the whole wind turbine, we have selected the Periodic AutoRegressive with eXogenous input identification algorithm. The PARX assimilates the wind turbine to a reduced order model, whose output is the sum of its free and forced responses. By simulating the system in the operative regions 2 and 3, we have seen that the BTC reduces the frequency and damping of the collective edgewise mode while leaving unchanged the edgewise whirling modes. In a dedicated study, we have considered the isolated blade, to measure the aerodynamic and the structural damping. We have found that the aerodynamic damping is negative for large regions of the pitch angle setting, a phenomenon known as stall-induced vibrations.
One consequence of Floquet theory is that wind turbine modes manifest with different frequencies in fixed and rotating frames. This feature suggests that by using multiple output channels, it is possible to get better estimates of the modal properties. To accomplish this result, we have extended the PARX to the multiple inputs and outputs case. By exploiting Floquet theory, we have been able to guarantee the stability of the identified system, and mitigate mode contamination problems. We have then applied this new algorithm to a simplified wind turbine model and found that it reduces the workload with respect to its single-output version.
The mode shapes of a wind turbine provide a great amount of knowledge to the engineers, knowledge that might be used to validate numerical models or to recognize anisotropic behaviors, caused for example by mass or aerodynamic imbalances. To our knowledge, the identification of the periodic mode shapes has never been performed with a high resolution. We have solved this problem by tailoring to wind turbines an already existing algorithm: the Periodic PO-MOESP. This algorithm belongs to the subspace category and hence copes very well with systems having many output channels. However, differently from the PARX, it does not allow the *nP* to be present in the output, and hence it is necessary to pre-process the measures. We have applied this algorithm to the AVATAR wind turbine, when subject to a wind having a normal profile. In this way, we have completely identified the first low-damped modes of the system with good accuracy.
Conducting identifications on experimental measures should be the goal of every identification algorithm. In the wind energy community, the most widespread methodology to achieve this result is the Operational Modal Analysis. The OMA aims at letting the wind excite the structure and then identify the modal content by using only measures of the output, therefore without knowing the wind. The OMA represents a family of techniques, but in its most common sense requires that the modes are sufficiently separated and that the input is randomly distributed in space and time. The OMA has been extended to periodic systems, but when it is applied to wind turbines, its hypotheses are not well fulfilled, and this motivated us to study other techniques. To this end, we have added the Moving Average part to the PARX, to model also the atmospheric turbulence. The MA part acts as a shape filter and therefore allows to model a generic turbulence spectrum. To compare our algorithm against the Periodic OMA, we have selected a low turbulence intensity and identified a wind turbine numerical model in the operative region 2. The analysis shows that our algorithm generally performs better than the Periodic OMA. Furthermore, the Periodic ARMAX requires shorter time histories, which is important for field testing, where the wind is never stationary for a long time.

GUIDANCE NAVIGATION CONTROL AND ROBOTICS FOR ON ORBIT SERVICING

Aureliano Rivolta - Supervisor: Michèle Lavagna

A revolution is bound to happen in space in the near future as focus is shifting on colonization and commercialization of the Earth sphere and beyond. The Revolution takes the name of On Orbit Servicing (OOS) and is an old concept revived by the new spur of commercial endeavours in the space industry. Research on related topics like economics, liability, property rights, international cooperation and of course engineering is catching up again. Technical issues in OOS are not show-stoppers but can hinder the growth of the sector incredibly. Reliability, safety and costs of proximity operations are central in the development of OOS and the key aspects are related to Guidance Navigation Control and Robotics (GNCR).

OOS is a hot topic in the space community and source of continuous research. Recently contracts have been signed by interested parties and some providers, others are starting to display the intent to bring OOS to life in the next couple of years. Since the first OOS was achieved by astronaut's Extra Vehicular Activity (EVA) on Intelsat VI and the Hubble space telescope during the STS-49 and STS-61 missions there has been widespread research on how to expand the concept without EVAs. In the years the concept of automated resupply to the International Space Station (ISS) has been perfected (especially by ATV missions), however the ISS is one of a kind and commercial OOS involving civilian and non civilian endeavours requires a different perspective. Space industry is bound to be mostly driven by military and private companies and economic exploitation of OOS is the main concern, hence any OOS mission shall be sustainable in a market perspective without relying continuously on governmental agencies founds.

There are many technological challenges on the road to achieve robotic/automated OOS, which have sparked various research programs in the last decades. For example the DARPA funded Orbital Express mission successfully demonstrated autonomous rendezvous and docking and refueling operations. During the mission also berthing and servicing functionality have been accomplished. Robotic manipulators can be used to grab, un-dock and replace Orbit Replacement Unit (ORU) and this capability has been also demonstrated by the Engineering Test Satellite VII (ETS-VII) of NASDA where autonomous rendezvous and berthing, visual servoing, ORU exchange and refueling have been accomplished. Such feats were accomplished also thanks to previous missions like the STS-72 with the retrieval of the Space Flyer Unit.

The first OOS commercial mission will mark the beginning of a new era in the space industry and possibly be marked as a revolution. This might sounds excessive at first, but if one looks at all possible applications and the radical shift in the design of satellites that will happen as a direct consequence of the serviceability paradigm the definition of revolution is not at all resounding. While big players and small disruptive endeavors fight against the current system in order to establish OOS, research in many fields has to follow. In OOS the intertwining of multidisciplinary area of interest is so deep that one can hardly disjoint them during research. Any OOS mission would require a deep planning of a servicer satellite lifetime in order to be profitable, hence mission analysis optimization and economical analysis should be looked at together. Another example is the use of cameras in close proximity hovering applications that could also generate issues about property rights. According to that principle, this thesis represents the analysis on one core aspect of OOS operations: the GNCR subsystem that provides the means to deliver the OOS service.

The first step has been to simulate the mechanical system at the highest level of detail permitted by hardware and engineering judgment. In this work a multibody software with capability of simulating many sensors, including cameras with photorealistic features, has been coded, validated and used to simulate a space robot. Equations of motion have not been linearized and for the timeframe and orbits considered delivers expected performance. The second step was to prepare all blocks that compose the GNCR loop in order to perform full simulations. This required to plunge into the guidance and control of satellites and robots, but also to look at attitude estimation and relative vision based estimation techniques. Neglecting one of these aspects would have compromised the final analysis and peering too much into the depths of each field would have made impossible to get the big picture. Hence, focus was given to characterize all parts at the highest level of precision for a preliminary assessment of the GNCR system.

One of the main contributions in subsystems is probably the Principal Inertia Adaptive Dynamic Inversion Controller applied to attitude control and robotics. The strife was to find a suitable adaptive scheme that would not require estimation of many parameters and was easily implementable. Being de facto a PD controller with adaptive derivative terms, it is more than suitable to be looked at in the industry. The main reason behind this study is the acknowledgment that in many OOS scenarios considered the servicer satellites undergoes geometrical variation or mass/inertia variation due to docking/capture. All possible sources of errors have been pointed out (noise, drift, overestimation, stability) and verified through simulations and the structure has been simplified at the maximum level possible. The controller can be further improved and connected to a robust estimation of the nominal parameters and performance.

Simulation studies were presented and results analyzed. Vision sensors prove to be effective in the estimation of target position and pose with encouraging level of precision. However, precision is not the only concern, as the robustness of image processing in space is a huge problematic.

What is recommended to possible OOS provider/OOS system manufacturers is to spend time in preparing a robust vision system capable of doing both pose estimation in close proximity and centroid estimation for long range approach. The two approaches presented here are compatible but would require more study to provide a fusion of the two that is able to guarantee the level of robustness capable of not jeopardizing the OOS mission they were designed for. In general it has been seen that, with the provided control architecture, it gets fundamental to reduce the noise in velocities estimation, especially for robot control.

This would reduce the effect on flexibility and cross-system frequency interference. For example, the frequency of the position control (force determination and thrusters wise) has huge impact on the attitude control and the robotic arm movement shall be slow enough to keep the adaptive controller in the global convergence region.

The frequency content of position control is then influenced by the pose estimation sampling time, which should be increased hardware wise and not only through a upsampling process (that can either add delays or high frequency noises). The bottom line of this consideration is that the GNCR system is heavily coupled and it is easy to reduce global performance by overlooking a simple aspects in one of the loop parts or the influence on other subsystems. It is here stated and stressed the need for complete loop simulations when dealing with OOS scenarios because, unlike many commercial scenarios, the GNCR system plays a key role for the economical growth and stability of a OOS provider company. In the end the company that delivers the best and more reliable OOS service will be the victor as consequences of a failed OOS mission would be catastrophic especially in the early development stages of the next two decades.

POLYNOMIAL ADAPTIVITY FOR LARGE EDDY SIMULATION OF COMPRESSIBLE TURBULENT FLOWS

Matteo Tugnoli - Advisor: Antonella Abbà

The Large Eddy Simulation (LES) of a compressible turbulent flow is an effective trade off between a Direct Numerical Simulation and a Reynolds-Averaged Naviers-Stokes simulation to model complex turbulent flows, balancing a good accuracy with a reduced cost. However it is still an expensive solution, also because in most of the cases is not possible to obtain a locally accurate mesh resolution, leading especially on new configurations to under and over resolved areas. The aim of this work is to start developing adaptation techniques specifically tailored for LES to obtain a better resolution distribution and an increased efficiency of the accuracy with respect to the number of degrees of freedom. Since in the present framework as well as in most of the modern LES the filter which cuts off the smaller unresolved turbulent scales is defined by the spatial resolution, a change in the resolution does also change the filter size and the local amount of turbulent scales resolved. For this reason a simple error estimation cannot be used to drive the adaptation, and a physically based indicator, developed from the structure function, was devised and employed.
Polynomial adaptivity in a high order discontinuous Galerkin framework was employed for its simplicity, high order accuracy and parallel performance. In this way the mesh is not modified by adaptation, but rather the number of polynomial basis functions in each element is changed according to the indicator requirements.
First static adaptivity was employed and validated. Employing a preliminary computation the indicator can be calculated in each element, the polynomial resolution adapted and the adapted computation run. Employing accurate high order pre run the structure function based indicator was shown to be superior to other more common indicators. Then employing very coarse and inexpensive preliminary run it was possible to calculate the indicator with the same accuracy, leading then to a similar polynomial resolution and accurate results during the adapted run but with around 60% saving on the computational time. Those tests were performed principally on two turbulent test cases: the flow around a square section cylinder at Re=220000 and the flow over periodic hills at Re=2800. In both of the cases similar positive results were obtained. Static adaptivity is a rather simple procedure which however proved to lead to robust and efficient results, without an excessive complication in both the formulation and implementation.
Following the dynamic adaptivity was developed, where the same structure function indicator is employed to adapt the resolution during the simulation time evolution. Rather than calculating the indicator and adapting once, the indicator is calculated in each element at runtime, averaged on a short time and employed to adapt the polynomial resolution with a prescribed frequency.
Such kind of adaptation is ideal to adapt the resolution to follow non stationary phenomena, and in this case was used first to simulate the advection of an isolated vortex. In this configuration it was shown that the adaptation effectively creates a resolution that follows the vortex, and leads to accurate results comparable with full polynomial resolution, at a fraction of the degrees of freedom.
The dynamic adaptivity was then employed to simulate the interaction of such advected vortex with the square section cylinder previously tested. This is an example of vortex-body interaction which happens in various engineering contexts. Several different configurations were tested, varying the position and configuration of the vortex and the phase in the shedding mechanism. It was shown that with a small change in the vortex interaction configuration the loads on the cylinder may be either slightly affected by the interactions, or a significant change of up to 40% of the peak values can be introduced, both increasing or decreasing the loads according to the configuration.
This highlights both how the interaction can have dramatic effects on the loads, and how difficult is to predict such effects.
A high interest in the case of vortex-body interactions lies in the evaluation of the noise produced by the interaction, as in many other fluid dynamic contexts. The use of high order methods for solving compressible flow equations as in this case allows to accurately simulate both the fluid dynamic phenomena as well as the generation and propagation of acoustic waves, in what is known as direct aeroacoustic computation.
However a sudden variation in the spatial resolution, which may be caused by adaptivity, might lead to the introduction of acoustic disturbances. The advection of the vortex in a uniform flow was first forced to pass through a fixed jump in polynomial resolution, and then dynamic adaptivity was employed to follow the vortex movement as done previously.
In the first case it was shown that a fixed jump in the resolution does not introduce significant acoustic disturbances. Some disturbances are instead introduced by the dynamic adaptivity, however only when the simulation is performed on a very coarse grid, while a slightly more refined grid significantly reduced the entity of such disturbances.
In conclusion the use of a specific indicator did not just lead to some robust adaptation procedures which led to accurate and efficient results, but also proved that it is possible to successfully apply adaptation to LES, which hopefully will lead to an increased research effort in this important field.

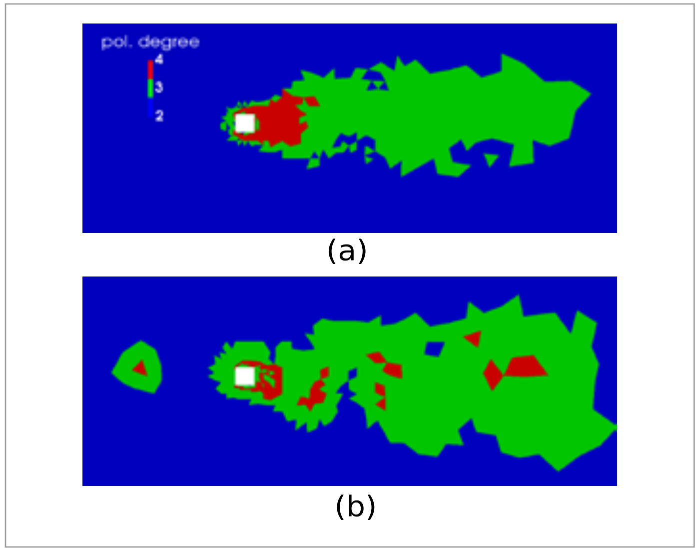

Fig. 1 - Polynomial degree distribution for the flow around the square cylinder, (a) static adaptivity, (b) dynamic adaptivity with vortex introduction

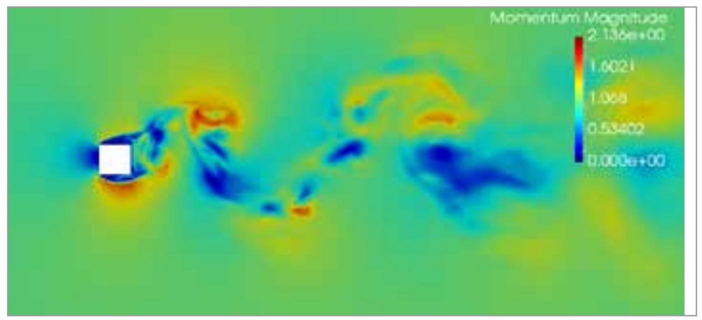

Fig. 2 - Momentum magnitude in the flow around the square cylinder.

MODELING AND CONTROL OF ADAPTIVE GEOMETRICALLY NONLINEAR THIN-WALLED BEAMS WITH PIEZO-COMPOSITE: APPLICATION FOR ROTARY AND FIXED WINGS

Xiao Wang - Supervisor: Pierangelo Masarati

Composite materials and structures, due to their vast advantages, such as light weight, specific high stiffness, and elastic couplings, have been increasingly used in aerospace industry and other fields of advanced technology. They have even been identified as a major thrust for designing high-performance aerospace structures. Anisotropic composite thin-walled structures are expected to meet the increasingly aggressive missions of the next generation of high-performance flight vehicles.
The design of advanced aircraft wings or rotor blades characterized by thin-walled structures was significantly influenced by the incorporation of composite material technology. As compared to their metallic counterparts, composite design of thin-walled structures offers considerable advantages with respect to strength and weight criteria, in addition to providing adequate means of efficiently controlling static and dynamic response via implementation of structural tailoring. Although elastic tailoring is a powerful technology that can offer a beneficial influence on the dynamic response characteristics, this technique is passive in nature in the sense that, once implemented, the structure cannot respond to the variety of factors under which it must operate. As a complementary option, the active control via the implementation of the smart materials system technology can be applied.
Since piezoelectric materials have a lot desirable characteristic, such as self-sensing, structure embeddability, fast response and covering a broad range of frequency, they are well suited for the active control of deformable beams. Due to the brittle nature of ceramics, they are however vulnerable to damage and can hardly conform to a curved surface. These drawbacks are overcame by piezo-composite materials such as the Active Fiber Composite (AFC) and the Macro-Fiber Composite (MFC).
In the existing literature, a lot publication on modeling or studying adaptive thin-walled structure based on the assumption of fiber orientation of piezo-composite along the spanwise missing the discussion of the isotropic properties. Thus, the system can only be controlled by the piezoelectrically induced bending moments. As a result, a comprehensive study allowing to get a better insight into the influence of piezoelectrically induced extension, transverse shear, twist, bimoment and bendings is still missing.
The main target of the Ph.D. thesis is developing a geometrical nonlinear rotating thin-walled beam theory incorporating fiber-reinforced and piezo-composite. Transverse shear strain, warping inhibitions and three-dimensional strain are accounted for. The governing equations and the associated boundary conditions are derived via Hamilton's principle. The applications of the beam model on rotary blades and aircraft wings are further discussed.

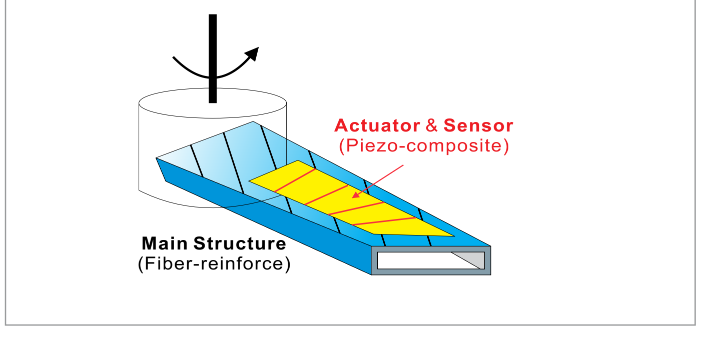

Fig. 1

Active control of pretwisted rotating blades that modeled as thin-walled beam structures is investigated. The adaptive capabilities provided by a system of piezo-actuators bonded or embedded into the structure are also implemented in the system. The effects induced by high speed rotation, e.g., centrifugal stiffening, tennis-racket effect, that are essential for a reliable prediction of free-vibration characteristics of rotating blades are highlighted. Based on the classical feedback control and linear quadratic regular (LQR) control, the control authority of the implementation of piezo-actuators with different ply-angles, considered in conjunction with that of the structural tailoring, are highlighted. In addition, the rotating thin-walled beam model developed in this dissertation can also serve as the basic model of flexible spacecraft. Problems related to active vibration suppression of piezo-actuated spacecraft during attitude maneuvers are discussed.
The model developed in this dissertation can also serve as the basic model of advanced adaptive aircraft wings when ignoring the rotating effects. The effective damping performance of piezo-actuated aircraft wings is investigated by studying lay-up configurations of piezo-composite, in conjunction with elastic tailoring of the fiber-reinforced host structure.
Problems related to nonlinear dynamics of advanced aircraft wings are also discussed. Modal interactions of swept aircraft wings carrying heavy external stores in the presence of simultaneous internal and external resonance are investigated. Moreover, the conditions for mode saturation and jump phenomena during modal interactions are highlighted.
At last the active control effect on flutter suppression and dynamic aeroelastic response enhancement of a smart aircraft wing is studied. The unsteady aerodynamic loads in subsonic compressible flows are based on 2-D indicial functions considered in conjunction with aerodynamic strip theory extended to 3-D wing model.

INVESTIGATION ON THE HELICOPTER/OBSTACLE AERODYNAMIC INTERACTION

Daniele Zagaglia - Supervisor: Prof. Giuseppe Gibertini

The helicopter is a very versatile flying machine which is often required to operate within confined areas, due to its capability of managing hovering flight. These challenging operational areas comprise naval environments, e.g. the landing manoeuvre on a helicopter carrier, and rescue operations in confined areas and urban environments where the helicopter interacts with the surrounding buildings.
The aerodynamic interaction between the rotor-induced wake and the surrounding obstacles, such as buildings and mountain walls, typically generates, on the one hand, a degradation of the helicopter performance and high compensatory workload for the pilot, on the other hand unsteady forces which can stress the structure of the surrounding obstacles. Important issues of noise may also arise which have the potential to create discomfort to the community residing in the proximity of the area. This situation can be further complicated by the presence of wind, since the helicopter has to interact with the highly unsteady and turbulent wake generated by the obstacle.
Despite the presence of a fair number of numerical and experimental investigations, a systematic study of these aerodynamic phenomena is still lacking. Moreover the past studies usually involve very specific geometries (e.g. ship decks, specific buildings) or focus just on the helicopter performance, neglecting de facto the environmental effects that the helicopter has on its surroundings. The idea behind the present Ph.D. Thesis is thus to experimentally investigate this problem, simplifying the obstacle geometry up to a well-defined cubic or parallelepiped shape in order to disclose the key fluid-dynamic mechanisms that occur when a helicopter is hovering in its proximity. The interference problem was analysed for several positions of the helicopter model with respect to the obstacle, in order to appreciate how it affects both the rotor performance and the loading on the obstacle itself. The effect of the presence of external wind was also taken in consideration as a following step. The investigation was carried out through two different test campaigns. The first, carried out at the University of Glasgow, consisted of a set of tests reproducing hovering flight conditions at different positions with respect to a simplified obstacle with a cubic shape, in absence of external wind. This experimental campaign took advantage of several experimental techniques, such as force and moment measurements on the rotor, Laser Doppler Anemometry (LDA) measurements of the rotor inflow and Stereo-Particle Image Velocimetry (PIV) measurements of the interacting flow-field.
The second test campaign was instead carried out at Politecnico di Milano and consisted in the analysis of a helicopter model interacting with a parallelepiped-shaped obstacle in both windy and not-windy conditions.
This experimental campaign took advantage of following experimental techniques: force and moment measurements on the rotor, steady and unsteady pressure measurements on the obstacle and PIV measurements of the interacting flow-field.
The purpose of the present work was thus to understand the key aerodynamic mechanisms that occur when an helicopter is hovering in proximity to a well-defined, simplified, obstacle in both windy and not-windy conditions, and to understand how they affect both the helicopter performance and the obstacle.
The produced experimental database was also of use for the GARTEUR Action Group 22 "Forces on Obstacles in Rotor Wake". This action group originated from the idea of promoting activities which could contribute to a better understanding of these phenomena and comprised several universities (Politecnico di Milano, University of Glasgow, National Technical university of Athens) and research institutes (CIRA, DLR, ONERA, NLR).
The first activity, carried out both at the University of Glasgow and Politecnico di Milano, was the analysis or the helicopter/obstacle interaction in absence of external wind. The investigation showed two main regions of interest. The first region is the one above the edge of the obstacle, where the helicopter experiences a gradual ground effect as it is positioned over the obstacle. In this case also a gradual reduction of the inflow velocity is observed, as prescribed by the ground effect. Since only part of the rotor is over the obstacle, one would expect the inflow to be non-symmetrical. However, it results to be indeed symmetrical, leading to the generation of almost null pitch and roll moments.
The second region, probably of more interest, is the one just beside the obstacle where a recirculation region between the rotor and the obstacle develops. Its morphology is deeply dependent on the rotor position. This recirculation region implies a severe thrust loss (up to 8%) with respect to the one without obstacle at the same height. This thrust loss has a maximum at approximately 2 radia from the obstacle, whereas its influence appears to be negligible when the rotor is more than 4 radia away from the obstacle. Another important feature of this region is the arising of strong pitching and rolling moments, due to the non symmetrical inflow pattern on the rotor. Despite the differences in the test rigs and test conditions adopted in the Glasgow and Milan experimental campaigns, very comparable results were obtained in terms of rotor performance, thus giving a rather strong trust in the fact that the highlighted phenomena are indeed quite general and not typical of just one configuration.
The effect of the presence of external wind was then investigated at Politecnico di Milano. A first set of measurements without the obstacle showed that the ground effect in windy conditions appears to be less intense with respect to the one without wind, and it affects the helicopter only at very low heights. Moreover, as it was appreciated for the wind-off case, the ground effect experienced by the helicopter over the obstacle is practically equivalent to the one over an infinite surface, thus highlighting the reduced influence of the obstacle wake during a landing on its upper surface.
The effect of the obstacle wake becomes definitely more relevant when the helicopter is behind the obstacle. In particular the detrimental effects caused by the recirculation region that develops for the wind-off test seems to be mitigated in windy conditions, due to the fact that the wake of the obstacle does not allow the complete development of such recirculation region. However the helicopter is affected by a severe thrust coefficient reduction when it interacts with the lateral flow structures of the obstacle wake (i.e. the horseshoe vortex), where strong velocity gradients are present.
From the point of view of the loads on the surroundings, the obstacle experiences remarkable spatial and time-variation of the pressure patterns, strongly dependent on the helicopter position. High pressure regions occur on the obstacle in the regions directly underneath the rotor or in those regions where the rotor wake impinges after being deflected by the ground. These regions are usually also characterized by a fair degree of unsteadiness. When the helicopter model is placed directly over the obstacle edge, the pressure distributions on the front face of the obstacle present a diagonal pattern on the front face, probably due to the helicoidal structure of the rotor wake. This region is characterised by remarkable pressure fluctuations and the presence of contextual high and low-pressure regions. The effect of the wind on the obstacle usually leads to a reduction in the pressure peaks, even though the pressure fluctuations on the obstacle are even magnified in certain positions.

EXPERIMENTAL OBSERVATION OF SUPERSONIC NON-IDEAL COMPRESSIBLE-FLUID FLOWS

Marta Zocca - Supervisor: Prof. Alberto Guardone

Co-supervisor: Prof. Andrea Spinelli

The branch of fluid mechanics devoted to the study of compressible flows whose behaviour deviates from the one predicted by the ideal-gas model is termed Non-Ideal Compressible-Fluid Dynamics (NICFD). Departure from ideal behaviour is typically observed in fluids made of complex molecules, operating in thermodynamic conditions close to the liquid-vapour saturation curve and critical point. Differently from the ideal-gas case, non-ideal flow dynamics is strongly influenced by the process conditions, and peculiar flow patterns such as rarefaction shock waves, shock waves with either upstream or downstream sonic states, and split shocks are physically admissible. Complex thermodynamic models were devised and applied to the theoretical analysis and numerical simulation of non-ideal flows. However, only few experimental data in the NICFD regime were available up to date.
In the present work, experimental benchmark tests are devised and measurements are performed to provide assessment to NICFD theory, thermodynamic models and numerical simulation tools. Experiments are carried out in the Test Rig for Organic VApors (TROVA), the blow-down wind tunnel of the Laboratory of Compressible-fluid dynamics for Renewable Energy Applications (CREALab) of Politecnico di Milano, while numerical simulations are performed using the open-source NICFD solver SU2. Two main flow configurations are considered, namely adapted flows in planar converging-diverging nozzles and uniform supersonic flows with oblique shock waves and expansion fans.
An experimental campaign is carried out to study the NICFD flow of siloxane vapour MDM (octamethyltrisiloxane, $C_8H_{24}O_2Si_3$) in a planar converging-diverging nozzle. The nozzle is designed using the method of characteristics, complemented with state-of-the-art Equations of State (EoS) dealing with non-ideal flow behaviour. Operation of the nozzle is characterised through pressure and temperature measurements, schlieren visualizations, and numerical simulations. Numerical simulations and theoretical predictions based on the isentropic hypothesis for nozzle expansions agree well with experimental data. Consistently with NICFD theory, reservoir conditions are found to significantly influence both the pressure ratio and the Mach number distribution along the nozzle axis.
Numerical simulations and the NICFD theory are then extensively applied to the study of supersonic expansions in converging-diverging nozzles, both in the ideal and NICFD regimes. Two different topics related to the design and operation of converging-diverging nozzles are addressed. First, a design solution aimed at fixing the location of the minimum-area section of the nozzle is discussed. The geometry of planar converging-diverging nozzles operating with air and MDM is modified by the introduction of a small recessed step at the geometrical throat. The recessed step triggers boundary layer separation and fixes the location of the minimum-area section of the nozzle. Experiments and numerical simulations are applied to the analysis of the adapted flow. A complex perturbation wave pattern originates at the step location, and propagates up to the exhaust section of the nozzle through multiple reflections at the nozzle walls and interactions at the nozzle symmetry axis. Pressure measurements performed along the nozzle axis show that the perturbation introduced by the step influences the flow only locally. For the nozzle operating with MDM in the NICFD regime, the configuration of the perturbation wave pattern in the throat region is found to depend on reservoir conditions. Second, a key parameter for the design and performance analysis of supersonic nozzles is investigated, namely the discharged massflow rate. A closed-form expression for this parameter is derived analytically. The massflow rate is found to be dependent on the radius of curvature of the nozzle profile at the throat section, on the molecular complexity of the working fluid, and on process conditions. A numerical verification of the dependence of the discharged massflow rate on relevant design parameters is performed, both in the ideal and non-ideal flow regimes. The dependence of the massflow rate on the fluid properties and on process conditions is confirmed. Moreover, the discharged massflow rate is found to be affected by the overall shape of the converging portion, and not only by the local curvature of the nozzle profile at the throat section. This is true even in the case of smooth convergents.

A second experimental campaign is carried out to characterize oblique shock waves and expansion fans occurring in the NICFD regime. A diamond-shaped airfoil with semi-aperture 7.5° at leading edge and 10° at the trailing edge is placed in a uniform supersonic stream of MDM, which in test conditions is a single-phase vapour lying in the NICFD region. Two oblique shocks at the airfoil leading-edge and centred expansion fans at the shoulder are observed (Fig. 1). Oblique shock waves and expansion fans are studied at varying upstream stagnation conditions, for six deviation angles in the range θ = 6.5°-10° obtained by changing the attitude of the model with respect to the wind tunnel axis. Experimental results are assessed against the inviscid shock-expansion theory for two-dimensional steady flows, complemented with state-of-the-art EoS. All the geometrical configurations and operating conditions explored in wind-tunnel tests are reproduced numerically. In the inviscid core of the flow, where measurements are performed, numerical results agree fairly well with experimental data. A significant dependence of the pre-shock, post-shock and post-expansion states on the corresponding upstream flow conditions is found, and the speed of sound is seen to decrease across shock waves and increase upon expansion fans, consistently with the NICFD theory applied to the tested thermodynamic conditions.

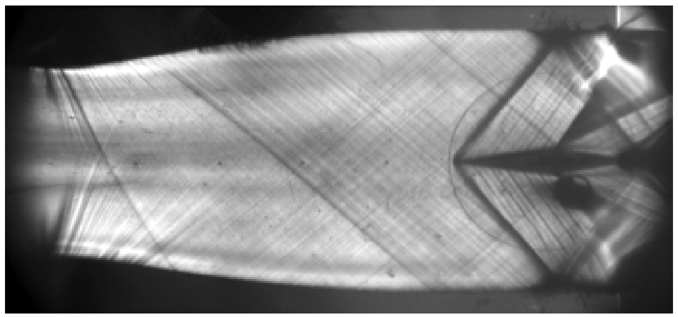

Fig. 1 - Schlieren visualization of the non-ideal flow of MDM in the diverging portion of the wind-tunnel nozzle and around a diamond-shaped airfoil. Darker gray levels are associated to positive streamwise density gradients (compressions) and lighter gray levels to negative ones (expansions). Mach waves are visible both in the diverging portion of the nozzle and in the flow around the airfoil.