DOCTORAL PROGRAM IN ROTARY WING AIRCRAFT

Chair:
Prof. Luigi Vigevano

Objectives

The Ph.D. program in Rotary Wing Aircraft aims at educating students and creating world-class researchers in all main technological disciplines relevant to rotorcraft vehicles. Helicopters and tilt-rotors present some of the most interesting and difficult challenges of the aerospace sciences; mastering such problems requires the understanding of the underlying physical processes, the integration of multiple disciplines, an effective use of sophisticated mathematical models, and of numerical and experimental methods. To reflect this situation, the Ph.D. program gives special emphasis to developing multi-disciplinary thinking and problem-solving skills in students, while striving to give the students a solid knowledge of the fundamental physical phenomena and of all necessary state-of-the-art methods and tools. Successful graduates of the program are expected to be able to conduct and manage original cutting edge research in the rotorcraft technology domain, with an ability to rapidly move in neighboring areas such wind power, fixed-wing and automotive engineering, or other related high-tech engineering fields.

Organization

The Ph.D. program has a duration of three years, and it is organized in three main educational areas:

1. Introduction to research (30 credits): specialized courses covering fundamental aspects of the basic rotorcraft disciplines, which aim at giving the student a solid understanding of the physical principles and methods used in rotorcraft research.
2. Advanced research (30 credits): various activities aimed at educating the student to become a successful researcher, while improving the technical understanding of the rotorcraft disciplines which are specific to his/her thesis. Activities that are developed in this part of the Ph.D. program include:
· Elective courses offered at the Politecnico di Milano or other Universities in Italy or abroad;
· Participation to short courses, summer schools and seminars;
· Co-authoring papers published in international peer-reviewed journals;
· Co-authoring and presenting papers at international conferences;
· Spending exchange periods at other research institutions.
3. Development of the doctoral thesis (120 credits): work on the thesis starts in the first year of the Ph.D. program (20 credits), and is developed in the second (40 credits) and third years (60 credits). In their theses, students are expected to develop original scientific work in any one of the areas that are relevant to the fields of rotorcraft technology.

Each student is assigned an Advisor, who is responsible for overseeing the scientific development of the research work, and a Tutor, who follows the students throughout the Ph.D. course and acts as a mentor. Students report every six months to the Doctoral Program Board, presenting their progress in terms of course and research work. At the end of each year, students are graded and admitted to the next year based on their performance. One or more external referees are nominated by the Board towards the completion of the thesis for its review.

Students should spend at least three months of the Ph.D. program in an external institution, and financial support is provided for this purpose.

Students collaborate in the rotorcraft-related research activities developed at the Departments of Aerospace Engineering, Mechanical Engineering and Information and Electronics of the Politecnico di Milano, and faculty members from all three departments participate in the Doctoral Program Board. Students have access to state-of-the-art laboratories, as the large wind tunnel of the Politecnico di Milano, various labs specializing in vehicle safety and crash testing, structural dynamics and aero-elasticity, composite and smart materials, robotics, sensing and many others, including computing and super-computing facilities.

The participating departments have wide networks of scientific collaborations with companies, research centers and academia in Italy and abroad, which expose students to the relevant national and international scientific communities. Much of the research developed within the Ph.D. program is conducted in close collaboration with the national rotorcraft industry.

The Ph.D. program in Rotary Wing Aircraft creates specialists in the design, analysis, testing, certification and operation of rotary-wing vehicles and their sub-systems. Specific competences are gained either in a single discipline or in the integration of disciplines, which include dynamics, fluid mechanics, flight mechanics and control, structures and materials, active and passive safety, and avionics.

Career opportunities for the students of the program are as researchers in academia or research centers, as highly-qualified research engineers, research managers or private consultants for rotorcraft, aeronautical, wind energy and mechanical engineering companies, in roles such as:

1. Expert in computational and/or experimental fluid mechanics, capable of developing methods, models, experimental devices and testing procedures for aeronautical applications, in particular for rotors and interacting surfaces;
2. Expert in the active and passive control of aerospace structures, with skills in both global and sub-system level design;
3. Expert in the control of vibration and noise in rotorcraft and vehicles in general;
4. Expert in the dynamics and control of vehicles, including the design and implementation of flight control systems for piloted and autonomous systems;
5. Expert in active and passive safety of vehicles, including the design of crashworthy structures, their numerical simulation and experimental testing;
6. Expert in the design of rotary-wing systems, with a global vision of the vehicle as an integration of complex sub-systems.

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# WING–ROTOR AERODYNAMIC INTERACTION IN TILTROTOR AIRCRAFT

Giovanni Droandi - Supervisor: **Giuseppe Gibertini**

Throughout history, the idea of an aircraft with the capability of Vertical Takeoff and Land-ing (VTOL) attracted the interest of many inventors and designers who proposed numerous solutions characterized by a wide variety of lifting and propulsion devices. An interesting solution is represented by the tiltrotor concept. A tiltrotor is an aircraft that combines the capability to hover, typical of helicopters, with the possibility to flight in cruise at high speed, like propeller driven aircraft. After about 50 years of research, tiltrotor aircraft are today a reality in the modern rotorcraft scenario combining together the advantages and the peculiarities of helicopters with modern propeller aircraft and representing a concrete possibility to overcome the main limitations of both of them. For these reasons and thanks to their high versatility, tiltrotor aircraft represent nowadays a very attractive compromise for the civil industry. How¬ever, some important limitations are still present in conventional tiltrotor design where the capability to convert from helicopter to aeroplane and vice versa is only given by the tilting rotors. For instance, in helicopter flight mode, the presence of the wing under the rotor modifies the rotor wake and is responsible for the loss of rotor performance. Moreover, the interaction

which occurs in helicopter mode between the wing and the rotors negatively affects the lifting capability of the aircraft. In particular, when the rotor wake impinges on the wing surface, an aerodynamic force of approximately 10%-15% of the rotor thrust is generated on the wing in the opposite direction of the thrust (download). As a consequence, to guarantee acceptable hover performance, large rotors have been adopted on conventional proprotors (XV-15, V-22 Ospray and BA609) however limiting the rotor effciency in cruise flight at high speed and preventing the take-off and landing in aeroplane mode.

Since the improvement of the performance in aeroplane mode is one of the focus points for future developments of new tiltrotor aircraft, non conventional tiltrotor configurations have been investigated during the years in order to preserve the performance in helicopter mode and to overpass the problems of interaction shown by existing tiltrotors. A possible approach to improve the performance in aeroplane mode, i.e. the propulsive effciency of the rotor, the maximum cruise speed reachable, and the aircraft operative range, is to significantly modify the blade shape by reducing the rotor diameter to get a propeller similar to the propeller aircraft ones. This

solution led to the tiltwing concept that has been recently adopted for the development of the European project ERICA (Enhanced Rotorcraft Innovative Concept Achievement). The main characteristic of a tiltwing aircraft is represented by the possibility to tilt the external part of the wing with the rotor, minimizing the wing surface on which the rotor wake strikes. Good hover performance are preserved in this way and the resulting download force on the aircraft is less than 1% of the rotor thrust. During the last fourteen years the ERICA concept has been studied under several points of view and it has been the subject of many research projects founded by the European Community. Even if ERICA has been widely studied, many aspects of this non conventional tiltrotor configuration, as same quite basic aspect of the aerodynamics of wing-rotor interaction, could be investigated more deeply for possible future evolutions of the tiltwing concept.

In the present research activity the aerodynamic interaction between wing and rotor on a high-performance tiltwing aircraft has been investigated. Both experimental and numerical approaches have been used to give a detailed description of the main physical phenomenon related to the interaction between wing and rotor in this kind of aircraft. At the beginning

of the activity, a tiltwing aircraft in the same class of ERICA has been defined. Thanks to its non conventional configuration and due to the tiltwing design, the aircraft had small rotors compared with the span of the wing. It follows that close to the aircraft symmetry plane the wing-rotor and rotor-rotor interferences were rather small and thus an half–model configuration could have been used instead of the full–span one. For this reason, all the studies of this research made use of an half-model configuration where just one half-wing and one rotor were reproduced. Numerical calculations have been adopted to design both the shape of the blade and the wing. In particular, the aerodynamic blade design has been performer by means of a multi-objective constrained optimization based on a controlled elitist genetic algorithm. The optimizer was founded on the NSGA-II (Non-dominated Sorting Genetic Algorithm II) and embedded a simple BEMT (Blade Element Momentum Theory) aerodynamic solver to evaluate the blade performance. Afterwards high accuracy calculations have been carried out on the resulting blade making use of the CFD (Computational Fluid Dynamics) code ROSITA (ROtorcraft Software ITAly) to verify its performance and to refine the shape of the tip which has been modified to reduce power losses due to onset of compressibility effects. In order to define the wing layout, the span of the tilting portion of the half-wing has been defined minimizing the drag force that raises on the half-wing in helicopter mode when the rotor wake impinges
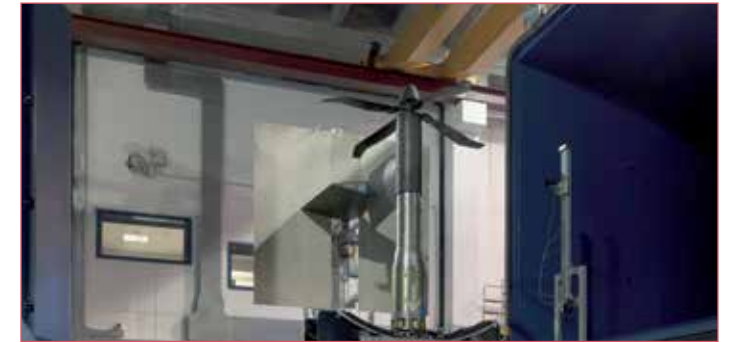
1. Experimental test rig for hovering tests in the open test section of the Politecnico di Milano Large Wind Tunnel.

on it. CFD calculations have been used to define the position of the tilt section along the span of the half–wing and an estimation of the wing download force has been done numerically at full-scale. Once the aircraft design was concluded, a 0.25 scaled wind tunnel half-model has been designed and manufactured to study the hovering condition in helicopter mode flight. The experimental test rig, reported in Figure 1 has been designed to test different wing configurations and different wing positions with respect to the rotor hub. The test rig consisted of two main components that were the rotor and the half–wing with an image plane. With the aim to measure the rotor and the wing loads separately, the two main systems were not linked one to the other. The systems have been designed to test both the isolated rotor and the aircraft half–model. A four–bladed fully articulated rotor hub was placed over an instrumented pylon and was powered by an hydraulic motor. The thrust given by the rotor has been measured by an holed six-component strain gauge balance located under the rotor hub while the torque has been measured by an instrumented

holed shaft directly linked to the rotor hub shaft. During the experimental tests, the nominal rotational speed of the rotor, which rotates in anti-clockwise direction, was n = 1120 rpm. The tip Mach number was 0.32 which corresponds to 1/2 the tip Mach number of full-scale aircraft at design point in hover. The wing, that was mounted on an independent traversing system, was linearly tapered and untwisted. Forces and moments on the wing have been measured by a seven-component strain gauge balance located at the wing root. The test rig was used to produce a extensive experimental database which allowed to well describe the flow field and the performance of the aircraft, as well as to offer the possibility to validate CFD codes. Since in hover the interaction between the rotor and the wing is very complex, force measurements may give only partial information about the phenomena related to this non conventional configuration. Therefore, the hover flight condition has been analysed also making use of an extensive PIV (Particle Image Velocimetry) measurement campaign.

INVESTIGATION OF MECHANICAL BEHAVIOR OF MATERIALS FINALIZED TO IMPROVE NUMERICAL ANALYSES OF DAMAGE ON AIRCRAFT STRUCTURES

Andrea Gilioli - Supervisor: **Prof. Marco Giglio**

Nowadays, structural numerical simulations are common and commercial Finite Element software allow to reproduce even very complex fracture phenomena. From a common point of view, such technological progress is obviously positive, but on the other hand, the existence of user-friendly software, is at the same time source of several possible issues. Indeed, even without a full understanding of the problem theory background, it is quite easy to perform simulations. However, the obtained results could be misconceived and they could potentially lead to severe design errors. The most common disregarded aspect in numerical analysis concerns the material calibration, even though this element is always present in every structural simulation. Very often for usual numerical applications, the importance of material modelling is forgot, and designers just blind trust literature material data. This approach is reasonable for common industrial applications, when the reduction of time-consuming activities is a priority. However, for some critical components, a very high numerical accuracy level is required. Such components are especially the ones whose fracture could lead to severe safety issues. Examples of these applications are common

for the aerospace industries, where safety is a priority task. Besides, vehicles like aircrafts or helicopters are not mass products, so the adoption of a more time consuming and accurate material calibration is feasible, only marginally affecting the final price.
In the present thesis, a complete methodology has been developed in order to demonstrate how is possible to manage a finite element analysis of an aircraft component, starting from the material calibration, up to the final validation in a complex load scenario. Among all the possible load cases, impact has been chosen as a relevant example. The idea is to calibrate the mechanical properties of the material, starting from simple tests, validate them in standard applications, and finally apply such calibration in complex impact simulations. Specifically, the thesis deals with the characterization of the mechanical behavior of sandwich panels adopted as helicopter frames, and the characterization of thin walled shafts, which are part of the tail transmission of a helicopter. To be more specific, the tested structure are sandwich panels with aluminum skin and Nomex honeycomb core and Al6061-T6 aluminum alloy shafts. Each of these components has been tested
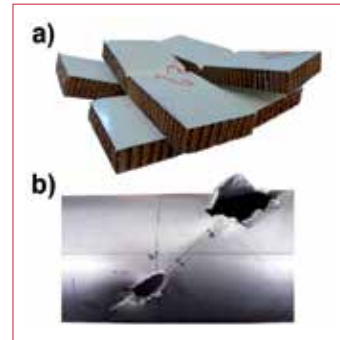
1. a) Sandwich panels after the three point bending test b) Aluminum shaft after the ballistic impact test

in a realistic load framework: sandwich panels have been examined investigating low velocity impacts, which is a reasonable load condition for helicopter frames (take off\ landing debris, hailstones, bird impacts) whilst the transmission shaft has been tested by means of a ballistic impact, which is the most critical impact scenario for such components.
The thesis can be divided into two parts. The first one deals with sandwich panels and it consists into a comprehensive experimental/numerical program, aimed at the description in detail of the mechanical behavior of sandwich panels for a wide range of applications (from flatwise compression test up to low velocity impact and three points bending test). The mechanical behavior of the material has been assessed

through experimental/numerical comparisons based on simple tests (such as the flatwise compression one) and finally, the same numerical model has been exploited to describe low velocity impacts. The developed model belongs to the category of the micromechanical ones. This means that each honeycomb core cell has been reproduced adopting a geometry very close to the real one. The consequence of this approach is a very heavy model but at the same time able to reproduce with an impressive accuracy, the real behavior of the sandwich panels core. This has led to obtain a very good similarity between the numerical and experimental damage shape of low velocity impacted panels. The first part of the thesis offers also peculiar findings regarding the evaluation of the residual structural integrity of sandwich panels after low velocity impacts. Indeed, through an experimental compression after impact (CAI) program, the residual strength of damaged panels has been investigated and applying statistical methods, the most important factors influencing the strength of the panel have been highlighted.
The second part of the thesis deals with the material calibration of an Al6061-T6 aluminum alloy. Two different phenomenological ductile damage criteria have been
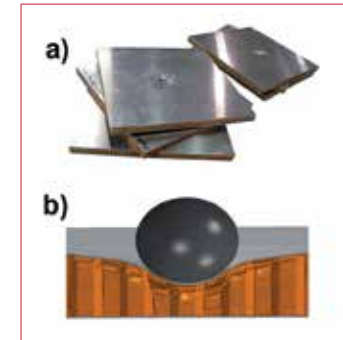
2. a) Sandwich panels after the low velocity impact test b) Numerical model of the low velocity impact test

calibrated: the Bao-Wierzbicki and the Modified Mohr-Coulomb. Material data have been acquired through an experimental program based on uni and multi-axial test on round and notched specimen. All the test have been numerically reproduced, and by means of numerical models, it has been possible to calibrate the damage criteria. The validation of the material model has been done on the base of a series of different applications including tensile test on dogbone specimen, tensile test on a specimen cut from a thin wall tube, the reproduction of a fracture toughness test and finally the simulation of a ballistic impact test on a section of a helicopter transmission. The material model demonstrates its accuracy for all the different load cases. In particular, concerning

3. Numerical reproduction of the ballistic impact on the aluminum shaft at two different instants

the high velocity impact, a high similarity in the reproduction of the damage and an impressive estimation of the residual speed of the bullet have been obtained. Finally, the thesis demonstrates the potential of a well-applied virtual test methodology, which can reduce experimental, difficult, expensive and time-consuming tests, replacing them with numerical, more controllable and cheaper models. The key aspect of the entire virtual test approach is the initial very accurate material calibration, based on relatively simple tests, followed by the validation of the goodness of the model, applying the calibration to much more different and complex load cases compared with the ones adopted for the calibration.

MULTIDISCPLINARY CO-SIMULATIONS FOR MICRO VEHICLES AEROELASTICITY

Tommaso Solcia - Supervisor: **Prof. Pierangelo Masarati**

Micro Aerial Vehicles (MAVs) promise very interesting solutions in several fields, such as environmental monitoring, homeland security and over the hill military missions.
As the size of vehicles becomes smaller than few centimeters, fixed wing designs encounter fundamental challenges in lift generation as well as in flight control. Flapping wing MAVs represent an interesting solution to the challenging task of designing efficient, hover-capable micro-vehicles, overcoming the reduced efficiency at low Reynolds numbers of hover-capable vehicles based on conventional rotary wing designs. Flapping wings have the capability to produce both lift and thrust forces: as demonstrated in nature by insects and small birds, this offers the possibility to stay aloft and hover, and also to perform extreme manoeuvers.
To design high performance machines, it is always of major importance to understand the physics governing the behavior of all components involved in its functioning. After this target is achieved, it will be possible to define efficient and reliable methods to predict the overall behavior of the final product. The final objective, of course, is to provide the designers with the methods developed.

Even if MAVs prototyping is not extremely expensive, it can be significantly time consuming, error prone and subjected to reproducibility issues. Thus, the possibility to build efficient, reliable and accurate simulation models becomes important. The problem requires the capability to take into account the flapping and pitch mechanisms, together with the aerodynamics coupling. It is also necessary to model geometrical nonlinearities to correctly describe the structural dynamic behavior of rather flexible structural components.
This thesis is intended to present the issues related to the definition of such a simulation environment, and to show a possible solution: a software environment has been constructed and is shown to correctly predict the aeroelastic behavior of flapping wings. For this kind of problems, Multibody System Dynamics (MSD) represent an ideal modeling environment, since it allows to directly consider mechanism modeling together with structural dynamics, and is well suited to interact with external solvers capable to model the aerodynamics. The optimal layout to tackle this kind of problems is to exploit the so called co-simulation technique.
Resorting to efficient

interprocess communication, a multidisciplinary environment has been constructed, in which different software are dedicated to solve the numerical models of each involved discipline.
The free general-purpose multibody solver MBDyn is selected as the core of the fluid-structure coupled simulation. This has been connected to solvers developed within the OpenFOAM environment, which are dedicated to solve the Navier-Stokes equations to evaluate aerodynamic loads and fields surrounding the vehicle components. OpenFOAM is basically a library containing the necessary objects to build solvers for partial differential equations: users are expected to develop their own solvers. Thus, it will be shown in the thesis how, starting from an incompressible RANS solver (known as pimpleFoam), communication capabilities have been added to integrate this tool into the co-simulation toolbox.
An Immersed Boundary implementation capable of simulating moving objects is also proposed to give the possibility to tackle even the most promising (and challenging) solutions, such as the clap and fling layout.
Within this context, a new implementation of a low-order membrane element has been

proposed. The need to consider the membrane structural model arose in consideration of the fact that advanced solutions for flapping wing MAVs require very thin structural components, capable to undergo very large geometrical deformations. This type of structure has been already analyzed in previous works, where the implementation of a geometrically nonlinear shell element was presented and used in conjunction to an already available nonlinear beam element: these investigations were based on geometrically nonlinear shell elements with the thickness set to a very small value. Their replacement with a membrane model promises the possibility to reduce the computational cost, by halving the size of the model, the complexity of the formulation and the ill-conditioning of the problem, by eliminating the need to resort to extremely thin shell elements.
The capabilities to model both a precise kinematics and a flow dominated by large vortices is a key aspect to simulate the flapping wings aeroelastic behavior. Also, many different flapping wings configurations can be exploited, all of which promise high performances, either in terms of stability, maneuverability and control, and in terms of weights, dimensions and overall costs. The main idea behind this thesis is to present an efficient and versatile software toolbox dedicated to the numerical simulation of flexible micro flapping wings. One additional aspect of the development will be to propose a complete free software environment, such that

it will be publicly available and eventually easy to be modified and enhanced in the future. Since the need is to develop a software that would be suited to simulate the behavior of many different configurations, rather than showing one conclusive application relative to a particular machine design or optimization, several applications will be shown, each relative to a particular solver characteristic: i.e. one application will underline the structural model behavior, while a different one will be dedicated to show an original feature implemented in the aerodynamic solver, such as the Immersed Boundary technique. This approach is followed to demonstrate the software feasibility in predicting the behavior of actual solutions, and, possibly, even future layout enhancing the Micro Vehicles characteristics. In particular, a description will be given about the approach that will be followed in building the software environment. Since the multibody solver will be dedicated to the solution of the structural dynamics, its details will be discussed, together with the presentation of the new structural element specifically dedicated to the flapping wing structures modeling. Detailed informations will be given about the different aerodynamic solvers exploited during the development of this work (both a Vortex-Lattice and a Navier-Stokes implementations have been used). Since the Navier-Stokes solver has been extended through an original solution in order to simulate body motions through the Immersed Boundary Method, this implementation

is briefly described, together with the validation of the approach. Some numerical and physical concepts are recalled to justify the choices driving the definition of the interface algorithm to describe the way the aerodynamic and the multibody solvers interact. Finally, the feasibility of the software environment will be demonstrated through different practical applications, even if no simulation will be presented that exploits all of the features in one single case. In particular, the different aspects analyzed will be the capabilities in simulating flexible structures behavior when subjected to aerodynamic loads in typical MAV regimes; the limit of applicability of lower fidelity approaches, such as Vortex-Lattice method; the enhancement of computational efficiency by the multirate technique; the need to consider geometric nonlinearities in the structural behavior; and, finally, the extreme versatility of the Immersed Boundary Method, to even simulate the most challenging case of the clap and fling solution.