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

PhD Yearbook | 2017

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 Chair:
Prof. Luigi Vigevano 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 Tecnospazioprogram 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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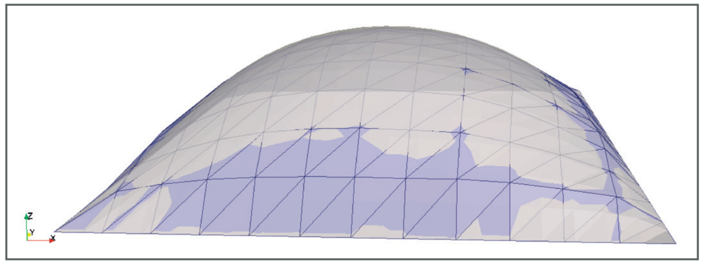
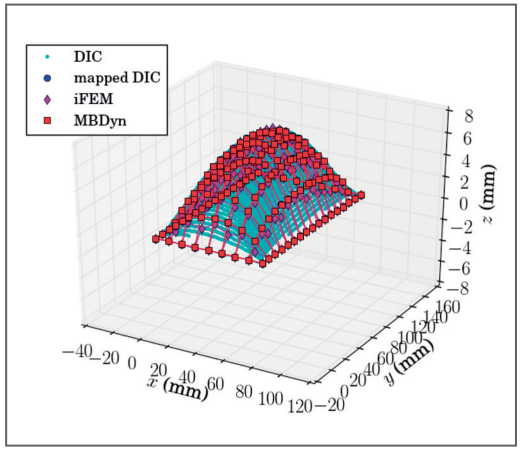
REAL-TIME WING-VORTEX AND PRESSURE DISTRIBUTION ESTIMATION ON WINGS VIA DISPLACEMENTS AND STRAINS IN UNSTEADY AND TRANSITIONAL FLIGHT CONDITIONS

Alioli Mattia – Supervisor: Prof. Marco Morandini

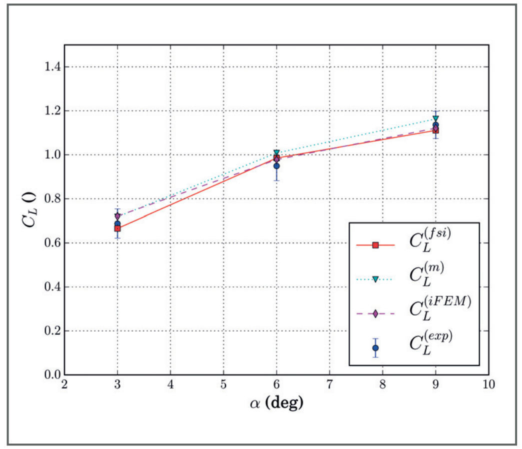
This thesis investigates the aeroelastic performance of membrane wings made of latex rubber for Micro Air Vehicle (MAV) applications, and seeks to obtain a full-field estimations of the structural displacement field.
A direct dynamics analysis is used to predict the deformed shape under specified loads. It is performed using a tightly coupled fluid-structure co-simulation in which the structural problem is solved using the free general-purpose multibody dynamics solver MBDyn (http://www.mbdyn.org) and the fluid problem is solved using a dedicated solver based on a stabilized finite element approximation of the unsteady Navier-Stokes equations (G2 method).
An inverse kinematics analysis is used to reconstruct the membrane shape from experimentally measured (discrete) surface strains. The reconstructed shape of the membrane is thus used to estimate the surface loads.
The inverse problem of full-field structural displacement reconstruction is addressed through the application of a variational formulation, leading to a versatile, robust and computationally efficient inverse membrane nonlinear finite element analysis (iFEM), which was inspired by analogous, although linear, approaches developed in the past for shell-like structures. In the current case, non-linear elasticity is mandatory to capture the essence of the transverse load carrying capability of membranes: the assumption of constant membrane pre-stress used in linearized membrane models is no longer acceptable. Moving Least Squares (MLS) are used to smooth and remap surface strain measurements, estimated from Digital Image Correlation (DIC), as needed by the inverse solution meshing. The same approach is used to map the structural and fluid interface kinematics and loads during the fluid-structure co-simulation.
The inverse analysis is first verified by reconstructing the deformed solution obtained with an analogous direct formulation (applied on a different mesh and subsequently re-sampled).
A direct (forward) problem of a square membrane inflated under the action of the distributed transverse loading (hydrostatic pressure) is considered. The exact strains are computed from the direct problem and are used to represent the measured strain data. Very good results have been obtained using a finite element implementation of the proposed inverse analysis concept within the programming environment provided by FeniCS (http://www.fenicsproject.org). **Fig.1** compares the deformed shape of the square membrane subjected to uniform pressure on one side, obtained by finite element analysis, with the corresponding deformed shape obtained using the proposed iFEM procedure.
Both the direct and the inverse analyses are then validated by comparing the direct predictions and the reconstructed deformations with experimental data for pre-stressed rectangular membranes subjected to static and unsteady loads. The load distributions reconstructed using the inverse analysis are compared with the corresponding ones obtained using the direct analysis. Correlation is sought with respect to experimental results obtained in test campaigns performed at Oregon State University, where elastic deformations and strains are measured using DIC.
The verification procedure is the following: the strain measurements, re-sampled onto the numerical grid that is subsequently used for iFEM analysis by means of the MLS procedure, are used as inputs for the iFEM analysis, whereas the resampled (transverse) displacements are used to evaluate the quality of the reconstructed displacements via iFEM and of those predicted using the tightly coupled fluid-structure co-simulation.
The first scenario is a hydrostatic pressure case where a pre-tensioned membrane is subjected to a constant known pressure. Strains and deformations of the membrane are measured using Oregon's DIC apparatus. Results in terms of transverse displacements are favorable (**Fig.2**). Furthermore, the average hydrostatic pressure estimate is reasonably close to the actual applied hydrostatic pressure. The proposed approach thus allows to estimate aerodynamic loads present on a flexible membrane wing from elastic strain sensors.
In the second scenario, a membrane wing is placed in a low speed wind tunnel, and wind speed and angle of attack are varied. Aerodynamic loads generated by the wing and DIC measurements of the membrane deformation are measured. The parameters considered in these tests are the AoA, the initial prestrain and the flow velocity. **Fig.3** shows the average coefficient of lift measured by the load cell attached to the wing (labelled "exp"), throughout the AoA-sweep, for V=15 m/s and PS=2%. It also shows the coefficient of lift calculated by the coupled fluid-structure simulation ("fsi"), and the estimated coefficients of lift found by integrating the estimated pressure distributions (from the remapped full–field DIC measurements, "m", and from the estimated displacements via inverse analysis, "iFEM", respectively).
The non-linear membrane structural model thus allows to predict the performance of inflated membranes. It is therefore applicable to both static and dynamic problems.
The proposed procedure for the reconstruction of shape and distributed loads is able to operate at sample rates of the order of 30 Hz, thus meeting the real-time operation requirements.



1. Deformed shape of a square membrane subjected to uniform pressure (surface: reference FEM solution; wireframe: iFEM)



2. Correlation of hydrostatic pressure problem, dp= 500 Pa



3. Static lift model and wind tunnel data, membrane at 2% prestrain, V = 15 m/s

FLEXIBLE SYSTEMS DESIGN FOR AUTONOMOUS CAPTURING, MANOEUVRING AND DISPOSING OF UNCOOPERATIVE SPACE OBJECTS DEVELOPMENT OF DYNAMICS AND CONTROL MODELS AND VALIDATION BY EXPERIMENTAL PROTOTYPING

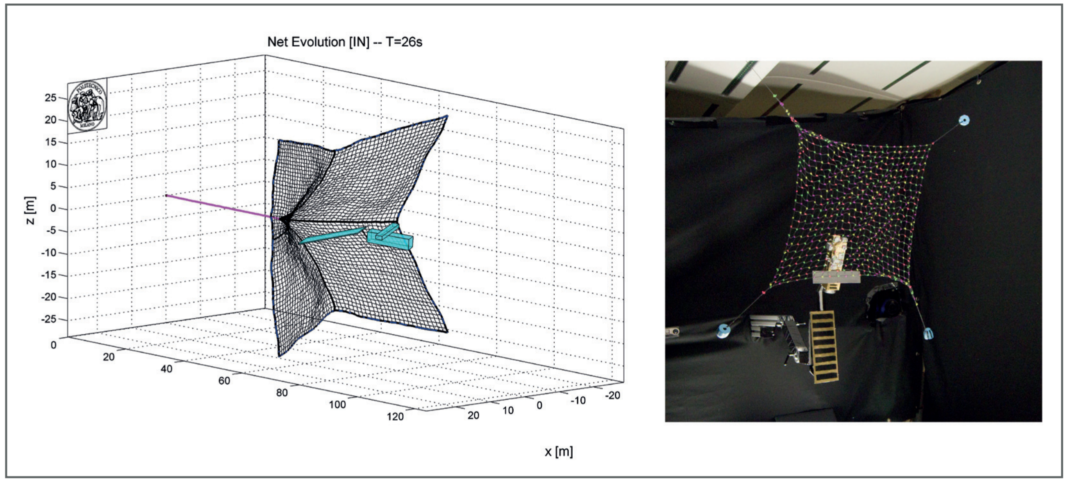
Benvenuto Riccardo – Supervisor: Prof. Michèle Lavagna

The steadily increase of the space debris population around Earth is threatening the future of space utilization for both commercial and scientific purposes: both a disposal policy, to properly manage new space vehicles end-of-life, and active remediation are necessary to guarantee safe operational life time for current and future space systems in Earth orbit. Active debris removal (ADR) deals with inactive spacecraft disposal from operational orbits, while on-orbit satellite servicing (OOS) is aimed at extending the lifetime of operational satellites through refuelling and maintenance. The development of a chaser satellite able to perform autonomous servicing/removal mission is a complex, multidisciplinary and challenging task: such missions require the application of many sophisticated technologies and reliable lightweight manipulators capable of autonomously capturing and manoeuvring uncooperative or partially cooperative tumbling objects which are not equipped with dedicated docking ports and whose physical and dynamics characteristics are uncertain and not known a priori. These tasks entail a high level of autonomy, hence defining new challenges for Guidance, Navigation and Control (GNC) systems. To perform ADR and OOS tasks, different techniques are currently being investigated and this research focuses on two: tethered-nets to wrap and pull the target and robotic arms to grasp and push it. From dynamics point view, these technologies differ for the flexibility involved in different elements and connections and for their control. Validated simulation tools describing multibody dynamics of ADR and OOS systems, and their stabilization via control laws, are considered of primary importance for technology development, future missions design as well as experimental breadboard prototyping.

During the thesis work, a validated software tool was developed to describe the multibody dynamics involved in these scenarios and to enable fast analysis and GNC design and testing. It provides a fast and accurate simulation environment to describe multiple bodies' six degrees of freedom dynamics, possibly linked by different flexible/rigid connections and including flexible appendages, propellant sloshing and a detailed environmental model. Upgrades of the abovementioned simulator were also implemented to model robotic manipulators dynamics as well as the deployment and wrapping dynamics of flexible nets around targets, with the inclusion of collision detection and contact dynamics algorithms. To discretize and model the structural flexibility of different elements and connections, lumped parameters models were chosen as the best compromise between fast and accurate, allowing numerically stable simulations, faster management of collision detection and contact dynamics, an arbitrary discretization of the problem and the parallelization of the code. The developed simulator allowed to assess the capture techniques feasibility and to describe the overall dynamic behaviour, including the unforeseen dynamics arising from the interaction between two isolated bodies, becoming a single multibody system to manoeuvre.

Guidance and control laws for capturing and proximity manoeuvring were also synthetized to demonstrate the feasibility of such kind of missions and study the performances of different control techniques to trade-off the most adapted ones with respect to every configuration and grasping technique, i.e. flexible versus rigid.

Precise numerical simulations results were obtained for all the considered scenarios, to drive



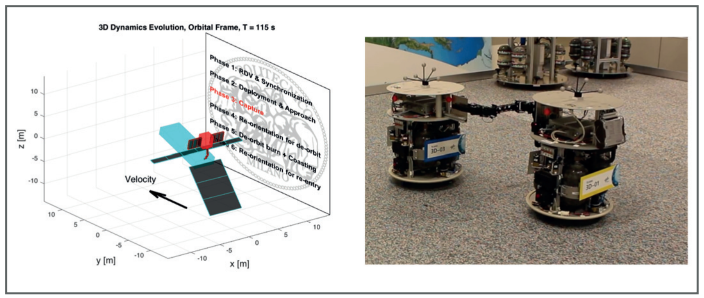
1. Net capture simulation of reference orbital scenario and scaled model microgravity testing in parabolic flight facility

system design: tethered-net and robotic arm technologies were researched in detail both from engineering design and control points of view.

To validate the developed dynamics models and test the implemented control laws, prototyping and implementation of experimental breadboards as well as tests on the scaled prototypes were performed in relevant environments exploiting parabolic flights and air bearing, force/torque free, facilities. A microgravity campaign was successfully conducted in June 2015, in the framework of the ESA funded activity *Patender*, to validate both net flexible dynamics and contact dynamics models, through stereovision, exploiting a 3D trajectory reconstruction tool, implemented ad hoc for the experiment. In Figure 1 the tethered-net scenario is presented: an example of the orbital reference scenario simulation is reported as well as the scaled prototype during microgravity tests.

As a part of a research stay at the German Aerospace Agency (DLR), a robotic arm breadboard was implemented in the low friction facility *TEAMS* and a hardware-in-the-loop (HIL) test campaign was executed to validate the combined arm-vehicle control techniques. Figure 2 depicts the robotic arm scenario, showing examples of the orbital reference scenario simulation and the HIL testing. Finally, a second parabolic flight campaign was carried out in the framework of the European Space Agency's *Fly Your Thesis' SatLeash* Project, to test and validate tether dynamics and stabilization via wave-based and input-shaping control laws.

By exploiting these experimental data, mathematical models and simulation tools were eventually validated, obtaining accurate match of dynamics behaviours and good performances of control laws. Today, the analysed techniques have acquired a high level of design maturity and are ready for an autonomous in-orbit demonstration mission, as the next phase of technology development.

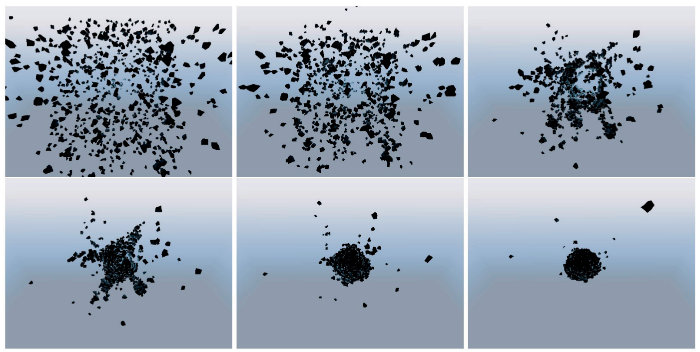


2. Robotic capture simulation of reference orbital scenario and hardware-in-the-loop testing at the DLR's TEAMS facility

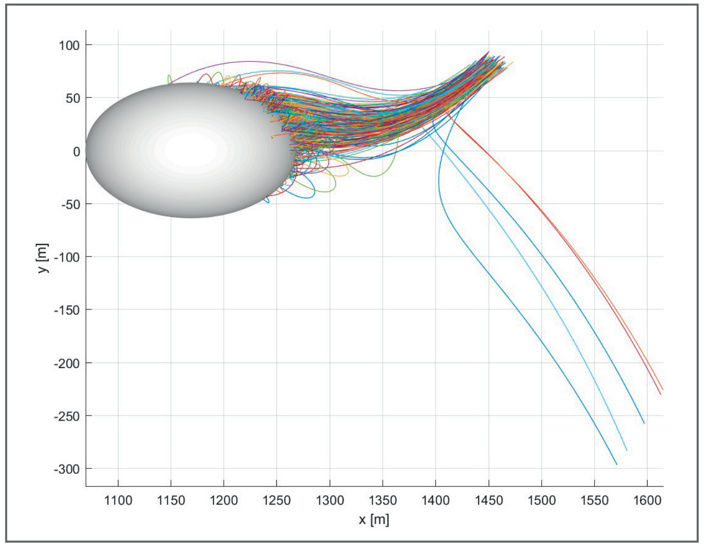
NON-KEPLERIAN MODELS FOR MISSION ANALYSIS SCENARIOS ABOUT SMALL SOLAR SYSTEM BODIES

Ferrari Fabio – Advisor: Prof. Michèle Lavagna

Non-Keplerian gravity models are the present and future frontier of astrodynamics. They provide unique opportunities for mission analysis and open to a great variety of design solutions not available whenever a single point-mass gravity source is dealt with. From the space mission design point of view, the modeling of the gravitational environment through the use of multiple or non-spherical gravity sources can be effectively exploited to design convenient orbital paths, to meet challenging requirements due to on-board payloads, to decrease the cost of maneuvers to be provided by the spacecraft.
The use of non-Keplerian dynamics to fly space missions was largely studied in the second half of the 20th century and found interesting applications since the launch of ISEE-3 in 1978, the first spacecraft whose mission analysis was designed using a three-body strategy. In the last few decades the space community has put a lot of effort into the exploration of small Solar System bodies, such as asteroids and comets. Motivated by a great scientific interest, the exploration of small celestial bodies represents the current and future frontier to extend the mankind's knowledge on how our Solar System was formed and how it evolves. In addition, small bodies represent an ideal place for technology demonstration missions as they can serve as a test bench for deep-space In-Orbit-Demonstration (IOD) experiments. Due to their peculiar properties, small celestial bodies provide the unique opportunity of having a natural low-gravity environment that can be used to study gravitational dynamics and for many technological-related applications.
The thesis work focuses on the implementation of non-Keplerian models and their applications to space mission analysis scenarios. Non-Keplerian dynamics are used to accurately reproduce the gravity field around small Solar System bodies such as asteroids or comets and to conveniently exploit their gravitational environment for trajectory design purpose. Compared to Earth or other planets in the Solar System, small celestial bodies are characterized by very weak and irregular gravity field. This turns into a highly challenging mission analysis to be solved when designing a space mission. From the dynamics point of view, irregular field means highly chaotic motion, with dynamics extremely sensitive to initial conditions. From the spacecraft design point of view, this means that a very small deviation in the state, which can be due e.g. to navigation or maneuver errors, can result in a very large discrepancy in the subsequent motion. This is very relevant for the case of close-proximity operations and for example when collision avoidance or soft-landing constraints are to be considered. In such case the chaotic nature of the environment can lead to real world trajectories that does not satisfy the constraints (colliding or not landing on the asteroid), even when they are fulfilled by the nominal trajectory. For these reasons, the effective design of trajectories to fly a spacecraft in the proximity of an asteroid requires the knowledge of the physical, inertial and dynamical properties of the target body. Due to their non-spherical mass distribution, a simple Keplerian model is not suitable to accurately represent the dynamics around small bodies. In some cases, when the mass distribution is very far from being spherical, the Keplerian model can lead to very inaccurate results, which are not acceptable for mission analysis design applications. This motivates the use of non-Keplerian dynamics to model the environment in the close proximity of such objects. The mass distribution of such bodies is modeled by means of either mass-concentrated or shape-based models. Mass-concentrated models have the significant advantage to require less computational effort and also, they naturally simulate the effect of having a non-uniform density distribution and the presence of voids in the internal structure of the celestial body. The mass-concentrated model is obtained here by means of asteroid N-body gravitational aggregation (Figure 1). Shape-based models can reproduce to higher fidelity the gravity field around homogeneous small bodies, given their shape and density distribution, at the cost of a higher computational effort required, compared to mass-concentrated models. Relevant solutions, of interest for space mission scenarios aimed at the exploration of asteroids or comets, are found by using nonlinear system dynamics techniques applied to non-Keplerian astrodynamics problems. Such solutions include periodic motion and invariant manifolds associated to equilibrium or periodic solutions in the proximity of such bodies. Mission analysis scenarios are studied for the case of exploration of binary asteroid systems. Investigated scenarios include landing about a binary asteroid with a two-lobed elongated primary, designed through a patched three-body approach. Close-proximity operations in the context of the Asteroid Impact Mission (AIM), the European contribution to the Asteroid Impact and Deflection Assessment (AIDA), a joint mission between ESA and NASA aimed to rendezvous with binary asteroid (65803) Didymos, are investigated and suitable solutions are presented to land a probe on the smaller asteroid of a binary couple. The design strategy foresees the use of manifold dynamics associated to the three-body system of Didymos binary asteroid to safely land a probe on the smaller asteroid of the couple (Figure 2). More in detail, the dynamics of the probe in the proximity of the binary asteroid are studied using a three-body model with non-spherical gravity sources: since the mass distribution of the asteroids is expected to be very irregular, shape-based models are used to model the two asteroids. The last scenario studies formation flying dynamics in the proximity of libration point orbits associated to a binary system.



1. N-body aggregation process for asteroid formation



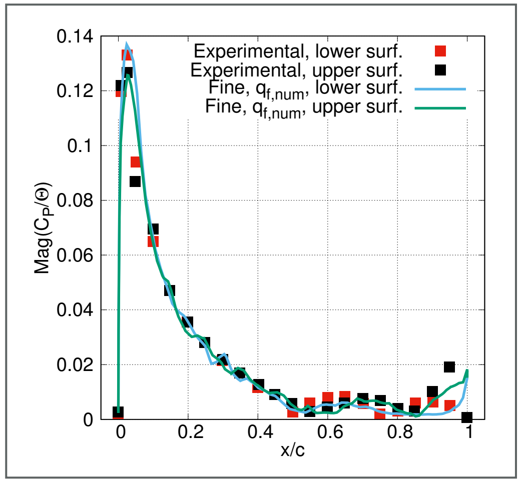
2. landing dispersion analysis after MASCOT-2 release (Asteroid Impact Mission)

A UNIFIED GPU-CPU AEROELASTIC COMPRESSIBLE URANS SOLVER FOR AERONAUTICAL, TURBOMACHINERY AND OPEN ROTORS APPLICATIONS

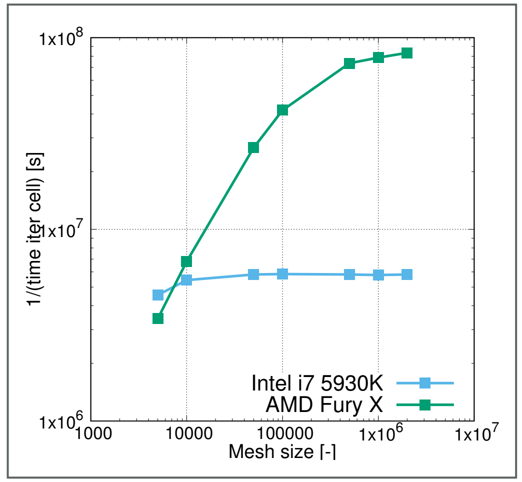
Gadda Andrea – Supervisor: Prof. Paolo Mantegazza

Co-supervisor: Prof. Giulio Romanelli

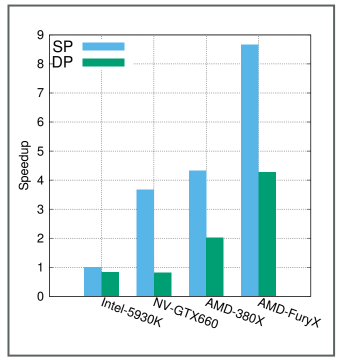
The goal of this PhD thesis is the development of a modern C++/OpenCL-based aeroelastic compressible URANS solver (finite-volume, cell-centered), called AeroX. The idea is to use cheap gaming GPUs (from the most important vendors like NVIDIA and AMD) in order to accelerate CFD/FSI simulations while maintaining costs and power consumption under control. The C++ based OpenFOAM framework is adopted for the pre-processing and post-processing stages while the bulk of numerical computations is performed by ad-hoc OpenCL based kernels. The choice of OpenCL allows the possibility of running simulations also on multi-core Intel and AMD CPUs, exploiting multi-threading. In order to fully exploit the single precision computational power of gaming GPUs, the compressible URANS equations are solved in a non-dimensional form. AeroX is also natively compatible with double precision. The limited amount of graphic memory and the typical SIMT architecture are exploited by implementing an explicit time-advancing scheme. AeroX is capable to handle hybrid unstructured meshes, guaranteeing the compatibility with different mesh generation tools. Convergence is accelerated using Local Time Stepping, Residual Smoothing and Multi Grid, to get an implicit-like residual damping. While these strategies allow to quickly find steady-state solutions, they cannot be directly applied for unsteady simulations. Dual Time Stepping is thus implemented for unsteady simulations. High resolution convective fluxes (e.g. Roe), Spalart-Allmaras and SST turbulence models are implemented to guarantee accurate solutions. Analyses that require wall shape changes (e.g. trim, flutter, forced oscillations) are handled using a Radial Basis Functions strategy to interface the aerodynamic and structural meshes. An Inverse Distance Weighting scheme is adopted to allow a smooth mesh deformation. Furthermore, a modal-based model reduction strategy is employed in order to represent the structural behavior in a both accurate and computational efficient manner. Alongside typical aeronautical cases, such as aircraft, AeroX is also aimed to simulate the flow-filed around turbomachinery and open rotors blades. In order to exploit the spatial periodicity of such configurations with the aim of reducing the computational domain to single or multiple blades sectors, different strategies such as periodic boundary conditions, time-delayed boundary conditions, Moving Reference of Frame and Mixing Plane are implemented.
The credibility of the CFD solver is assessed by tackling a number of aeronautical, turbomachinery and open rotor cases. The purely aerodynamic formulations are validated through well known cases such as the 2nd Drag Prediction Workshop, the Onera M6 wing and the Aachen 1.5 stages turbine.
Besides classical CFD simulations, AeroX is also aimed to perform both static and dynamic aeroelastic analyses. Trim analyses are employed to improve results accuracy of steady cases by considering the effects of the structure deformability.
The solver is validated using the well known HiReNASD wing, considering both inviscid and viscous analyses. Given the fact that in the literature it is difficult to find static aeroelastic analyses of turbomachinery blades, the trim of the NASA's Rotor 67 fan blade is performed, highlighting that the very high blade stiffness is responsible for the small differences between trim and purely aerodynamic results.
In this work dynamic aeroelastic investigations are aimed to predict flutter for different kinds of configurations, providing results in agreement with experimental data and numerical reference data. Different well-known cases like the flutter of the AGARD 445.6 wing, the flutter of the SR-5 open rotor blade and the aerodynamic damping analysis of the Standard Configuration 10 turbine blade are used to perform the solver validation. The most important result is represented by the flutter prediction of the BSCW wing of the 2nd NASA's Aeroelastic Prediction Workshop (2015), for which AeroX provides good results, comparable with what provided by other research groups employing the state-of-the-art aeroelastic solvers. As an example, for this case, figure 1 shows the comparison between AeroX results and experimental data at computational flutter dynamic pressure (98% of the experimental dynamic pressure). These results are obtained with a single 240€ AMD 380X GPU in 133h with a 1.1M cells mesh, simulating 9.0s with a 2.4E-4s physical time step.
Computational performances benchmarks are also performed to asses the advantages provided by the exploitation of gaming GPUs. Both low-end and high-end CPUs and GPUs are adopted for the comparisons. To be fair, the solver is executed with real test cases like the Rotor 67.
CPU executions exploit all the available cores. The GPU speed-up dependency from the mesh properties is also investigated. Figure 2 shows the time/iteration/cell performance parameter dependency from the mesh size, highlighting that GPUs are fully exploited with at least 1M cells. Finally, tests are also performed to prove the accuracy of results using single precision instead of double precision and to prove that ECC memory, provided by high-end expensive HPC GPUs is not mandatory for this work. An average one order of magnitude speed-up is obtained when performing simulations with CPUs and GPUs of about the same price level, power consumption and time period. Figure 3 shows the speed-up obtained with different devices, taking as reference the high-end 6-core CPU execution times.



1. AeroX vs. exp. data, FRF of the normalized Cp over the 95% wing span section



2. Speed-up dependency from mesh size, CPU vs. GPU

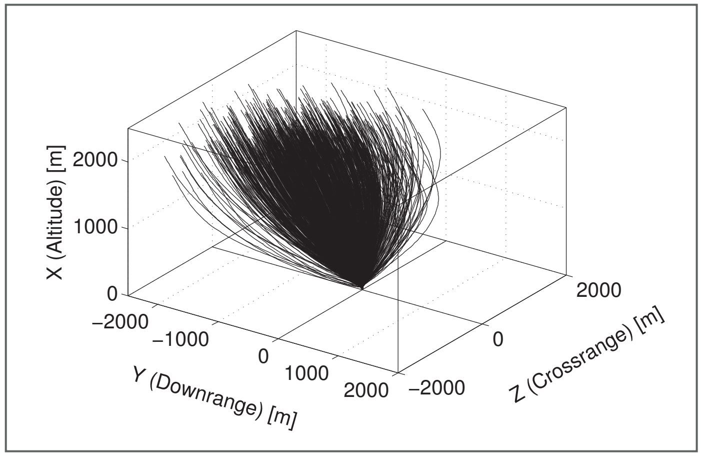


3. Speed-up provided by gaming GPUs, single vs. double precision executions

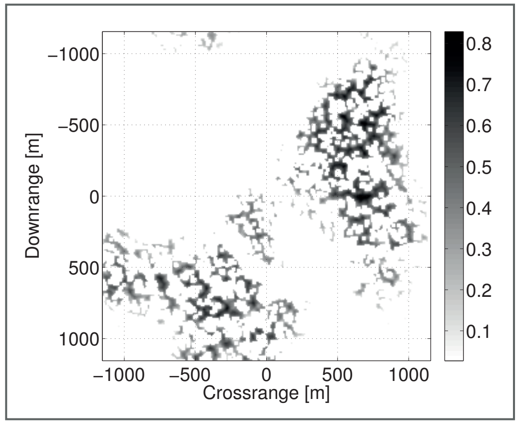
HAZARD DETECTION AND AVOIDANCE SYSTEMS FOR AUTONOMOUS PLANETARY LANDING

Lunghi Paolo – Advisor: Prof. Michèle Lavagna

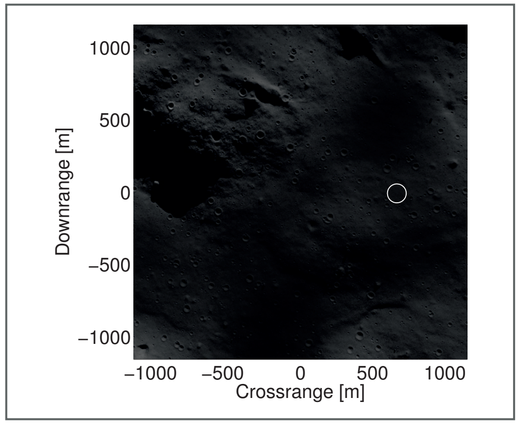
Landing is one of the most critical tasks that could be involved in a space mission: a failure encountered in this phase would lead with high probability to the complete loss of the spacecraft. A renewed interest in Solar System exploration has brought in the last years to the design of several missions in which landing is involved, but uncertainties in attainable position at touchdown still impose severe requirements on the selection of the landing site. The traditional selection process is complex, with the strong limitation of fitting the absolute landing site dispersion ellipse in a safe area that can be tens of kilometers wide. These limitations are not going to be acceptable for the next space systems generation: scientifically relevant places are often associated with hazardous terrain features or confined in small areas; in other cases there is no possibility to characterize an interesting region in advance with the required accuracy. The short duration of the maneuver, together with communications delays, make a continuous control from the ground impossible, as well as an efficient counteraction to unexpected events or failures. This is why precise and autonomous landing capability is a key feature for the next space systems generation. The possibility to adapt the trajectory during the descent would reduce the landing dispersion, making possible the execution of both absolute and relative correction maneuvers. At the same time, in conjunction with the capability to distinguish hazardous landing areas, the safety requirements could be relaxed, leaving to the system the task of the Hazard Detection and Avoidance (HDA), dramatically increasing the robustness and the flexibility of the mission.
This work focuses on the two most innovative components of the autonomous landing GNC chain: the *Adaptive Guidance* and the *Hazard Detection* subsystems. The former is devoted to the on-board computation of the spacecraft reference trajectory, once a target is defined, achieved by solving an optimum control problem. The latter analyzes the landing area in search of the best place to land, selecting the best target.
In the first part of the work, a novel guidance algorithm is presented. On-ground trajectory optimization is indeed a well-known topic, for mission analysis purposes. On the contrary, the adaptation of the trajectory on-board, to autonomously cope with dispersions, navigation errors or ordered diversions for hazard avoidance is still an open point. Classical guidance algorithms do not consider path constraints put by the system architecture in term of available thrust magnitude or attitude control torque, and they are unsuitable for HDA tasks. More recent schemes, based on pseudospectral collocation associated with convex optimization, are able to find nearly optimal solutions to large diversions, but involving hundreds of optimization variables.
In this work, the trajectory is modeled as a polynomial of minimum degree required to satisfy the boundary constraints. A reduced set of parameters is left free to be exploited in a constrained optimization process. The proposed method allows the computation of large diversions, with a suboptimization of the fuel consumption, ensuring at the same time the satisfaction of all the constraints imposed by the system in terms of control torques, thrust, and allowed hovering area. Only 2 or 3 optimization variables are needed, making the algorithm light enough to run on-board.
The flexibility of the guidance is addressed with two different applications, a lunar landing and the close approach to an asteroid. The robustness of the formulation is demonstrated in several simulations coupled with a basic solver (an example for a lunar landing is shown in **Figure 1**).
Moreover, a novel, ad hoc optimizer, based on Differential Algebra, is developed, capable to solve the guidance optimization in a fast and reliable way. Objective and constraints functions are modeled as low order Taylor maps. The general features of the functions are easily got, leading in a few iterations in the neighborhood of the optimal solution. There, the current point is refined, exploiting the property of the Taylor series to converge to the true function value in proximity to the expansion origin.
In the second part of the thesis, a novel hazard detection and target selection algorithm is presented. The capability of Artificial Neural Networks (ANNs) to extrapolate underlying rules in complex datasets is exploited to obtain an automatic classifier that, given a single image of the landing area, is able to build a hazard map of the terrain surrounding the target. This method removes the need to manually establish heuristic correlations between image features (e.g intensity mean and variance, etc.) and terrain features (like slopes and rocks), leaving to the ANN training process the task to identify these correlations automatically; the training is completely run off-line, before flight, while only the trained network runs on-board, with a minimum computational burden. Based on the hazard map, the target selection algorithm locates and ranks the candidate landing sites following safety and reachability criteria, leading to the selection of the best target.
A visual simulation tool is also developed to build a coherent and effective image dataset used for the networks training for a lunar landing case. An example of target raking and selection is shown in **Figures 2** and **3**.
A possible research roadmap toward a full integration and testing of the algorithms developed is outlined in the end, in prospect of a future exploitation in real space systems.



1. Adaptive guidance, Monte Carlo simulation of lunar landing



2. Hazard detection, target ranking example



3. Hazard detection, the target with higher rank is selected as new target (white circle)

BLADE PASSIVE SOLUTIONS FOR LOAD MITIGATION ON MULTI-MW WIND TURBINES

Montinari Pierluigi – Supervisor: Prof. Carlo L. Bottasso

Over the last twenty years wind energy sector has grown remarkably. At the same time, the size of the wind turbine has increased exponentially, mainly for the following reasons: first, larger wind turbines capture more wind power because of greater area swept by the blades; second, the costs to control, connect to the grid and maintain are sometimes higher than the capital value of the wind farms, therefore installing greater wind turbines implies reducing the costs for grid connections; third, larger wind turbines provide better land utilization. To satisfy this trend of growth, a simple upscaling of the existing ones using the same technology is unfeasible, since the cost of a wind turbine is typically well correlated with its weight and weight with the size of the rotor, following the well known cubic law. Therefore, a naive scaling would translate into an unacceptable growth of cost. Among other approaches, load alleviation techniques help address this issue, by increasing the efficiency of the aerostructural configuration and limiting the cost grow rate of wind turbine components through the design of lighter structures and/or the reduced usage of high performance materials. In this dissertation, blade solutions for load alleviation are investigated. The first part of the thesis describes new concepts, based on the deployment of distributed appended devices, with the goal of demonstrating that passive means of actuation can lead to enhanced performance comparable to more complex active architectures. They move in response to the structure accelerations and/or in response to the airloads. The analysis is conducted on the DTU 10 MW wind turbine aeroservoelastic model. Results highlight very interesting capabilities of such devices in mitigating both fatigue and ultimate loads.

Passive flap concept for wind turbine load alleviation

The passive flap is implemented within a complete aeroservoelastic model of the machine, with the scope of demonstrating the effectiveness of the system in high-fidelity simulation tool. Multiple scenarios and load cases were considered to characterize the load mitigation of the passive flap system, as required by the certification standards. The most critical design loads cases were simulated, including possible device faults scenarios. The sizing of the passive flap was performed with two flap extents. The load analysis has considered both fatigue and ultimate loads, including also device fault conditions, following accepted standard certification procedures. Based on the results of this analysis, the following conclusions may be drawn:

- The proposed passive flap solution improves on the baseline in terms of fatigue and ultimate load alleviation. These results might possibly be further improved by a more complete optimization of the devices, including their aerodynamic shape.
- The more significant effects on fatigue are reported at the tower base. The fatigue at the main bearing is also mitigated, and this is essentially due to the driven flap response by the blade flapping. Detailed analysis on the blade root bending components reveals an increased drag fluctuation induces by the flap deflection and the increased blade weight due to the installation of offset masses increases the bending moment DEL in the edgewise. At the same time a considerable reduction of the bending in the flap wise is encountered.
- Ultimate loads see a considerable decrease at the three main spots, i. e. blade root, main bearing, and tower base. Therefore the passive flap system, even if not its primary function, appears to be lowering also the ultimate peaks. Furthermore, the increased flap.

3D analysis of blade tip device architectures

The pitching tip concept is investigated to asses the load alleviation capabilities when the outermost portion of the blade rotates with respect to the rest of the blade. In particular, a passive solution is compared with semi-passive and active architectures. In the passive and semi-passive configurations tip pitching is mainly driven by aerodynamic means, obtained by putting the hinge ahead of the device aerodynamic center, while for the active case the rotation is obtained with an actuator commanded by a feedback control law. The passive solution achieves the simplest configuration because it does not involve active components, while the active tip requires sensors and servo motors and implements a feedback control algorithm. The semi-passive tip is in a sense in between the other two configurations, requiring active slow regulation of the hinge preload but no feedback control. The free motion of the passive and semi-passive devices is driven by the tendency to align with the wind of the tip due to the choice of a suitable chordwise location of the hinge, together with a restraining spring. The active tip implements a centralized IPC control strategy. The analysis considered both fatigue and ultimate loads, including also tip fault conditions, following accepted standard certification guidelines. Based on the results of this analysis, the following conclusions may be drawn:

- All proposed tip devices improve on the baseline both in terms of fatigue and ultimate load alleviation, although to a different extent on different wind turbine components. The passive tip shows similar performances to tho other architectures, but achieved with simpler configuration, not involving active components, therefore it appears very interesting at the light of considerations on the CoE.
- The more significant effects on fatigue are reported at the blade root and tower base. For the passive and semi-passive devices, this seems to be attributable to a smoothing of the airloads. Ultimate loads see the largest decrease at the main bearing, while they are essentially unaffected on blade and tower.

Realization and wind tunnel testing of scaled aeroelastic blades with bend-twist coupling

The second part of the thesis describes the characterization of full-blade span solutions, with the goal of demonstrating via experiments the potential of this means to mitigate loads, withstanding and sometimes complementary to active control architectures. To this end, a scaled representation of a multi-MW wind turbine featured with bend-twist coupling is realized and characterized in terms of structure, aerodynamics and fatigue loads. Blade structural characterization is conducted at bench, by means of dynamic frequency response analysis and static tests. The blade structural properties' identification problem is formulated as a maximum-likelihood constrained optimization, and is performed successfully.
Wind tunnel of Politecnico di Milano is used for the aerodynamic and load characterization. The former requires the determination of thrust and power coefficients. To this end, some tests are conducted in the aeronautical section with low turbulence intensity, where different blade pitch angles and tip speed ratios are tested. For the load characterization, boundary layer chamber is used to generate atmospheric scaled turbulent wind conditions. The model is also tested in partial wake conditions, as likely to occur in wind farm operations. The synergy effect with the active load mitigation strategy is also shown by enabling the IPC. Based on the results obtained so far, the following conclusions may be drawn:

- The test in the wind tunnel showed little differences with respect to the rotor without BTC in the power coefficient, achievable with a lower pitch angle.
- Turbulent partial wake tests highlight the capability of the BTC to reduce the fatigue loads on the main bearing and the tower base, but inertial load contributions determine an increased bending moment on the shaft. Also the ADC is reduced considerably. The use of hybrid model IPC+BTC showed a further reduction of the fatigue loads, and a cut-out of the 1xRev component at the shaft, at the cost of an increased ADC and loads at the blade root.

DEVELOPMENT OF ACTUATED MORPHING STRUCTURES BASED ON COMPOSITE FLEXIBLE ELEMENTS

Panichelli Paolo – Supervisor: Prof. Alessandro Airoldi

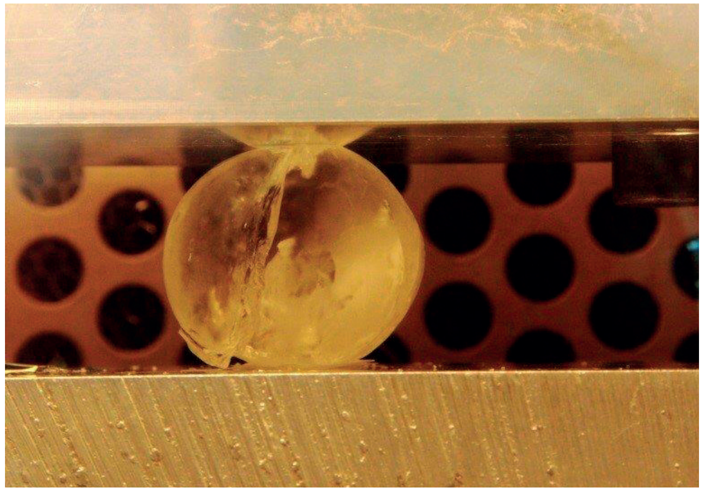
The scope of this research is to prove the feasibility and the efficiency of morphing actuated structures in the aeronautic field. Both experimental and numerical activities have been undertaken to assess the technological process of flexible elements, made of composite material, which constitute the principal components of the adaptive solutions that are meant to be developed.
Detailed virtual prototypes of aeronautic application have been implemented, relying on the characterization of the mechanical properties shown by technological demonstrators of the constitutive components, which have been manufactured. These numerical model have allowed a fast and complete investigation of the performances that could be obtained in term aerodynamic and structural aspects by such adaptive configurations.
The general configuration which guides the design of these morphing application is based on a structural layout where an internal chiral composite rib sustains a composite corrugated structure and a flexible skin, with an actuation system embedded, consisting in shape memory wires.
From the technological point of view there was an experimental investigation of the integration between actuators and skin, the evaluation of different corrugated shapes and the characterization of shape memory alloys to understand their behaviour when embedded in an elastic structure. This experimental activity provided all the data for the implementation and validation of a numerical technique able of modelling the behaviour of shape memory alloys, both in heating and cooling phase. Also different topologies of chiral honeycombs where investigated to find out the best compromise between auxetic behaviour, technological feasibility and structural integrity.
The chiral internal ribs and the skin actuated system represent the basic elements to develop morphing aerodynamic surfaces that could guarantee a gapless and extremely flexible adaptation of the shape to generate aerodynamic loads and to adapt with maximum efficiency to different mission or flight phases. A first case study is represented by a trailing edge high lift device. The resulting solution is a morphing flap which collects the benefit of a fowler mechanism and a variable camber profile. This morphing solution shows adaptability to much more flight conditions than a rigid configuration, and such adaptability is made possible thanks to an internal structure made of chiral honeycomb with polygonal topology, a highly deformable skin based on a corrugated composite panel and an actuation system that combines the contributions of conventional actuators applied to the chiral rib and shape memory alloys embedded in the skin.
The second application presented is a morphing aileron whose design started from an aeroelastic condensed model implemented to set up an optimization process, aimed at obtaining the most performing distribution of actuators and stiffness, maximizing a performance index depending on increase in lift coefficient and work done by actuators. The final step of this work consists in the transition, from the condensed, to a detailed finite element model, of the morphing trailing edge, for the complete assessment of overall morphing behaviour and structural integrity, under the action of actuation and aerodynamic forces.
This study proved that morphing design philosophy in the aeronautic field can bring to high performances and aerodynamically efficient structures. Indeed, on one side, technological demonstrators of the principal subcomponents assessed the feasibility of such flexible solution and of diffused actuation system embedded; on the other side, the virtual prototypes of the real application showed the capability of reaching high performances in a very wide range of configurations, without problems of structural integrity or energetic efficiency.

HAIL IMPACT PROBLEM IN AERONAUTICAL FIELD: HAIL IMPACT AND ICE MATERIAL CHARACTERIZATION

Prato Alessia – Supervisor: Prof. M. Anghileri

The impact of hailstones against structures can have both visible and barely visible effects. At high speed, the behaviour of ice belongs to the so called soft body class and the hydrodynamic theory can be used to describe its behaviour during the impact. Following this approach, some studies have been done in the last years but only hydrodynamic materials have been used. However, ice has a solid nature that appears clearly at low speeds and even during high speed impacts at the beginning of the events. In this research work, some additional studies regarding the solid-fluid behaviour of ice in different conditions has been performed.

After a review of the soft body impact problem in aeronautical field, from a theoretical point of view, some numerical models have been performed. The attention has been focused on the mesh dependency effect and on the variation of impact velocity and impact angle. A detailed study on differences/similarities in numerical approaches both mesh (Lagrangian, Eulerian, Arbitrary Eulerian-Lagrangian) and meshless (Smoothed Particle Hydrodynamics, Element Free Galerkin) has been done and used to simulate fluid/structure interaction problems. A particular attention has been posed on the use of the new FEtoSPH approach: a switch that allows the users to transform Lagrangian elements into SPH particles as a failure criterion has been reached or due to an high distortion of finite elements. In addition, due to the combined compression-tension response of the ice during impacts at high speed, static experimental tests have been performed to evaluate the mechanical behaviour of ice under compression and bending conditions. Different ice geometries (cylindrical and spherical, with an increasing values of diameter and high) and temperatures (from -2°C to -41°C) have been considered to evaluate the effect of a change in shape.

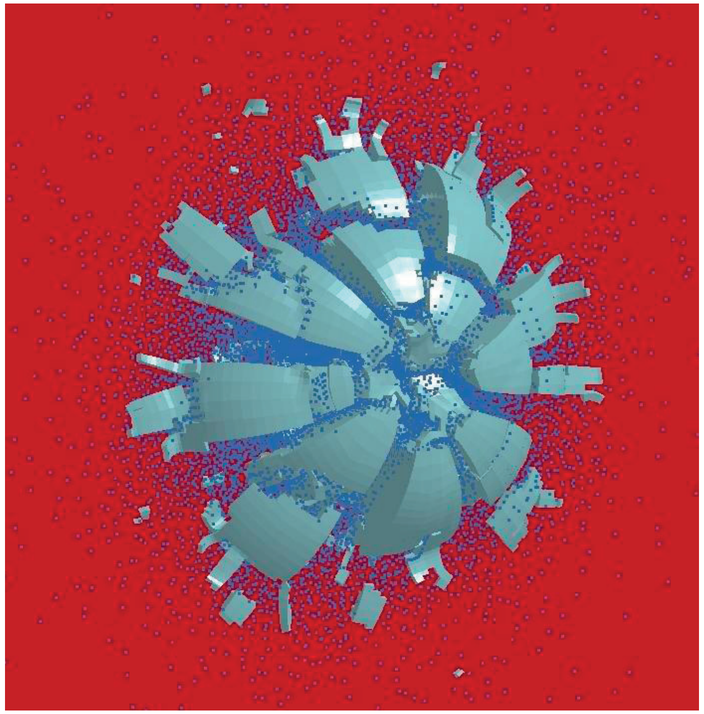


1. Static compressive test on spherical ice

As a result, a brittle behaviour of ice has been noticed as the temperature decreases and a ductile-to-brittle transition regime has been found around -20°C. As a consequence of these tests, and in particular from the static loading –unloading experimental results, the analysis of the microstructure of ice has been performed using a scanning electron microscope to investigate the geometry of grain boundaries and dislocation planes, the presence of micro-voids and of stable/unstable structures, as a function of water type and freezing process. Starting from these last study, a new investigation on numerical models has been performed.

New material models for LAG ice approach have been considered and results compared with experimental tests performed by Carney e al. From that, a new material model based on damage mechanics and microstructure has been adopted in the FEtoSPH approach only for the LAG part, whilst an hydrodynamic one continues to be used for the SPH component. In addition, considering the importance of the thermal contribution, as obtained from the static experimental tests, a thermo-structural analysis has been performed. Knowing that the greatest damages on structures occurs during high speed impact evens, some experimental tests have been performed using a gas gun, in the range of the typical aeronautical speed, and both rigid and deformable targets. From results, a comparison in terms of impact loading has been done and the effect of the impact speed, of the thickness and of the curvature of the deformable plates has been found. In additioan, numerical models of these tests have also been performed using SPH, LAG and the new FEtoSPH.

However, considering that it is possible to have damages on structures also at low speed, low energy impact tests have also been performed, at University of Bristol, using a particular drop tower typically used for puncture tests on plates. In this case, both rigid and ice impactors have been adopted. Metal and composite plates have been considered as target structures to investigate the effect on different materials. Results from the drop tower (force, energy, impact velocity and max plate deflection), from the Digital Image Correlation (DIC) and from the high speed video camera have been collected and compared to investigate the phenomenon.



2. FEtoSPH model of an hailstone impact against a rigid target

In conclusion, all these aspects have been considered together to have a more complete perspective on hail impact problems. To present a final, more realistic, ice impact event, the impact of a single and multiple hailstones against an engine have been numerically presented as a final case study applying the new FEtoSPH approach, developed and based on the previously described activities.