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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STABILITY AND CONTROL OF BLUFF BODY FLOWS

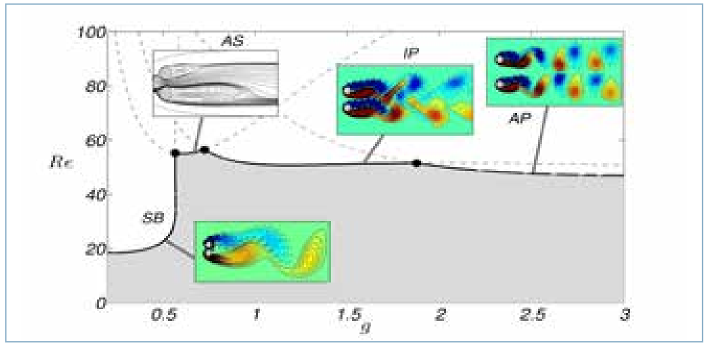
Marco Carini - Supervisor: **Franco Auteri**

Flows over bluff bodies are found in many engineering applications with the occurrence of massive flow separations and *vortex shedding* phenomena. Classical examples are given by the flow past tube bundles, high-rise buildings and trucks, among the others. In addition, also streamlined bodies can exhibit typical bluff body behaviours, when a deep aerodynamic stall develops. It is well known that low frequency unsteadiness arising in the wake of a bluff body may excite structural vibrations, acoustic noise and resonance and leads to significant increases in the mean aerodynamic forces. Therefore a deeper understanding of such flow instabilities and their control could be of great importance not only from the viewpoint of basic research but also for industrial applications. With respect to bluff body flows, the flow past a single circular cylinder has been established so far as a model problem on which new methodologies and concepts are assessed, thus becoming a classical topic in fluid mechanics. Besides the single cylinder wake, flows past two or more cylinders in various arrangements have also received considerable attention being prototypical of *wake interference* phenomena. An example is represented by the flow past two identical circular cylinders in side-by-side configuration. Despite the simple geometry, it is well known that the wakes of the two cylinders can experience complex interactions resulting in several different flow patterns that significantly depend on the Reynolds number, and even more on the gap spacing between the cylinder surfaces. In the present work both the single cylinder and the two side-by-side cylinders are assumed as cases of study.

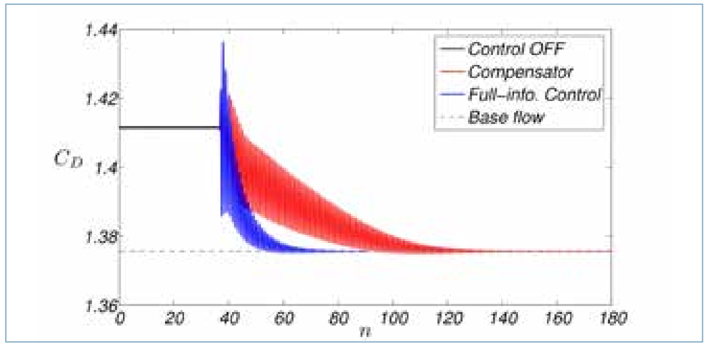
The onset of two-dimensional instabilities in the flow past two side-by-side circular cylinders is numerically investigated at low Reynolds numbers by performing a linear global stability analysis of the steady symmetric base flow. Three harmonic modes and one steady anti-symmetric mode are found to become unstable, each one being at the root of a distinct flow regime, for increasing gap size: *single bluff body* (SB), *asymmetric* (AS) and *in-phase/anti-phase synchronized* (IP/AP). For each unstable mode, the corresponding neutral curve is described in the parameter plane and the inherent *structural sensitivity* is examined to identify the core region of its self-excitation, thus providing useful information on the underlying physical mechanism of instability and wake coupling.

In the stability diagram three co-dimension two bifurcation points are identified. In such a situation where distinct global modes become unstable for the same values of the parameters, neither stability nor pattern selection can be completely explained in terms of the linear picture alone and the stability analysis must be performed within a genuine nonlinear framework. The problem of mode selection among competing instabilities can be tackled by the *centre manifold* approximation of the nonlinear dynamics for which a systematic approach is proposed. This approach is fully automatizable and moreover it is computationally feasible for large scale dynamical systems such as those arising from the numerical discretization of the Navier-Stokes equations. The effectiveness of the proposed technique is assessed by illustrating the reduction to centre manifold in the neighbourhood of the Hopf bifurcation of the single cylinder wake and near the pitchfork-Hopf bifurcation of the flow past two cylinders at which both the steady AS mode and the harmonic IP mode are marginally stable.

The origin of the well-known *flip-flop instability* of the two cylinder wakes within their asymmetric regime is also addressed. In this case the gap flow is alternatively deflected toward one of the cylinders, i.e. flip-flops. Such



1. Linear stability diagram of the flow past two side-by-side cylinders *g* being the nondimensional gap width. The gray shaded area denotes the asymptotic stability region of the symmetric base flow as delimited by neutral branches pertaining to the different flow instabilities



2. Minimal energy control of vortex shedding behind a single cylinder (*Re=50*): drag coefficient as a function of the number of shedding cycles during the transient state. A single cross-stream velocity sensor is used for state estimation

behaviour has been ascribed, in the past literature, to a bistability of the flow. On the contrary, the simulations performed herein provide new evidence that at low Reynolds numbers the flip-flopping state develops as a secondary instability of the two cylinder wakes from their in-phase synchronized vortex shedding. This new transition scenario is confirmed and explained by means of a two-dimensional Floquet analysis of the in-phase shedding cycle.

Finally, the control of vortex shedding is investigated by means of both passive and active strategies. In the first case, the simultaneous stabilization of the in-phase and anti-phase synchronized shedding modes is achieved using two small secondary cylinders. Their effective placement in the near-wake of the two main cylinders takes advantage of the structural sensitivity analysis of the two shedding modes with respect to base flow modifications. In the second case the *minimal energy* (or small gain) solution of the linear optimal control problem is leveraged in order to design a full-dimensional compensator for the suppression of the first instability of the single cylinder wake. For such a compensator all control and estimation efforts concentrate on stabilizing and estimating the unstable modes of the uncontrolled linearized flow system only. A realistic configuration is considered where actuation is obtained by means of angular oscillations of the cylinder surface while velocity sensors located in the wake are used for state estimation. Preliminary results show that the control is able to drive the flow from the natural limit cycle to the unstable steady state, which is finally restored.

THEORY AND EXPERIMENTS ON NONLINEAR CONTROL FOR SPACE PROXIMITY MANEUVERS

Giuseppe Di Mauro - Supervisor: **Michele Lavagna**

The successful proximity operations during a docking maneuver involving two space vehicles has provoked great interest in last decade due to the continuous increase of space orbit activity. In fact, rendezvous and docking (R&D) operation is a key element in missions which provide in-orbit assembling of large units, serving/refuelling of orbital platforms and stations, malfunctioning satellite capturing or installing improved technology.

The first rendezvous and docking between two spacecraft took place on 16 March 1966, when Neil Armstrong and Dave Scott manually performed rendezvous in a Gemini vehicle and then docked with an unmanned Agena target vehicle. The first automatic R&D took place on 30 October 1967, when the Soviet vehicles Cosmos 186 and 188 docked. Thereafter, R&D operations have regularly been performed by the Russian, US and European space programs.

The main challenge related to R&D maneuvering problem relies on the development of robust and reliable guidance, navigation, and control (GNC) technique for on-orbit evolving systems. Particularly, the proximity to the target spacecraft makes all operations safety-critical, requiring particular safety features for trajectory design and an high accuracy level for the control and navigation systems.

Since docking manoeuvring control problem involves nonlinear kinematics and dynamics, the traditional linear control strategy might fail or be unsuited to satisfy the stringent requirements needed for proximity operations, especially when large position or angular maneuvers are required. This has motivated the rapid development of nonlinear control methodology for R&D maneuvering application.

To date, one of the most promising nonlinear feedback control technique is the *state-dependent Riccati equation* (SDRE), which was detailed by many researchers over the last decade. The SDRE became very popular within the control community since it provides an effective tool for the synthesis of nonlinear feedback controls by allowing nonlinearities in the system state and, additionally, offering great flexibility through the design of weighting matrices. The method involves the factorization of nonlinear equations of dynamics, referred to as *State-Dependent Coefficient* parameterization or *extended linearization*, into the product of a matrix-valued function and the state vector to include the nonlinearities of the system into the controller formulation; therefore the nonlinear control law is obtained by minimizing a non-quadratic performance index having a quasi-linear structure, that is solving online an Algebraic Riccati Equation (ARE) where all matrices depend on the current state. Thus it represents a valid option to issues involved with solving nonlinear Hamilton-Jacobi-Bellman partial differential equations associated with nonlinear optimal control problem.

Basically, the SDRE represents the nonlinear counterpart of the Linear Quadratic Regulator (LQR) for linear systems; thus it inherits the trade-off design flexibility due to the possibility to regulate the control signal and system performance by tuning the penalty matrices. On the other hand, it is sensitive to computational cost due to the online solution of an ARE; this aspect represents the main drawback of the SDRE technique, which might demand significantly more computational resources than conventional control algorithms, especially for high-order systems control. For this reason the hardware implementation of SDRE approach was scarce and restricted to low-order systems.

This doctoral research focuses on the development of an alternative nonlinear approach to nonlinear optimal feedback control, aimed at reducing the computational cost of SDRE method. The proposed approach exploits the *differential algebra* (DA) framework, that serves the purpose of computing the derivatives of functions in a computer environment. More specifically, by substituting the classical implementation of the real algebra with the implementation of a new algebra of Taylor polynomials, any function *f* of *v* variables can be expanded into its Taylor series up to an arbitrary order *n* with a fixed amount of effort. Thus, the proposed DA-based algorithm allows to compute an high order Taylor expansion of the SDRE solution of the relative motion problem around a reference trajectory. The computation of new SDRE solution in a relatively large neighborhood of the reference trajectory is reduced to the mere evaluation of polynomials, avoiding the online solution of ARE and reducing the computational cost. The accuracy of the solution can be tuned by selecting the proper expansion order.

In addition to an effective control law design, performing a successful R&D maneuver also involves the problem of relative navigation and relative attitude determination between the two space vehicles. Thus, an *Extended Kalman Filter* (EKF) was designed in order to determine the relative navigation and the relative attitude between the satellite involving in R&D operations by using the only data coming from a vision sensor. In fact, this type of sensor offers some advantages such as the small size and light weight, excellent rejection of ambient light interference under a wide variety of operating conditions, low power consumption and high reliability.

Since the high accuracy required for R&D manoeuvring, an high-fidelity dynamic model which includes the *kinematic coupling* due to the displacement of the sensor with respect to the chaser centre of mass was considered for the EKF design.

Another important contribution of this research was the testing of computational performance of combined SDRE/EKF technique as well as the validation of computational cost benefit of the proposed DA-based algorithm when they run on a real hardware designed to emulate on ground the proximity operations. Two different test-beds, designed by *DLR Institute of Space Systems* and by *Dynamic and Control Systems Laboratory* (DCSL) at Georgia Institute of Technology respectively (see Figure 1), were exploited to simulate both 3DoF and 5DoF R&D maneuvers.

Both numerical simulations and hardware experiments showed the effectiveness of proposed GNC solution for R&D manoeuvring problem.

1. Facilities for simulation of R&D maneuver: Georgia Institute of Technology facility (Spacecraft Simulator for Autonomous Rendezvous and Docking platform) (left); DLR Space Systems Institute facility(Test Environment for Application of Multiple Spacecraft platform) (right)

LABORATORY HYPERSONIC JETS

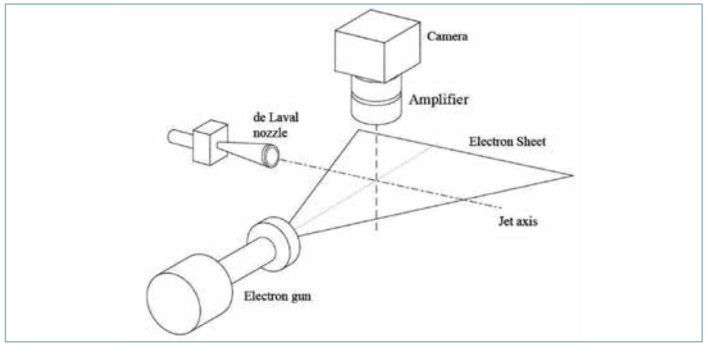
Mohsen Mirzaei - Supervisor: **Marco Belan**

Context

The free hypersonic jets can be found in several technological applications and even in astrophysical observations. The astrophysical context is that of the jets issuing from Young Stellar Objects (YSOs). In the present dissertation the propagation of hypersonic jets in a laboratory vessel has been mainly studied.

Aims

In order to have a further insight into the jets from YSOs, a set of experiments is performed in the range of Mach numbers from 7 to 20 and for jet-to-ambient density ratios from 0.85 up to more than 100, using different gas species and observing jet lengths in the order of 100 initial radii or more. Exploiting the scalability of the hydrodynamic equations, we intend to reproduce the YSO jet behaviour as far as the diagnostic quantities as head velocities and elapsed times are concerned. In some cases, we have made comparisons between our experimental results and the existing numerical ones and also made comparisons with the observed morphologies obtained by other research groups. Also the jet morphology after the impact at the end of the vessel and the interaction with the backward flow has been investigated.



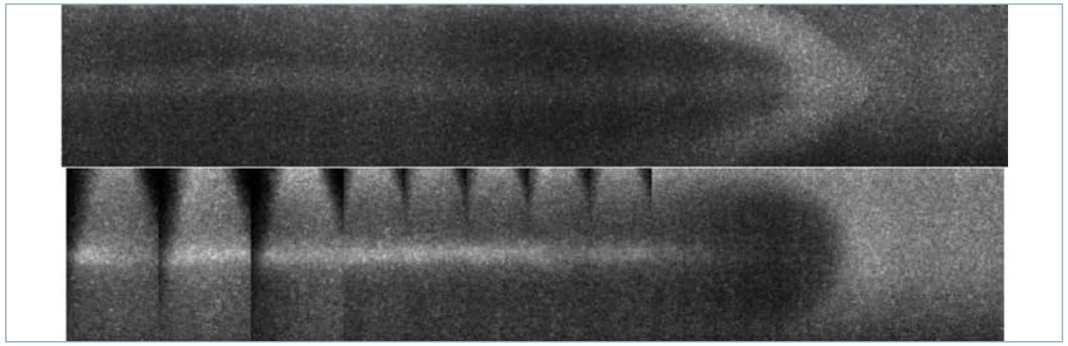
1. Working principle of visualization

Methods

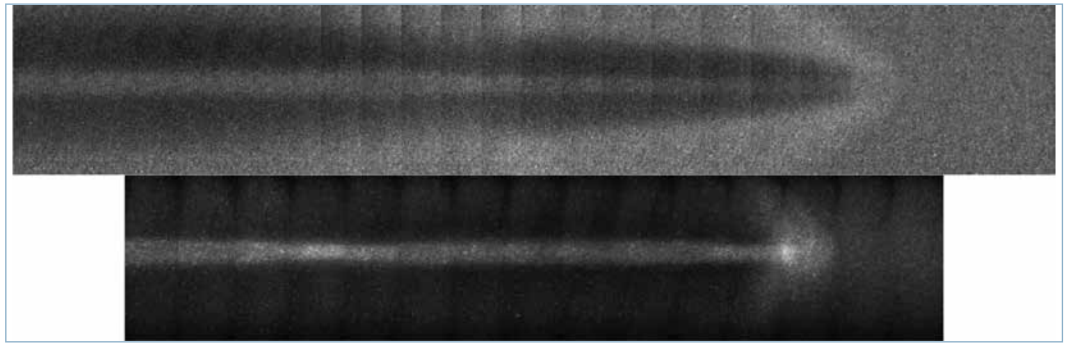
In the experiments the gas pressure and temperature are increased by a fast, quasi isoentropic compression by means of a piston system coupled with suitable de Laval nozzles; by selecting the nozzles and the gases for each test, the jet Mach numbers (in the range of 5 to 20) and the jet to ambient density ratios (in the range of 0.1 up to values exceeding 100) can be set independently of each other, what permits the investigation of a wide parameter range in the relevant physics. The visualizations and measurements are based on the electron beam technique (fig. 1): the jets are weakly ionized, and then a fast camera captures fluorescent images. Indications about the jets propagation and morphology, as well as density and velocity measurements, are obtained by means of several image processing techniques carried out on the acquired images.

Results

Our experimental results about long scale jets, owing to their originality, could serve as a benchmark for existing and future numerical simulations and also as reference for future experimental investigations. These results, showing the collimated jet flow, has given an answer to a famous issue about the jet morphology: "the jet shape, as it is observed, is just due to fluid dynamics or it does require magnetic confinement, periodic energy pumping or any other complex causes?". The effects of density ratio and Mach number are explored, giving interesting results to understand the general morphology (fig. 2&3). In some cases the results are compared with the existing numerical simulations: the formation of knots, the appearance of travelling structures after the jet impact with the vessel end, the jet head advance speed, and also the density distribution, give rise to fairly good comparisons in the majority of the considered tests.



2. Two underdense jets at the same density ratio (0.9) and different Mach numbers (top panel: Mach=20, bottom panel: Mach=10)



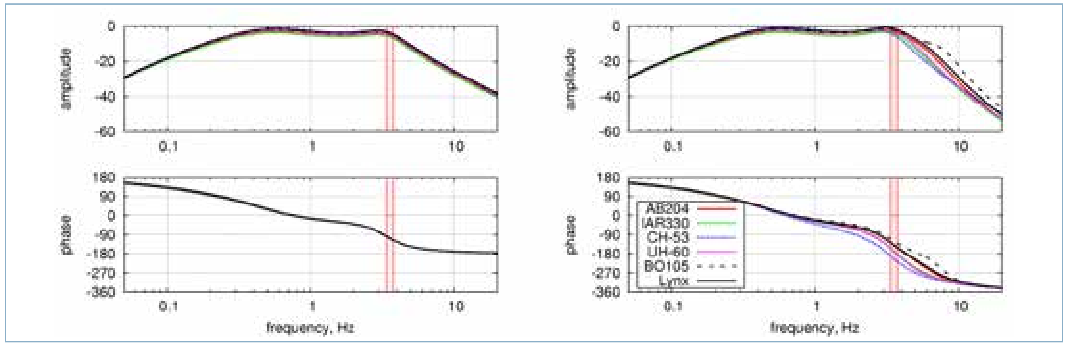
3. Two jets at the same Mach number (15) and different density ratio (top panel: density ratio=0.9, bottom panel: density ratio=1.3)

Conclusions

Pressure-matched hypersonic jets maintain their collimation for long distances in terms of the initial jet radii, without including magnetic effects, leading to a qualitative good agreement with the observed YSO jets morphologies. Also their evolution with regard to the effective variables, the combination of the Mach number and density ratio, can be safely related to the known global morphologies.

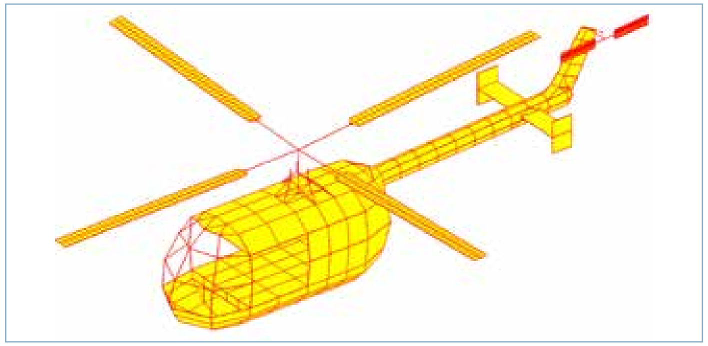
INVESTIGATION OF AEROELASTIC ROTORCRAFT-PILOT COUPLING PHENOMENA

Vincenzo Muscarello - Supervisor: **Pierangelo Masarati**

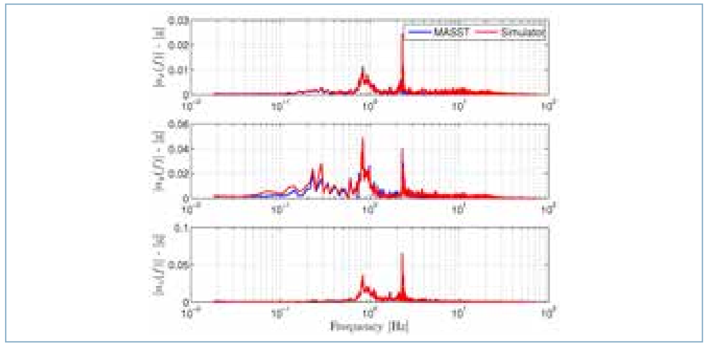


1. Bode plot of helicopter Loop Transfer Function with pilot involuntary control model; without rotor coning mode (left) and with rotor coning mode (right)

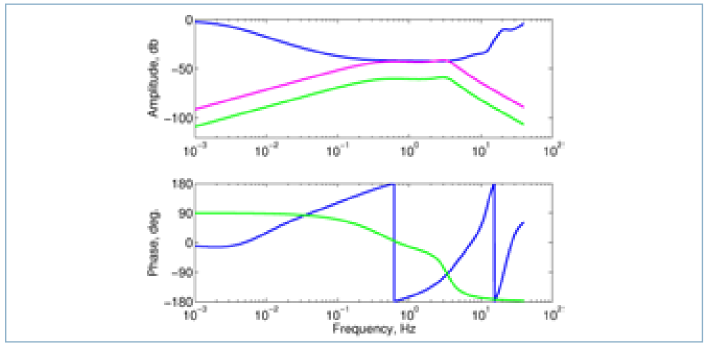
This thesis focuses on aeroelastic Rotorcraft-Pilot Coupling phenomena, usually known in the literature as Pilot Assisted Oscillations (PAO). During PAO occurrences the pilot, seated in the cockpit, behaves as a passive element that transmits the vibrations of the elastic airframe from the seat to the control inceptors. Unintentional high-frequency control actions, filtered by the pilot's biomechanical impedance, are introduced in the flight controls, resulting in unstable events. These phenomena usually occur in the frequency range between 2–8 Hz, and thus require to consider the most significant rotorcraft dynamics, ranging from flight mechanics to rotor blade modes.
The software MASST (Modern Aeroservoelastic State Space Tools) has been initially developed as "Virtual Helicopter" simulation environment to perform massive analyses of linear(-ized) aeroservoelastic rotary wing aircraft. The pilot biodynamics are then introduced in feedback loop with the aircraft dynamics. PAO phenomena are analyzed and discussed using both simple and detailed rotorcraft models, in order to investigate several design parameters.
The "collective bounce" phenomenon has been investigated in detail. The collective bounce is an aeroelastic Rotorcraft Pilot Coupling (RPC) phenomenon caused by vertical vibrations in the aircraft cockpit that are transmitted to the collective lever through the torso, the left arm and the hand of the pilot, and fed back to the rotor through the collective pitch control. This work shows how the occurrence of collective bounce is rooted in the coupling of the pilot biodynamics with the rotor coning mode. The damping of the coning mode, usually large, introduces significant phase delay in the response to collective pitch input, as shown in Figure 1 for different helicopter models. When coupled in feedback with the damped pilot biodynamics, this delay may lead to marginal stability conditions or even to instability. Simple analytical models are used to explain the basic mechanism of this coupling and possible means of prevention are discussed.
Subsequent analyses are based on detailed aeroservoelastic helicopter models. Aeroservoelastic and bioservoelastic stability analyses are performed on models representative of the IAR330 Puma and of the MBB Bo105. Results are compared with the simple analytical model analyzed during preliminary analysis. Overall stability analysis, including the passive pilot dynamics in feedback loop on aeroservoelastic models of the IAR330 Puma, confirm the essential role of the rotor coning mode in collective bounce proneness.
PAO phenomena are also analyzed on the aeroservoelastic MBB Bo105 helicopter, where unstable lateral oscillations appear when considering the pilot/lateral stick model in feedback loop with the rotorcraft dynamics. Flutter analysis at 80 Knots, considering a time delay of 100 ms typical of Fly-By-Wire vehicles and increasing the gain factor on the lateral cyclic control, shows a PAO instability at 2.3 Hz, due to the interaction of the pilot lateral biodynamics with the poorly damped 1st lead-lag regressive mode of the main rotor.
Experimental results, obtained at the HELIFLIGHT simulation facility of the University of Liverpool, confirm the numerical PAO predictions for the lateral PAO instability on the MBB Bo105, during roll step maneuvers performed by trained test pilots at 80 Knots.
Figure 3 clearly shows a pronounced acceleration peak slightly above 2 Hz, in addition to significant activity slightly below 1 Hz. Activity up to 1 Hz is the consequence of intentional control action of the pilot, while activity above 2 Hz is related to involuntary control action, induced by lateral vibrations associated with the regressive cyclic lead-lag motion of the rotor.
Finally, the robust approach is used to determine parameter bounds that may help the designer when highly uncertain elements, related to the biodynamic response of the pilot, are taken into account.
In the case of large gearing ratio ($G_c = 1.5\pi/10$), as shown in Figure 4, the transfer function magnitude of the pilot crosses the limit pilot curve (blue line). A conservative design must consider the possibility to reduce the gain, for instance by increasing the length of the collective bar, or its angular range, compatibly with ergonomic considerations.



2. Aeroservoelastic model of the MBB Bo105 implemented in MASST



3. MBB Bo105 – FFT of the accelerations at pilot seat during PAO occurrence

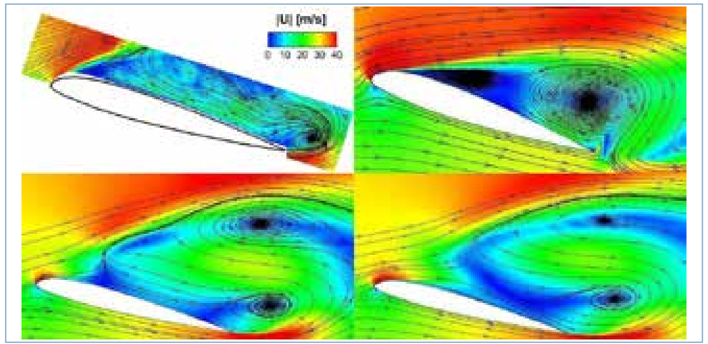


4. Amplitude and phase for the limits of pilot biodynamic models (Blue line) with Mayo's transfer functions overlapped. Green line: Mayo's model with $G_c = 0.2\pi/10$ radian; Magenta line: $G_c = 1.5\pi/10$ radian

ASSESSMENT OF THREE-DIMENSIONAL EFFECTS IN DEEP DYNAMICS STALL OVER OSCILLATING AIRFOILS

Reza Nilifard - Supervisor: **Alberto Guardone**

Dynamic stall (DS) around oscillating airfoil substantially affects the aerodynamic performance of a large variety of rotating machinery such as helicopter rotors, compressors and wind turbines. For example, in rotary-wing applications, DS can possibly be observed during forward flight over the retreating blade and results in a strong reduction of the overall performance of the rotor.
DS is encountered when the angle of attack of an airfoil or any other lifting surface is rapidly changed by pitching, flapping and/or plunging motion beyond its static stall angle.
In these situations, the occurrence of DS causes the stall angle to be delayed to incidences which exceed the static stall angle significantly.
DS is characterized by the occurrence of a number of different flow features including attachment during the upstroke motion, leading edge separation, massive vortex shedding and reattachment.
The accurate description of this complex flow-field remains a challenging problem, under both an experimental and a computational point of view.
Current research on dynamic stall is focusing on the evaluation of reliable numerical tools, capable of accurately resolve the dynamics of strong vortexes.
In particular, the study of three-dimensional effects on dynamic stall phenomenon is probably the most active research topic, because of their importance when comparing wind tunnel and numerical results, as it is demonstrated bythe several recent works in literatures.
The goal of the present thesis is to further assess the capabilities of available numerical methods in order to improve the computational fluid dynamic (CFD) predictions of deep dynamic stall.
Hence, several parameters known to have a significant influence on DS prediction are considered for both 2D and 3D models ofoscillating airfoils using the EDGE code of FOI.
Numerical results are compared to wind tunnel experiment carried out at the Aerodynamics Laboratory of the Aerospace Science and Technology Department, Politecnico di Milano.
In particular, the evaluation of the convective fluxes in the Navier-Stokes equation is carried out using both central schemes with artificial viscosity and upwind techniques. Results for 2D simulations are compared with measured lift and moment coefficients.
Three different turbulence models are also considered. These are the explicit Algebraic Reynolds Stress Models (EARSM), the W\&J EARSM model together with the Hellsten k - ω and the Detached Eddy Simulation model.
Indeed, the choice of the appropriate turbulence model is shown to have a large impact on the determination of the integrated forces and moment.
The quality of the numerical prediction is known to depend on the grid used.
In DS application where flow experiences several complex conditions during its evolution, the required resolution for computational grid is somewhat different with respect to conventional aerodynamic applications.
For this purpose, a grid resolution study is also carried out using three different grid resolutions in 2D simulation.
Furthermore, two levels of spatial resolution along the span-wise direction are considered to study the impact of grid resolution effect on the results of 3D models.
In addition, the accurate numerical simulation of DS requires the flow solver to be capable of accurately resolve a wide range of time scales, thus it strongly depends on the temporal resolution.
The effect of physical time step size on the integrated forces and moment are therefore assessed using different time steps for all studied cases in both two and three spatial dimensions.
The time convergence study for 2D computations illustrated a completely different behaviour with respect to 3D computations.
The lift and moment coefficients in the 2D cases are found to be highly sensitive to the choice of the physical time step size and on the number of sub-iterations and the Courant-Friedrichs-Lewy (CFL) number during the pseudo-time integration, whereas integrated forces obtained from the 3D calculations were found to be much less sensitive to the physical time step size.
For the deep dynamic stall condition with mean angles of attack of 10°, the 2D model can reproduce fairly well the measured airloads hysteresis during the downstroke motion.
Nevertheless, the 2D model fails to reproduce the detailed flow physics and vortex dynamics exposed by the PIV surveys at the model midspan.
Indeed, the comparison of the pressure distribution over the airfoil upper surface and of the streamwise velocity profiles showed important discrepancies between the 2D numerical representation and the experiments.
On the other hand, the flow fields obtained by the 3D simulations capture well the fine details of the dynamic stall phenomenon observed with PIV surveys and in particular the formation and shedding of strong vortex structures that move along the airfoil upper surface (see Figure 1).
Therefore, it was demonstrated that a three-dimensional representation is required to reproduce the flow structures typical of this DS regime, which exhibits and intrinsic three-dimensional nature.
Three-dimensional effects on the flow field are of particular relevance in post-stall conditions and are strongly influenced by the finite-span of the wind tunnel model and by the presence of wind tunnel walls.
The good agreement between experimental and numerical results confirms the suitability of the numerical models for the characterization of deep DS aerodynamics.
It can be expected that DS three-dimensional effects on helicopter blades are different from those measured during the wind tunnel experiments considered in the present thesis due to e.g. centrifugal effects.
Fortunately, the present results indicate that numerical simulations can accurately complement experimental investigations.



1. Flow field comparison between experiments and CFD: streamlines superimposed on color maps of velocity magnitude at 16° downstroke: $\alpha = 10° + 10 \sin(\omega t)$, k= 0.1 . (Re = 0:6 x 10^5 and Ma = 0.0862). a) top-left: Experimental results b) top-right: 2D case with 204 time steps. c) down-left: 3D, 30 nodes on span using 720 time steps. D) down-right: 3D, 60 nodes on span using 68 time steps

TECHNOLOGY FOR ADVANCED MORPHING STRUCTURES

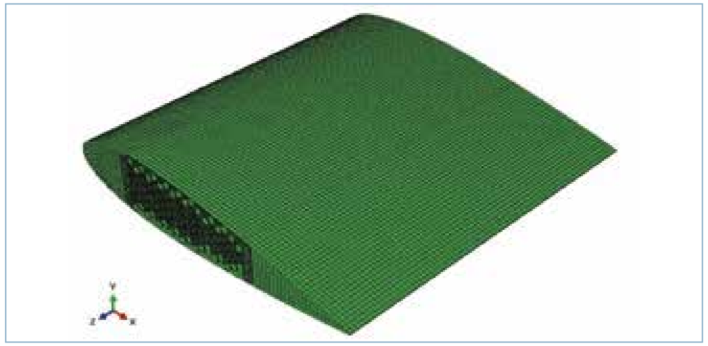
Mehmet Fatih Oktem - Supervisor: **Giuseppe Sala**

The objective of the morphing concept is to provide continuous controllable deformations thus changing the stiffness of the structure. A possible solution to design morphing structure can exploit the peculiar characteristics of chiral topologies, which are a relatively new design concept for composite aerospace materials. A honeycomb based on a chiral topology shows auxetic features which leads to negative Poisson coefficients. In the Figure 1 two chiral units could be seen; the first one is made from CFRP (Carbon Fiber Reinforced Plastics) and the second one is made from GFRP (Glass Fiber Reinforced Plastics).
This thesis investigates the design of a technological demonstrator of a morphing wing that uses the auxetic features of chiral cells. The research is concentrating on the manufacturing of the chiral composite cell network inside a rib. The design of the technological demonstrator is composed of two ribs connected to each other by means of corrugated flexible skin. The Leading edge (LE) and Trailing Edge (TE) provide housing for two ribs. The ribs are connected to the corrugated flexible skin by means of pin – hinge mechanisms. LE and TE are filled with a foam material to provide shear and pressure resistance.
The foam material thought to be utilized is Rohacell and this material offers high strength/weight ratio.
The morphing wing has the property of increasing the camber when subjected to a gust load. The aeroelastic performances have been studied in previous works, where the topology of the chiral honeycomb has been optimized. Basing on the knowledge of the aerodynamic loads this study presents the basic aspects of the technological solutions and the development of the structural design of the demonstrator.
The manufacturing of the ligaments and assembly of these specific parts to form chiral cells are described. Finite element analyses are carried out based to verify the rib design and choose the best configuration. Experiments are also performed to validate the design and to verify the manufacturing techniques. The manufacturing phase started from the production of the ligaments and then assembling them in the assembly mold. The experiments were carried out on four chiral unit cells. This phase also includes the design and manufacturing of the molds of the ligaments which are used for the production of the chiral unit cells and rib. Another mold was also designed and produced for the assembly of the ligaments to form the chiral unit cell.
The production of the rib started after the exploitation of the chiral unit cells was proven.
The previous production phase also gave some hints on how to proceed for the assembly of the full rib which is composed of up to three hundred ligaments.
Compared with the chiral unit cell, a full rib is relatively a more complex structure and more attention is needed for the assembly of the ligaments to create defect free structure.
After the production phase is completed static testing was performed on the rib. That was realized by suspending loads to the nodes of the rib and measuring the deflection by means of lasers and comparators.
The recent technological demonstrator is designed as a passive structure but the next step of this research could employ the use of sensing elements and actuators to create a controllable aerodynamic surfaces. The researcher also investigated the possible use of sensing elements and polymeric materials that could change their shape under several stimulus effects. The best polymeric material to be utilized should include both the shape memory effect and self healing effect.
In order to reach the desired goal, three points have been identified:

- Technology for chiral cell and rib
- Numerical activities
- Design and technology of rib and skin

These three points have also been detailed in the thesis.
The Figure 2 shows the FE model of two rib technological demonstrator with ribs attached to the LE and TE and covered with the skin.

1. Two chiral units made of CFRP and GFRP



2. FE Model of the 3-D demonstrator

NANO-METAL FUELS FOR HYBRID AND SOLID PROPULSION

Alice Reina - Supervisor: **Luigi T. DeLuca**

Nanosized powders (NP) show different properties with respect to the corresponding bulk materials. The enhanced reactivity connected to their very high specific surface area, arises interest also for energetic systems application: their use allows increasing solid propellants (SP) burning rate and reducing agglomerate formation at or near the combustion surface region. Moreover, addition of nanosized metals to solid fuel (SF) seems to be a promising pathway to solve the low regression rate problem of hybrid rocket propulsion. NP are also characterized by different surface interactions, resulting in difficulties in handling because of the tendency to form clusters that hinder the complete exploitation of nanomaterials potential.

In the experimental part of this work various strategies, ranging from sonochemistry to pre-dispersion in solvent to surface treatment, are investigated to improve the dispersion degree of NP into a polymeric matrix. Solid fuels for hybrid rocket engines (HRE) and propellants for solid rocket motors (SRM) are considered. In both cases HTPB is one of the main components: it represents the SF that can be loaded with various percentages of nanosized aluminum (nAl) in HRE and the binder entrapping fuel and oxidizer in SRM. In the former case, strategies to improve the dispersion degree of nanosized fuel (nAl) are evaluated as well as manufacture techniques to well dispersed nanosized Fe_2O_3, used as combustion modifier in SP.

The evaluation of dispersion degree is carried out, whenever possible, through the direct inspection of samples with an optical microscope, and in any case with indirect strategies, exploiting the connection between NP dispersion and some physical properties of the mixtures such as thermal conductivity or mechanical and rheological properties.

Combustion tests are performed to evaluate the effectiveness of the improved dispersion on the combustion features of SF and SP. SF are tested in a 2D radial burner at 10 bar under a gaseous oxygen mass flow rate up to to 350 kg/(m^2s).

SP combustions at pressure going from 1 to 70 bar, are conducted in a strand burner, using N_2 as pressurizing gas. Both for SF and SP optical methods are used to evaluate the regressing surface.

The experimental campaign shows that the best technique to prepare SF loaded with ALEX™ is the pre-dispersion of dry powders in ethyl acetate, that grants an increment of regression rate up to 64% at 350 Kg/(m^2s) with respect to the HTPB baseline.

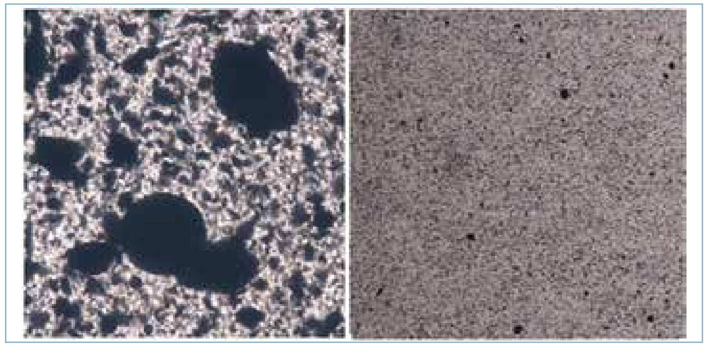
Nevertheless this procedure is not compatible with coated powders, for which dry addition remains the only possibility.

In this case, the best option is given by the use of an ultrasonic bath for the dry powders before their addition to the other ingredients, followed by 30' mixing of the whole compound with a propeller at 100 rpm using another ultrasonic device. Combustion tests on samples prepared with this procedure containing ALEX™, show an enhancement in regression rate up to 40% at 350 kg/(m^2s) with respect to unloaded HTPB. Optical and mechanical analyses show no improvement of dispersion quality given by coating, when stearic acid or fluorotelomer alcohol are considered, nevertheless in combustion tests these formulations exhibit a regression rate 50% higher with respect to the HTPB baseline at 350 kg/(m^2s).

Pre-dispersion of NP in ethyl acetate is considered also for SP. In formulations containing nanosized Fe_2O_3 and µAl this technique led to a burning rate augmented up to 215% at 40 bar with respect to the analogous SP prepared with the standard procedure.

The effectiveness of the technique is connected to the low percentage of combustion catalyst in the formulation (0.5%). In fact its application to SP containing 18% of nAl results rather ineffective.

For this kind of formulations another strategy to improve homogeneity in dispersion is evaluated: ALEX™ is coated with HTPB before the addition to the other ingredients (H-ALEX). Combustion tests show an enhancement in burning rate up to 26% with respect to uncoated ALEX™ containing SP and up to 117% with respect to the µAl filled composition.



1. Clusters in standard ALEXTM containing formulation (left) and in a formulation prepared with pre-dispersion of nanopowders in ethyl acetate (right). Optical microscope, magnification 20X

The quality of dispersion affects also rheological aspects of the uncured formulations with consequences in manufacture and castability, and thus in ballistic behavior of the SRM.

The theoretical part of the work aims to find a criterion to define the quality of dispersion of NP inside SP choosing the stiffening coefficient (H) as controlling parameter. First only µAl containing formulations are considered to investigate the connection between propellants microstructure and rheological properties. The simulation of realistic heterogeneous material is demanded to a packing code, that gives the distribution of the centres of each particle in a cube centred in the origin. The obtained distribution is used to evaluate the number of fine particles (µAl) around every coarse one (AP) enhancing the oxidizer fraction. The first result is the linear growth of the number of particles with AP fraction, up to 20% in volume. In this result it is possible to see the explanation for the limit of validity of Einstein equation, that states a linear relation between viscosity and the volumetric solid fraction into a fluid. For higher percentages of solid content the deviation from linear behaviour becomes clear and the number of Al particles around each AP grain increases faster and faster with AP content.

The research for the influence of microstructure on rheological properties of SP shows a cubic correlation between H and the number of Al particles around each AP grain. This correlation is used to evaluate the number of micrometric particles in nAl/µAl containing formulations. In the hypothesis of homogeneous dispersion of NP only µAl constitutes the fine fraction, while nAl is included in the liquid phase. In case of cohesion, clusters act as micrometric particles. In this way, the correlation obtained for H can be used to predict the theoretical viscosity of a well disperse formulation. The difference between theoretical and actual viscosity is used as a method to evaluate the quality of the dispersion, comparing ALEX™ and H-ALEX containing formulations: in case of 5% nAl, clusters increase theoretical number of µAl particle of 7% for the better disperse formulation and of 21% for ALEX™ containing ones. The number of cluster increases with nAl fraction; this is explained considering that particles are closer and attractive forces are more effective.

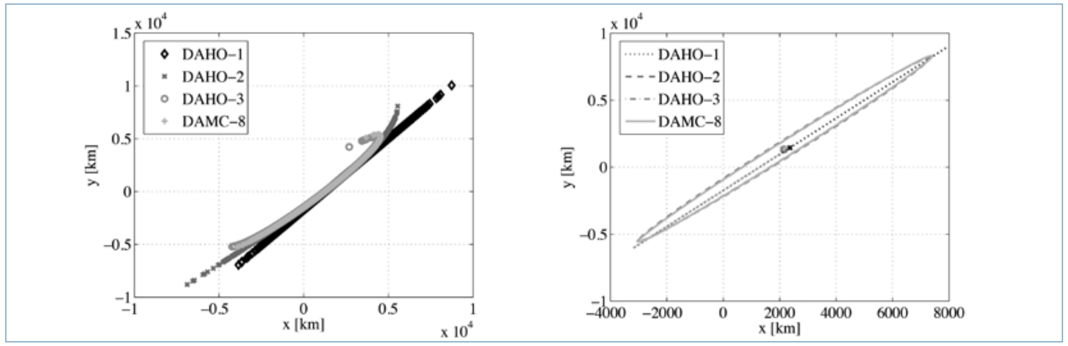
NONLINEAR ESTIMATION AND FILTERING FOR SPACE APPLICATIONS

Monica Valli - Supervisor: **Michele Lavagna**

The problem of nonlinear uncertainty propagation and filtering represents a crucial issue in celestial mechanics since all practical systems - from vehicle navigation to orbit determination or target tracking - involve nonlinearities of one kind or another. Nonlinear uncertainty propagation consists in studying how the statistics of an initial state that undergoes a nonlinear transformation can be computed and described, whereas nonlinear estimation consists in modeling the uncertainty about the world and the outcomes of interest by incorporating prior knowledge and observational evidence.

This thesis addresses the problem of nonlinear uncertainty propagation and estimation in celestial mechanics. In particular, due to worldwide increasing interest in autonomous navigation systems, great attention is paid to the computational requirements of the proposed algorithms. At this purpose, differential algebraic techniques are proposed as a valuable tool to perform accurate trajectory estimation in a reduced lapse of time. Working in the differential algebra framework, in fact, allows us to consistently reduce the computational effort of standard methods without loosing accuracy.

An introduction to the main differential algebraic structures used to develop the proposed methods is provided in the first part of the work.
In this thesis three main topics are treated: preliminary orbit determination, nonlinear mapping of uncertainties, and nonlinear filtering. First, we address the problem of preliminary orbit determination. In particular we analyze a method based on Taylor differential algebra for solving angles-only preliminary orbit determination problems and analytically mapping the uncertainties from the observations to the phase space. The proposed method can be used to recover newly discovered objects or, in space navigation, to compute the initial conditions and the related error statistics for any ground-based/on-board filtering algorithm.
Secondly, the problem of nonlinear mapping of uncertainties is studied. In particular, the problem is addressed not only by computing the estimate of the transformed mean and covariance, but also of the higher order cumulants to obtain an accurate finite-dimensional representation of the predicted state probability density function. The proposed method enables a general approach to uncertainty propagation that reduces the computational requirements of some popular techniques such as higher order Taylor methods and Monte Carlo simulations. The developed method is applied on typical problems in celestial mechanics, such as the two-body problem, and its general feature is also demonstrated by presenting long-term integrations in complex dynamical systems, such as the n-body problem or the simplified general perturbation model. Some results for this last case are presented in Figure1 showing that higher-order filters (DAHO-m, m=2,3) are closer to the "true" solution (DAMC-8) and succeed in describing the effects of system nonlinearities, providing better accuracy with respect to the linear solution (DAHO-1). In the thesis is also demonstrated that our differential algebra-based higher order approach is orders of magnitude more efficient than the variational one.
The nonlinear estimation and filtering is also a main subject of the work. In particular, it is demonstrated that working in the differential algebra framework improves the performance of well known filters such as higher-order and Monte Carlo-based filtering techniques by reducing their computational requirements.
At this purpose, in the thesis



1. Particles distribution and 3-σ uncertainty ellipse projection on the x- y plane in a True Equator Mean Equinox reference frame, after 7 days simulation, for the COSMO SKYMED 4 test case

we discuss and implement two novel differential algebra-based nonlinear estimation algorithms derived from standard higher-order filters. The structure of these filters eliminates the need to calculate the higher-order tensors at each time step by solving a complex system of augmented ordinary differential equations and therefore making the differential algebra approach more convenient than the variational one. We also demonstrate that the distribution of the state can be left unconstrained if we always estimate the state at a fixed epoch time and calculate the nonlinear map to transport it to any other epoch with the differential algebra framework.
The design and implementation in a differential algebra framework of two Monte Carlo-based filtering techniques is also discussed. In particular, we show that differential algebra can enhance and speed up the approach of classical Monte Carlo simulations by replacing thousands of integrations with fast polynomial evaluations.
The last part of the thesis is dedicated to address the problem of near-Earth objects orbit determination. More in detail, we present a software that couples preliminary orbit determination with the proposed differential algebra-based uncertainty propagation and nonlinear filtering methods. In particular, since nonlinear filters can provide better accuracy than the linearized solution, the presented software is proposed as a possible alternative to the least square method that, at the present time, is widely used to refine the preliminary orbit determination solution.
The application field of the techniques discussed in this thesis is not restrained to space and celestial mechanics applications, but can be extended to a more general framework. Whenever we have to deal with nonlinear uncertainty propagation and state estimation (such as in robotics, for instance), the proposed methods and the related considerations remain valid.