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

PhD Yearbook | 2019

DOCTORAL PROGRAM IN STRUCTURAL SEISMIC AND GEOTECHNICAL ENGINEERING

Chair:
Prof. Umberto Perego

Structural, Seismic and Geotechnical Engineering (SSGE) encompasses disciplines and techniques allowing understanding, modeling and controlling the behavior of: (a) structural materials (concrete, steel, masonry, composites, bio-materials, materials for micro-systems and metamaterials), (b) structural systems (from civil and industrial structures and infrastructures to bio-mechanical systems and micro-systems), (c) soils and (d) environment-structure interaction.
Deeply-rooted in the Civil Engineering, which is in itself highly inter-disciplinary, SSGE focuses also on environmental actions, either external (such as earthquake, vibrations, irradiation, wind and fire) or ensuing from soil-structure interaction (such as those caused by retained-earth thrust, landslides and water-table fluctuations). Due to their generality in materials and structural modeling, the methods developed within the domain of SSGE can be of great importance also in other technical-scientific fields, whenever understanding and controlling structural and material behavior is necessary to guarantee design reliability and structural safety, as well as serviceability and durability. Many are the themes arising in connection to SSGE: from tall buildings and bridges to industrial bio-mechanical and micro-electromechanical systems; from off-shore structures and dams to the rehabilitation of monumental buildings; from seismic design and structural dynamics to the behavior of geomaterials, tunnels and foundations, not to forget the topics shared with some branches of Industrial Engineering.
Within this framework, the main goal of our Graduate School is to promote the advancement of knowledge especially in the fields of: (a) innovation in materials and structures; (b) structural safety under highly-variable actions; (c) behavior of geomaterials and surface/buried structures.
We pursue this goal by offering our PhD Candidates an advanced, research-oriented background, based on both the pivotal role of Structural Engineering and the multi-disciplinary nature of Seismic and Geotechnical Engineering.

Contents of the Doctoral Program
Attainment of a PhD in Structural, Seismic and Geotechnical Engineering is conditional to: a minimum of three full-time years' study and research activities; the development of a PhD thesis; the achievement of the minimum credits required in terms of PhD courses.
Candidates are offered a variety of advanced courses on different topics, including mechanics of soils, materials and structures; computational and experimental methods; structural dynamics and earthquake engineering.

The study plan includes courses and seminars given by scientists, experts and researchers active either at the Politecnico di Milano or in other Italian and foreign Universities, research institutions and high-tech companies.

During their studies, PhD Candidates should develop their own original research work, consistent with the main disciplines dealt with in the Doctoral program, which will be reported in the PhD thesis.
The thesis should clearly state the goals of the research work, explaining the relation with the state-of-the-art, the used methods and the original results obtained.

The PhD research is developed under the guidance of a supervisor.

In order to widen and improve their research experience, PhD Candidates are strongly encouraged to spend a period abroad in one of the many Universities and research centers related to the Politecnico di Milano.

At the same time, the PhD School supports foreign scholars to give short courses and seminars in Milan, so that our PhD Candidates can constantly benefit from the opportunity to interact with the international scientific community.

TEACHING BOARD		
Perego Umberto	Della Vecchia Gabriele	Jommi Cristina
Ardito Raffaele	Di Prisco Claudio	Lualdi Maurizio
Bamonte Patrick	Di Prisco Marco	Malerba Pier Giorgio
Biondini Fabio	Fedele Roberto	Mariani Stefano
Bolzon Gabriella	Felicetti Roberto	Martinelli Luca
Bruggi Matteo	Ferrara Liberato	Paolucci Roberto
Comi Claudia	Frangi Attilio Alberto	Petrini Lorenza Maria
Corigliano Alberto	Ghisi Aldo	Rosati Gianpaolo
Coronelli Dario		

ADVISORY BOARD	
Luigi Albert (SOIL Geotecnica, Milano)	Guido Mazzà (ENEL-RSE)
Carlo Beltrami (Lombardi Ingegneria, Milano)	Paolo Negro (JRC, Ispra)
Roberto Borsari (Tetra Pak Packaging Solutions S.p.A.)	Silvia Scuri (Artech srl, Milano)
Giovanni Canetta (CeAS, Milano)	Maurizio Teora (Arup, Italia)
Stefano Cangiano (C.T.G. – Italcementi)	Massimo Zambon (Techint, Milano)
Giovanna Gabetta (ENI, Milano)	

LIFE-CYCLE ASSESSMENT OF DETERIORATING RC STRUCTURES USING ARTIFICIAL NEURAL NETWORKS

Silvia Bianchi - Supervisor: Prof. Fabio Biondini

The economic growth of a country relies on efficient transportation networks, which must guarantee adequate levels of functionality and safety over time. Bridges are frequently the most vulnerable elements of these systems and are at risk from aging, fatigue, and several deterioration processes due to chemical attacks and other physical damage mechanisms. For Reinforced Concrete (RC) structures, damaging factors include the effect of diffusive attacks from aggressive agents, such as chlorides, which may involve corrosion of steel reinforcement and deterioration of concrete. The detrimental effects of these deterioration processes associated with the continuous increasing traffic demand and severity of environmental exposure can lead over time to unsatisfactory bridge structural performance under service loadings. Nowadays, developed countries are facing with large stocks of existing RC bridges approaching 50 years of lifetime suffering aging and deterioration. The preservation of their structural and functional adequacy is a priority for administrations and decision-makers. Despite this critical situation, limited resources are usually available for inspection, maintenance and rehabilitation activities which must be rationally planned, optimizing the allocation of economic investments over the entire bridge stock.

Over the past decade, significant attention has been devoted by public authorities, private companies and professional associations worldwide to the condition rating of huge stocks of existing structures and infrastructure facilities including buildings, bridges, roads, railways, dams, ports and other construction facilities aimed at optimizing the limited resources investments in rehabilitation interventions. Technical, functional and performance data properly collected over bridge lifetime in an inventory can represent an important source of knowledge which can be managed through Bridge Management Systems (BMSs). BMSs are information systems composed by several modules aimed at supporting condition assessment of bridges and optimizing decision making related to the planning of maintenance activities and prioritization of rehabilitation interventions over time, also incorporating life-cycle methodologies, probabilistic predictive models and use of Structural Health Monitoring (SHM). In this context, SHM involves the observation of a structure over time using periodically spaced measurements, the extraction of damage-sensitive features from these measurements and the statistical analysis of these features to determine the current state of system health.

In this way, the results of the monitoring contribute to reduce the lack of knowledge associated to epistemic uncertainty and to improve predictive model accuracy. However, despite the availability of new technologies for data acquisition, the condition state of a bridge and the planning of its maintenance is traditionally based on expert evaluations and visual inspection activities. Therefore, BMSs often need to incorporate engineering judgment and to handle data severely affected by aleatory and epistemic uncertainty.

Soft computing techniques, including Artificial Neural Networks (ANNs), are particularly appropriate to be incorporated in BMSs since they can efficiently handle incomplete information and subjective data. To address this problem, the thesis proposes a general ANN-based framework for life-cycle assessment of deteriorating RC structures exposed to environmental hazard, with emphasis on individual RC bridges under corrosion and aging bridge networks. Two and three-layer ANNs are developed and trained to capture the overall system performance based on limited amount of information related to local damage of some components, typically obtained from visual inspections. The results of a probabilistic life-cycle analysis are used as training, validation, and test samples. The training datasets are formed to incorporate the results from several inspections carried out over given observation time intervals and to accommodate predictions over the remaining structural lifetime. The proposed approach is applied to the life-cycle assessment of RC structures, including frame buildings and bridges under chloride-induced corrosion, as well as to prioritization of maintenance and repair interventions of bridge stocks. The results show the effectiveness of the proposed approach to support public authorities in the decision-making process for optimal management of structure and infrastructure systems.

HYDRAULIC PRESSURE INDUCED FRACTURE AND PERMEABILITY EVOLUTION IN BRITTLE GEOMATERIALS

Gianluca Caramiello - Supervisor: Prof. Anna Marina Pandolfi

Co-Supervisor: Prof. Gabriele Della Vecchia

Hydraulic fracturing (HF) is a process characterized by the nucleation and propagation of multiple diffused fractures in soil or rock masses as a consequence of a localized solicitation driven by hydraulic pressure. HF is used extensively in the petroleum industry to stimulate hydrocarbon wells, in order to increase or activate their production. The application of hydraulic fracturing in the field of hydrocarbon extraction from unconventional reservoirs is widely spread over all the world, hence in different geological settings and increased a lot in the last decades due to the concomitant occurrence of favorable technical and economic conditions. However, from an operative point of view, HF treatments are performed in not fully conscious way.

The process is characterized by a strong hydro-mechanical coupling. To date, no predictive mathematical model is available to support the planning of operative procedures in realistic field conditions.

For optimal design of HF treatments, one of the most sought information is the extension (surface and volume) of fractures as a function of treatment parameters. Present day HF simulators used in the industry are based on rather old approaches, relying on questionable assumptions about fracture geometry and disregarding hydro-mechanical coupling when dealing with fluid pressure evolution. As a consequence, most of the commercial codes fails in the reproduction of the complex intricate fracture patterns shown by the field acoustic measurements.

The onset and the propagation of hydraulic fractures in brittle rocks is the topic of this work, as a first step towards a predictive model of HF procedures. A recently developed brittle damage model for porous rocks has been implemented into a finite element code and used to predict the evolution of the hydraulic conductivity during HF processes. The model is based on the explicit micromechanical construction of connected patterns of parallel equi-spaced cracks. A relevant feature of the model is that the fracture patterns are not arbitrary, but their inception, orientation and spacing follow from energetic consideration. The constitutive model has been validated against triaxial tests on several types of rocks (**Fig. 1**). The model, based on the Terzaghi effective stress concepts, has been implemented into a coupled hydro-mechanical finite element code, where the linear momentum and the fluid mass balance equations are numerically solved via a staggered approach. The coupled code is used to simulate laboratory and field scale fracturing processes induced by an increase in pore pressure, as in hydraulic fracturing jobs for reservoir stimulation. A sensitivity analysis at the laboratory scale has been conducted to clarify the meaning of all the parameters. Results show the capability of the code in reproducing the inception and propagation of the fault as well as the 3D shape of the damaged zone (**Fig. 2**). At field scale, a reference case, based on typical data of a HF process, has been used to ascertain the influence of different operational parameters on the outcomes of the process (**Fig. 3**). In particular, with reference to a simple geometry, a parametric study has been performed by varying the number of fracking processes (which define the distance between the different perforation slots) and the wellbore deviation from the minimum principal stress direction axis. The examples show the capability of the model in reproducing three-dimensional multiscale complex fracture patterns and permeability enhancement in the damaged porous medium.

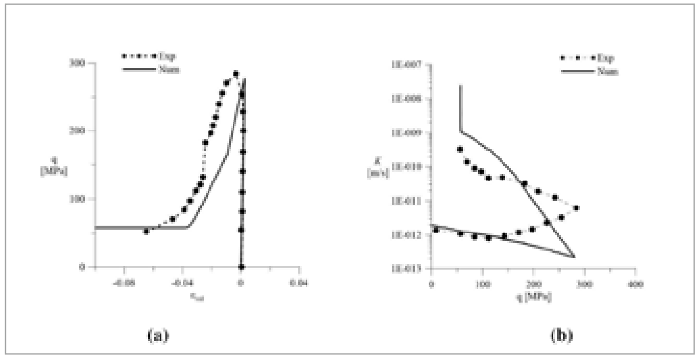

Fig. 1 - Triaxial test on Inada granite. Comparison between model prediction (continuum line) and experimental data (black circles). (a) Deviatoric stress versus volumetric strain. (b) Hydraulic conductivity versus deviatoric stress.

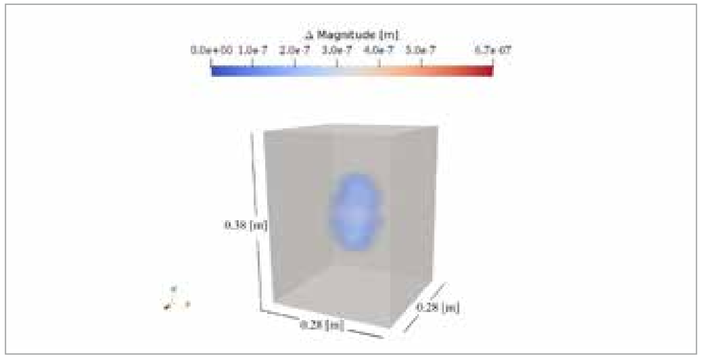

Fig. 2 - Laboratory test. Numerical analysis with applied fluid pressure. Visualization of the distribution of the damage in terms of magnitude of the opening displacements as obtained from the numerical simulation at the maximum of the applied pressure time history.

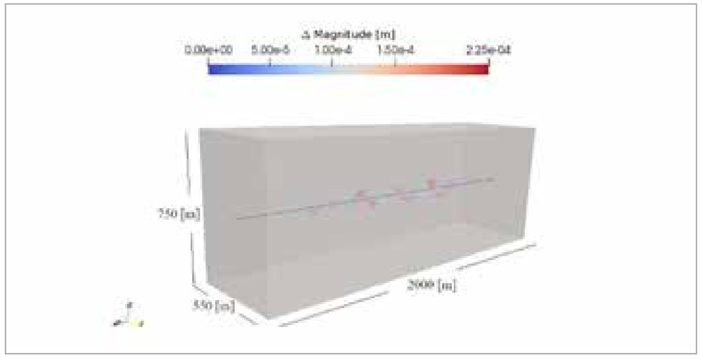

Fig. 3 - Field scale analysis. Visualization of the distribution of damage in terms of the magnitude of the opening displacement as obtained from the numerical simulation at the end of the process.

LIMIT ANALYSIS FOR ROBUSTNESS ASSESSMENT OF EXISTING STRUCTURES

Elisa Conti - Supervisor: Prof. Pier Giorgio Malerba

Reinforced concrete (RC) and prestressed concrete (PC) bridges and viaducts with more than 40-60 years of service life may exhibit severe damage states due to aggressive agents from environmental and service conditions. Damage reduces their structural reliability and requires increasing inspection and maintenance costs.
For these reasons, Road and Highway Administrations are faced with two typical problems: (a) in designing new bridges, estimating their bearing capacity after a certain number of years from construction under given environmental and service conditions; (b) for existing bridges, assessing their residual bearing capacity in the damaged state, after a certain number of years from construction time.
Many Authors have proposed general approaches for the assessment of bridge performances during their whole service life, taking into account the structural deterioration due to aging and environmental effects. These approaches present general procedures and methodologies for time-variant nonlinear and limit analysis of structures under static and/or seismic loadings, even in the presence of uncertainties. On the other hand, these approaches are time-consuming and required a specialized effort in order to create a representative numerical model.
In the usual practical approaches, the problem concerning the assessment of RC and PC bridges is analyzed through a model based on the actual geometry of the structure and the material characteristics, derived from original design reports or surveys and direct tests in situ. The deterioration state is described by assuming a certain reduction of the area of the main reinforcement and parts of the concrete volume. Such an approach is excessively simplified. In fact, and in greater detail, the steps of the assessment procedure usually consist in a linear elastic analysis followed by altering of the results (the internal forces regarding the critical sections) and the verification of these sections with respect axial-bending, shear and torsion resistance. The advantages of this procedure are: (a) it is easy to explain to the structure's managing authority, (b) it seems to take into account the presence of some degree of damage and (c) it develops the safety measurements according to standard code provisions.
However, the procedure also has some limitations: (a) through a linear analysis, the redistribution mechanisms are only partially represented; (b) the damage description is based on estimations deduced from visual surface inspections and, at the most, some core samples; (c) the checks on the sectional capacities give relatively good safety margins for the assessment of the bridge performance when taking into consideration the structural deterioration due to aging and environmental effects, but only if an accurate description of the section behavior and the mechanism redistribution suggested by the elastic analysis are considered.
This Thesis proposes a different solution to the same problem.
The first part presents the general aspects and the main requirements related to the problem of assessing the structural safety of existing structures. In particular, the identification of the most common weaknesses during the lifetime of the structure may have an influence on both the local and global integrity. Thus, a review of the factors which have an influence on the durability of a structure and a collection of the most frequent lacks depending on the weakening of structural details is outlined.
In the second part, aiming at proposing a methodology applicable to daily engineering

practice, the structural modeling based on finite beam-column elements is adopted because of their optimal balance between accuracy and computational efficiency. In the global structural framework, the matrix formulation of Limit Analysis is at first reviewed and developed through ad hoc computer codes. Comparisons with reference to the Nonlinear approach are carried out. Then, moving from the global level to the local one, a finite number of elementary "equivalent" frameworks or trusses of bars are adopted in studying continuous systems.
The damage state, measured at a particular time after construction, can be assumed as a given data or can be modeled by means of a general technique handling the damage diffusion and based on the Cellular Automata algorithm. Depending on the given damage scenario, such a degradation of the mechanical properties is incorporated in the structural analysis. It must be pointed out that the time parameter enters as an index of a particular sampling time at which the diffusion process is modeled. In this way, this tool allows assessing the structural performance at different times by taking into account the mechanical deterioration corresponding to the damaged state at that time.
Such an approach is applied in studying an existing RC grillage deck, having an edge beam damaged by leakage of salted water from the road platform. Usually, such zones exhibit chromatic alterations, indicating a material decay, signs of corroded main bars and the occurrence of stirrups cut at the bends. Sometimes, one or more elements of the grillage exceed in their entirety the serviceability limits, showing wide cracking patterns and evident curvature discontinuities. In these cases, after closing the bridge to traffic, a quick check is required to verify whether the damaged deck can be used as a platform for the repairing works, i.e. is able to safely carry workers and a load of equipment, such as small cranes or lifting systems and local power units.
A synthesis of these results is given by examining the damage evolution and the loading capacity of the structure over time and associating to this evolution a robustness index, which obviously decreases with time. In fact, the search for the limit behaviors is seen as a lifetime structural robustness estimation, tailored on the actual or supposed damaging characteristics of a given structure. In addition, the data resulting from the Limit Analysis is useful to highlight the essential details of such an evolution, showing how the internal forces redistribute from the weakest structural parts to the undamaged elements. Such an approach allows outlining the consequences due to different damage factors and the modes which lead to sudden collapses when neither weakness signals nor intermediate anomalous behaviors appear
Once the structure has undergone a suitable damage assessment, this type of analysis can be viewed like a virtual loading test, useful to highlight the evolution of the structural behavior, assess its residual bearing capacity and simulate the effects of the damage progression over time in order to estimate the residual service life. Moreover, such a virtual test better represents the evolution of the internal force redistribution in a loading process which can be extended until failure, without the theoretical limits of an elastic assessment and the experimental limits of not exceeding serviceability states.
Such a contribution may be suitable for solving the aforementioned problems and could provide a reliable reference to establish a hierarchy of protection techniques, as well as to plan proper maintenance actions and repair interventions.

MODELLING OF FERROELECTRIC THIN FILMS FOR PIEZOMEMS DEVICES

Patrick Fedeli - Supervisor: Attilio Frangi

Piezoelectricity has become very popular in innovative technologies and has been utilized in a wide range of industrial applications, including sensors, actuators, resonators, capacitors, transducers, energy harvesters, non-volatile FeRAM. Improvements in materials and processing technologies, on the one hand, and requirements of new and advanced applications on the other, have contributed to the development of this new market. The piezoelectric phenomenon couples the elastic response of a material to the electric field. There are two dual possible effects: the direct effect, when an electric charge appears in a mechanically deformed material; the inverse effect which consists in the deformation of a material subjected to an electric impulse. Most of the technological applications of piezoelectricity used nowadays are based on ferroelectric materials, due to the high piezoelectric effect which is larger in comparison with the conventional piezoelectric ceramics. While some materials, like quartz, naturally show the piezoelectric phenomenon, ferroelectric ceramics become piezoelectric under specific conditions and after a suitable treatment. One of the most prominent materials for piezoelectric applications is the lead zirconate titanate (PZT), a solid solution of ferroelectric $PbTiO_3$ and antiferroelectric $PbZrO_3$, which is typically processed in the form of polycrystals.
Ferroelectric ceramics are used widely as a bulk material, but in recent years they have been utilized in an increasing number of MEMS applications in the form of thin films. Ferroelectric thin films are used in sensors and actuators such as print heads for inkjet printers, ultrasonic transducers for acoustic applications as well as energy harvesting devices.
In general, ferroelectric materials present a spontaneous electrical polarization below a certain temperature, namely the Curie temperature. This is associated with a paraelectric-ferroelectric phase transition, which consists in the separation of positive and negative charge centers. The most common feature of the ferroelectric materials is the occurrence of domains, regions with uniform polarization, and the interface boundary between two adjacent coherent domains is called domain wall. A defining property of ferroelectricity is the switching between different metastable states, in which domains can be reoriented by applying an external electrical or stress field. The reorientation process leads to microstructural evolution and adds nonlinearity to the overall response. It is possible to say that the domain evolution is the origin of the macroscopic non-linear electromechanical behaviour of ferroelectric materials. Indeed, there is a strong correlation between the complexity of the domain structure inside the material and its global response. The concept of electric polarization is thus key to an understanding of ferroelectricity. Thanks to the capability to orient the remnant electrical polarization, randomly distributed in these materials, into a desired direction by applying an external electrical field, a unipolar direction of macroscopic preference could be imprinted to a device even after processing it. This electrical aligning, known as poling process, is fundamental to turning both an inert ceramic and thin-film material into an electromechanically active material with a multitude of industrial and commercial uses.
Therefore, it is of paramount importance, in design and optimization of piezoelectric devices for industrial applications, to be able to characterize the coercive field strength, i.e. the magnitude of the electric field required to switch the global polarization, and the remnant polarization value, i.e. the residual polarization when a zero electric field is applied. More in general one is interested in the whole hysteresis loop of the polarization versus the applied electric field.
Firstly, the shape of the hysteresis loop is strongly affected by the type of material considered, whether single- or polycrystal. Secondly, a number of contributions have proven that the occurrence of microstructural defects such as oxygen vacancies, space charges, dislocations, grain boundaries and voids arising from fabrication processes can dramatically change the material behavior. For instance, they have an impact on the coercive field strength, which is typically orders of magnitude higher in a single crystal than in real ferroelectric ceramics. Moreover, defects might be responsible for the experimentally observed fatigue and aging of ferroelectrics, i.e. the degradation of the material during electrical loading or in time even in the absence of an external loading. The aging phenomenon results in a pinching of the polarization hysteresis loop, whereas fatigue leads to a reduction of the hysteresis cycle. Given the significant industrial applications of ferroelectric materials, it is important to build models and tools to accurately simulate their behaviour. The linear theory is clearly not enough to predict the polarization distribution in the material. To understand material properties, one of the key issues is to develop the modeling capability to predict the microstructure evolution the relationship between microstructure and properties, and the impact of microstructural changes on the material response to applied fields. There are many theoretical studies on ferroelectric domain switching and the related non-linear electromechanical behaviours. The different approaches can be classified into several types, based on the scale of their applicability: macroscale, microscale, mesoscale and nanoscale methods. In this work, placing ourselves at the mesoscale, the behaviour of piezoelectric thin films has been investigated using the phase-field method.
Since the seminal contribution by Cahn and Hilliard, the phase field approach has emerged as one of the preferred tools to model the evolution of phases and micro-structures in materials. It has been recently applied to investigate the non-linear response of ferroelectric single crystals, polycrystals and thin films and to address the interaction between the domain evolution and microstructural defects. Therefore, a fully coupled electromechanical phase field model with polarization as the order parameter governed by the Ginzburg-Landau equation is presented and implemented in a Finite Element code. Then, a preliminary experimental campaign is conducted to establish the crystallographic properties and the grain structures of a real PZT thin film. Starting from the experimental evidence a simplified polycrystalline geometric configuration of the film is modelled and the developed simulation tool is applied. Finally, a novel numeric approach, the isogeomteric collocation, is investigated. The first obtained results are encouraging and propose isogeometric collocation as an inexpensive but very accurate alternative to standard FEM also for complex coupled problems.

NONLINEAR DYNAMICS PHENOMENA IN MEMS

Andrea Guerrieri - Supervisor: Prof. Raffaele Ardito

Co-Supervisor: Prof. Attilio Frangi

Micro Electro Mechanical Systems (MEMS) technology has revolutionized many industrial and consumer products by combining silicon-based microelectronics with micromachining process. The scaling of MEMS dimensions requires on the other hand to increase drastically sensitivity to detect signal barely recognizable from noise. Since sensitivity is most of the time proportional to the amplitude of device motion, the dynamical response easily exploits nonlinearities even long before the material linear behaviour fails. The understanding of typical nonlinear dynamics phenomena in commercial MEMS devices is fundamental in order to avoid them when they become the main reason for device failure or to exploit them when they can increase drastically device's performance. The objective of the dissertation is to investigate different nonlinear dynamics phenomena observable in commercial MEMS devices.
We consider an electrostatically actuated torsional micromirror, a key element of recent micro-optical devices (MOEMS). It has received increasing attention with specific reference to its main torsional mode. It has been shown that actuation of the mirror is based on parametric resonance. Theory predicts that parametric resonances is more likely to occur near drive frequencies that are twice the system's natural frequency. During operations, the mirror is driven like an oscillator in phase control. As a consequence its working frequency is expected to decrease linearly with ambient temperature according to the known variation of the Young modulus of silicon. However, for suitable geometrical features of the micromirror, a frequency sudden jump appears in experiments when a given temperature is reached. This cannot be explained with standard linearized theories and represents an important example of nonlinear mode coupling in microstructures.
A numerical model describing the mirror dynamics in terms of its three Euler angles has been introduced and implemented. Elastic actions haven been estimated with FEM codes allowing for large transformations. Refined capacitance analyses have been conducted on a full set of comb fingers. We have developed a new approach based on Finite Elements and material derivative allowing to compute the electrostatic force/torque exerted on solid bodies but also directly the electrostatic stiffness, i.e. their derivative with respect to parameters governing the movement of the mirror, without any finite differences, that reduce accuracy. The highly nonlinear response of similar devices typically presents both stable and unstable branches which can be simulated using continuation approaches. In these techniques, starting from a known solution corresponding to a given value of a parameter, the nonlinear governing equations are linearized following a Newton-Raphson procedure in order to compute the system response to a variation of the parameter. The electrostatic stiffness appears in the first order expansion of the equation, that is why it must be carefully evaluated in order not to spoil the quadratic convergence of the numerical scheme. All the previous numerical procedures have been validated with experimental data. Numerical results are able to reproduce quantitatively the frequency jump observed experimentally. Further, they showed that this phenomenon is induced by a sudden decoupling of two coexisting modes of vibration.
A frequency comb refers to a signal whose frequency response contains a collection of equidistant spectral lines packed around a reference frequency with an offset frequency. The popularity of frequency combs is largely due to their applications in optical metrology, but have been recently discussed with reference to mechanical systems. We aim here at proving that also contact between mechanical parts can in principle be responsible of similar effects. Indeed, standard inertial resonating MEMS sensors consist of structural elements separated by sub-micrometric and ever decreasing gaps, so for large oscillation amplitudes contact might be reached at some point, also due to geometric imperfections. In order to investigate these phenomena, we have developed a MEMS device, consisting of an oscillating mass contacting a clamped-clamped stiffer beam during its large amplitude oscillations. The device has been actuated electrostatically with comb-fingers in order to reduce the influence of electrostatic nonlinearities. The device can be easily modelled as a 1D oscillator having bilinear stiffness and its dynamic response has been integrated with a semi-analytical procedure which only requires the numerical identification of the instants when contact is activated or deactivated. The focus is on the experimental and numerical analysis of stable periodic solutions characterized by N-cycles and M-impacts with a rich composition of different tones that closely resembles the pattern of frequency combs. We show that, when the periodic solution is characterized by large N, the spectra of the displacements show a very rich content of spectral lines packed with small offsets around the resonant frequency and its multiples, as a result of a combined frequency and amplitude modulation. For a given actuation frequency and strength several different solutions coexist and can be obtained numerically by imposing different initial displacement and velocity. A smaller set of solutions have been identified experimentally due to the intrinsic difficulty in controlling initial conditions.
Geometrical nonlinearities can be addressed resorting to classical techniques, like the Proper Orthogonal Decomposition or the computation of Nonlinear Normal Modes (NNM), also in connection with the theory of Normal Forms. Taking inspiration from these contributions, we develop a simplified and approximate technique which is applicable to the family of devices with the following basic features: i) complex structures generating large scale FEM models; ii) high quality factors ($Q>10^3$). In the linear regime the second point practically guarantees that only one mode will be excited and the others can be disregarded. When the response becomes nonlinear, we still assume that MEMS oscillate with a form which is still very similar the linear mode but: i) internal resonances can be activated also due to the softening/hardening behaviour of the main mode; ii) higher order modes, which respond quasi-statically, can modify the distribution of internal stresses. Our aim is deriving a ROM with few equations of motion, in which the stiffnesses are manifold functions of the amplitude of each mode taken into account.
In a first phase, a series of static nonlinear analyses are performed in which the device is loaded with forces of increasing magnitude. A convenient choice is represented by body forces proportional to the inertia of the linear mode, since at resonance inertia forces dominate. For each value of the load multiplier the stress tensor is computed and recorded.
We assume that there exists a biunivocal relation between the load multiplier and a displacement control parameter (usually the amplitude at the nodal point of the relevant mode). The estimate of the stress manifold is done once and prior to the numerical integration, allowing a drastic reduction of the computational cost. First we validate the method against the analytical result for the clamped-clamped beam, where we observe hardening dynamic response as expected. Second we applied the algorithm to a DRG; here we find something unexpected, indeed a considerable amount of softening comes from geometrical effects. Further, considering the interaction between two degenerate modes, we address the simulation of the auto-parametric excitation already verified experimentally. Numerically we observe that while forcing one of the modes, the latter gets excited and amplified by auto-parametric mechanical resonance, even in the absence of Coriolis forces.

A FULLY EXPLICIT LAGRANGIAN FINITE ELEMENT METHOD FOR HIGHLY NONLINEAR FLUID STRUCTURE INTERACTION PROBLEMS

Simone Meduri - Advisor: Perego Umberto

The numerical simulation of Fluid-Structure Interaction problems is a topic of great relevance because of the wide range of applications in many engineering fields. In this thesis, a partitioned fully explicit and fully Lagrangian Finite Element Method (FEM) for FSI problems is presented.
A novel explicit version of the Lagrangian Particle Finite Element Method (PFEM) is employed for the fluid modelling, based on the hypothesis of weakly compressible fluid flow. A distinctive feature of the proposed FSI strategy is that the solid domain is modelled using the explicit FEM of the commercial software SIMULIA Abaqus/Explicit from Dassault Systémes. This allows to perform simulations with an advanced description on the structural domain, including advanced structural material models and contact interactions. The structure-to-fluid coupling is performed through the SIMULIA built-in Co-Simulation engine and it is based on a technique derived by the Domain Decomposition methods. The method ensures strong coupling and stability of the partitioned solver, retaining at the same time an overall system of fully decoupled explicit equations. Moreover, it allows for the use of different time integration steps and nonconforming meshes in the two subdomains.
The fully explicit nature of the coupled solver is appealing for large-scale engineering problems characterized by fast dynamics or high degree of non-linearity. The fully Lagrangian kinematic description is particularly effective in the simulation of FSI problems with free surface flows and large structural displacements, since the fluid boundaries are automatically defined by the position of the mesh nodes with no need for interface tracking algorithms.
A novel technique is proposed to simplify the imposition in Lagrangian methods of non-homogeneous boundary conditions which are of practical interest in several engineering applications, e.g., inflow/outflow conditions, fluid slip at boundary walls and symmetry surfaces. The method is based on a mixed Lagrangian-Eulerian description, which introduces fixed Eulerian nodes only on the boundaries where non homogeneous conditions have to be applied, leading to a simple and computationally convenient implementation.

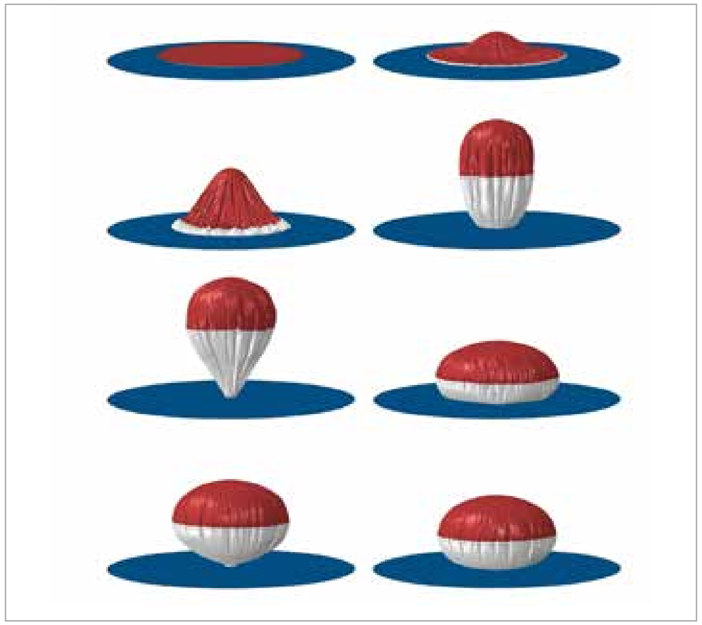

Fig. 1 - Flat airbag deployment. Snapshots of the simulation at different time instants.

A novel efficient runtime mesh smoothing algorithm for explicit Lagrangian PFEM simulations is proposed. The conditional stability of explicit time integration schemes requires the use of small time increments, proportional to the size of the element in the mesh with the worst geometrical quality. On the other hand, in the 3D framework the Delaunay tessellation employed in the PFEM loses some of its optimality properties holding in 2D, so that badly shaped tetrahedra are frequently added in the triangulation. This leads to unacceptably small stable time step size for explicit solvers. The novel mesh smoothing technique is able to correct overly distorted elements at an acceptable computational cost, so that it can be applied runtime in the frequent remeshing framework of the PFEM. More in general, it could be conveniently applied to regularize the mesh and improve the solution of other Lagrangian methods. This is achieved exploiting an elastic analogy that allows for the use of the same explicit and parallelizable architecture of the fluid solver.
The smoothing algorithm could be conveniently applied to regularize the mesh and improve the solution of other Lagrangian methods.
After an extensive validation of the proposed PFEM-FEM FSI approach against analytical, experimental and numerical results presented in the literature, the real engineering application of the automotive airbag deployment is addressed (Fig. 1). Despite the lack of available input data presented in the literature, the results seem to confirm the good potentialities of the method in this kind of applications characterized by an extremely fast dynamics and high level of non-linearity.