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PhD Yearbook | 2018

DOCTORAL PROGRAM IN MECHANICAL ENGINEERING

Chair:
Prof. Daniele Rocchi

The PhD Programme in Mechanical Engineering of Politecnico di Milano offers top-level knowledge in one of the most profitable sectors in Italy and Worldwide; it is a key instrument to access leading enterprises and to achieve prominent positions in large international companies devoted to research and development, innovation and design. The primary employment market is composed of leading companies and organizations dedicated to innovation, research and technical development, high-tech SMEs and governmental departments. Our Programme currently ranks 17th in the world according to QS World University Rankings (Mechanical, Aeronautical & Manufacturing Engineering 2018).

As for career perspectives, a recent survey (run by Politecnico in 2017) showed that our PhD Candidates are 100% employed after one year, in national and international companies and academic and non-academic research institutions, engaged in innovation, research and technical development. On average, the survey showed that people earning our PhD title are paid 35% more than the corresponding employees with a master title.

Within our Programme all Doctoral Candidates follow a minimum path of three-years, which includes specific courses and lectures, held by Faculty members and foreign professors and experts, in-depth research, laboratories and active cooperation with international industries, institutions and research groups. With this background, our Doctorates are able to blend the exactness of scientific knowledge with the ability to deal with management and industrial issues. In this view, their scientific profiles are suitable for prestigious positions at national and international level within universities and research institutions, large industrial and consulting companies, SMEs.
In the following pages 28 abstracts belonging to PhDs of the 29th (7) and 30th (21) doctoral cycles (defended in 2017) are proposed. They represent a good overview of the international vocation of our PhD Programme, with half of them having being developed by international fellows. Female presence accounts for 25%.
90% of the PhDs were supported by fellowships provided by the Italian Government, Industries, and European and National projects.

RESEARCH AREAS
The PhD Programme in Mechanical Engineering covers a number of different disciplines, being devoted, in particular, to innovation and experimental activities in six major research areas, and in an additional interdisciplinary area. All doctoral thesis displayed in the following pages belong to one of these areas:
***Dynamics and vibration of mechanical systems and vehicles**:* this research line is organized into five research areas, namely Mechatronics and Robotics, Rotordynamics, Wind Engineering, Road Vehicle Dynamics, Railway Dynamics. It features modelling of linear and non-linear dynamic systems, stability and self-excited vibrations, active control of mechanical systems, condition monitoring and diagnostics.
Measurements and experimental Techniques: the Mechanical and Thermal Measurements (MTM) group has its common background in the development and qualification of new measurements techniques, as well as in the customisation and application of well-known measurement principles in innovative fields. MTM major research focus is oriented towards the design, development and metrological characterisation of measurement systems and procedures, the implementation of innovative techniques in sound/vibrations, structural health monitoring, vision, space and rehabilitation measurements.
Machine and vehicle design: this research area is involved in advanced design methods and fitness for purpose of mechanical components. Advanced design methods refer to the definition of multiaxial low and high cycle fatigue life prediction criteria, and the assessment of structural integrity of cracked elements, the prediction of fatigue life criteria of advanced materials as polymer matrix composite materials (short and long fibres), the definition of approaches to predict the influence of shot peening on fatigue strength of mechanical components. Gears, pressure vessels and helicopter components are dealt with. Optimal design and testing of vehicle systems create a synergism between the theoretical and the experimental researches on ground vehicles.
***Manufacturing and production systems**:* this research field gives relevance to the problem of optimal transformation of raw materials into final products, addressing all issues related with the introduction, usage, and evolution of technologies and production systems during the entire product life-cycle. PhD activities, in particular, are developed within the following research fields: Manufacturing Processes (MPR), Manufacturing Systems and Quality (MSQ).
***Materials*:** this area is focused on the study of production process and characterization of materials, for structural and functional applications. Excellent research products were obtained both on fundamental research topics (e.g. nanostructured materials, foamed alloys, chemical phenomena in liquid melts, microstructural design ecc.) and on applied research (e.g. failure and damage analysis, texture analysis, high temperature behaviour, coatings for advanced applications, etc.). The research projects carried

out in recent years addressed specifically the following research topics: Steelmaking and Metallurgical Processes, Advanced Materials and Applied Metallurgy.

***Methods and tools for product design*:** two main research topics are addressed in this field: PLM-Product Lifecycle Management, which includes process modelling, engineering knowledge management, product innovation methods, systematic innovation principles and methods, topology optimization systems, and data/process interoperability, and Virtual Prototyping, which includes virtual prototyping for functional and ergonomics product validation, haptic interfaces and interaction, reverse engineering and physics-based modelling and simulation, emotional engineering.

Biomechanical Engineering: the objective of this research area is the development of mechanical engineering methodologies and techniques for improving health and human life. A wide range of objectives can be identified, corresponding to the different topics: improvement of the human-machine interaction; design of rehabilitation robots and devices; design or improvement of prosthetic devices (new materials, use of sensors and actuators); sensors and actuators for bio-mechatronic applications; development and optimization of managing solutions for improvement of health care activities; devices for improving or monitoring sport/training performance of normal and/or handicapped athletes.

LABORATORIES

One of the key elements of our Doctoral Programme is represented by our laboratories; we feature some of the most unique, active and innovative set-ups in Europe: Cable Dynamics, Characterization of Materials, DBA (Dynamic Bench for Railway Axles), Dynamic Testing, Dynamic Vehicle, Gear and Power Transmission, Geometrical Metrology, High-Temperature Behaviour of Materials, La.S.T., Manufacturing System, Material Testing, Mechatronics, MI_crolab Micro Machining, Microstructural Investigations and Failure Analysis, Outdoor Testing, Physico-Chemical Bulk and Surface Analyses, Power Electronics and Electrical Drives, Process Metallurgy, Reverse Engineering, Robotics, SIP (Structural Integrity and Prognostics), SITEC Laser, Test rig for the Evaluation of Contact Strip Performances, VAL (Vibroacoustics Lab), VB (Vision Bricks Lab), Virtual Prototyping, Water Jet, Wind Tunnel.

INTERNATIONALIZATION

We foster internationalization by strongly recommending and supporting candidates' mobility abroad, for short-term study and research periods up to 18 months. Our Institution is member of Idea League (www.idealeague.org) and Alliance4Tech (www.alliance4tech.eu), two strategic partnerships with leading European Techcnical Universities. We also promote, draft and activate European and extra-European Joint Degrees, Double PhDs and Joint Doctoral Thesis (Cotutelle); our Department is actively involved in EU-based and governmental third-level education agreements such as H2020, Erasmus Mundus, China Scholarship Council and Brazilian Confap.

We have ongoing agreements with MIT (Progetto Rocca), Technion – Israel Institute of Technology (Double PhD), Shanghai Jiao Tong University (Double PhD) École Centrale Paris (Cotutelle), Delft University of Technology (Double PhD and Cotutelle), TUM (Cotutelle), University of Illinois at Urbana Champaign (Cotutelle), Laval University (Double PhD), EAFIT (Cotutelle), Qatar University (Double PhD), AGH - Akademia Górniczo-Hutnicza (Cotutelle).
We also have ongoing collaborations within a wider international network, that includes some of the highest-level and best-known universities all over the world, such as the University of California at Berkeley (US), Imperial College London (UK), Tsinghua University (CN), University of Michigan (US), École Polytechnique Fédérale de Lausanne (CH), Norwegian University of Science and Technology (N), University of Southampton (UK), Technical University of Denmark (DK), Pennsylvania State University (US), Chalmers University of Technology (SE), Virginia Tech (US), Technische Universität Darmstadt (DE), University of Bristol (UK), The University of Sheffield (UK), Politécnica de Madrid (ES).

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NUMERICAL METHODOLOGIES FOR NOISE AND VIBRATION SOURCES ASSESSMENT IN POWERTRAIN APPLICATIONS

Antonio Acri - Supervisor: Prof. Roberto Corradi
Industrial Supervisors: Ph.D. E. Nijman, Prof. G. Offner

Noise legislations and the increasing customer demands determine the NVH (Noise Vibration and Harshness) development of modern commercial vehicles. In order to meet the stringent legislative requirements for the vehicle noise emission, exact knowledge of all vehicle noise sources and their acoustic behavior is required. There are several experimental method which can be used to assess and rank noise and vibration sources. Conversely, in industry there is a lack of numerical methodologies to assess noise and vibration sources which can be applied since the first steps of engine and vehicle design.

The Aim of this project is to define methodologies which are applied on numerical methods for noise sources assessment, validate them and analyse their limits of validity. In NVH problems, engineers use to optimize dynamic responses such as acceleration and sound pressure level. For this reason, this project starts from the definition of two methodologies which focus on these two quantities: dynamic substructuring for Numerical Transfer Path Analysis (NTPA) and Surface Contribution Analysis (SCA) within Wave Based Method (WBM). A validation on a particular case was also performed for the NTPA method. In addition, the robustness of these methodologies was investigated. Moreover, an newly energy based method was developed: Energy Flow Contribution Analysis (EFCA). EFCA is a methodology which can be also investigated in an experimental setup.

NTPA is based on dynamic substructuring of multi-body dynamic systems. The body under investigation is isolated and the body joint contacts replaced with contact forces. Each excitation is then treated as a separate source and its response is computed. Even though this methodology differs from TPA because no transfer functions are needed for the assessment of the different noise paths, it is shown how both methodologies have analogous results. The benefits associated with the proposed numerical methodology are also discussed. In particular it is shown how increasing the DoFs of the investigated model, the number of simulations required for the proposed methodology is reduced compared with TPA.

As an application example, the numerical TPA introduced in this paper is applied to investigate a numerical model of a four cylinder internal combustion engine and obtained results are related with literature references. Results investigated are surface velocities, sound pressure or vibration contributions at the engine mounts. These info can be used to understand engine noise radiation and how sources inside the engine contribute to interior noise. The consistency and the accuracy of NTPA methodology are also discussed showing how real engine modifications can be predicted with NTPA analysis.

SCA is a methodology thought to operate within a wave based method framework. It is based on the decomposition of the boundary conditions of the acoustic radiation problem, under the assumption of the validity of the superposition principle on the boundary conditions (structural vibrations can be treated with linear models). Different surfaces of the radiating object consider different boundary conditions and with this procedure the noise radiated from each different surface is separately investigated.

EFCA is similar to NTPA analysis but it directly operates with power quantities. At the interfaces of the investigated body, the transmitted power is evaluated giving direct information of the interaction of the different noise sources. Concerning the problem of sources assessment and ranking, no experimental methodologies work with power quantities. Hence, similar analysis can be done also on real systems via direct measurements of interface transmitted power.

Finally, this projects deals also with the estimation of the robustness of the proposed methodologies. Therefore, the influence of system uncertainties is investigated. In particular the effect of cyclic cylinder variability (uncertainties on excitation input) and the uncertainties on model parameters (applying random matrix theory) are considered. In these investigations it was shown the frequency range of validity, a sensitivity analysis and how to correctly perform multibody dynamic analysis or acoustic radiation analysis in order to derive useful information on the source assessment and ranking. The statistical information derived can be used to advance the knowledge of the multi-body analysis, the assessment of system sources when uncertainties in model parameters are considered and verify sensitivity analysis of NTPA and SCA. Despite of the system variability, the source assessment can be done taking into account magnitude information and phase information. If the variability is considerably high, it becomes important to study the source correlations, to understand if the variability influences the uniqueness ranking of the sources.

As a general conclusion, presented methodologies are robust and able to assess and rank system sources. Compared with an experimental analysis, a numerical analysis is able to clearly distinguish different noise sources. Hence, it is more convenient to investigate substructures like engines, where the measurement of the excitations is a severe issue, especially considering moving or distributed forces. Moreover, a numerical analysis can be performed starting from the first steps of the design process and do not require any prototype.

EXPERIMENTAL HIGH RESOLUTION ANALYSIS OF THE PRESSURE PEAKS ON A BUILDING SCALE MODEL FAÇADES

Luca Amerio - Supervisor: Prof. Alberto Zasso

Wind tunnel measurements are an established technique for the assessment of wind induced pressure on building façades. Despite having been used for more than fifty years, there are still some open questions on how to interpret the results of wind tunnel measurements.
Since the Eighties, indeed, as the instrumentation used in the wind tunnels improved, stronger and stronger pressure events have been observed. This growth of the observed peak pressure has been heuristically ascribed to the improvement of the sampling frequency of the equipment.
This, along with the fact that no damages had been observed in the buildings designed with the previous lower coefficients, led to the conviction that these stronger events had to be purged from the acquired signal by mean of a low-pass filter.
To support this hypothesis, an equation, the TVL equation, has been proposed to link the duration of the phenomena to their spatial width. Even if this equation has been used for more than forty years, however, very few experimental validations exist in literature.
In this thesis we present an experiment carried out at Politecnico di Milano, in collaboration with the Advanced Technology + Research group of ARUP UK, to experimentally study the validity of the above-mentioned hypothesis. During this experiment, the pressure has been measured on the surface of a prismatic model using extremely closely spaced pressure taps.
This allowed to study the spatial distribution of the pressure field and to investigate the relationship between the duration and the width of the dimensioning pressure peaks occurring on the leeward faces of the building.
The results highlight a situation much more complex than the one suggested by the simple TVL equation and raise some doubts regarding its validity. This will be then studied comparing the design value predicted using the time-filtered signals, with the one obtained with the area-averaged signals. The results allow to understand how large the error performed when using the time-filtered signals in place of area-averaged is and to assess which version of the TVL equation performs best.
Exploiting the high spatial resolution used in this research, we have been able to study the relationship between the duration and the spatial size of these events. It has been observed that the correlation between the duration and the size of this events is poor in many areas, raising doubts regarding the equivalence between time and space filtering.
The study of the proportionality parameter between the duration and the size of the phenomena, highlighted that the median value of such parameter is not far from the value predicted by the current state-of-the-art. Its dispersion, however, and the fact that the median value can significantly change depending on several factors (such as the portion of the building considered, the wind direction or the presence of the surrounding) proved how the time-averaging approach, adopting the same equation for whatever situation (exposure, surrounding, geometry, etc.), cannot be considered rigorous.
Despite the above-mentioned consideration on the relationship between the duration of the events and their size, in the wind-tunnel practice the time-filtering of the pressure data is a consolidated habit. Moreover, nowadays no real alternative exists. To support this technique, we tried to quantify the error that different time-filtering technique make when applied to single-tap data.
It turns out that despite the previous observations, the error made using a moving average filter with a span evaluated with the Lawson's TVL equation (i.e.) is smaller than 1 for most areas, while a moving average with a span evaluated with the TVL equation in the form produces design values that are generally over-conservative.
While this conclusion is valid for most areas and most flow situations, in some small portion of the building surface where the most extreme pressure peaks have been observed the design value obtained filtering the pressure time-histories with the moving average prescribed by Lawson still generates design value that are up to 3 higher than the area-averaged pressure time-history.
This finding seems to suggest that the large dispersion of the K value described could be driven by non-dimensioning peaks and that, if we limit our study only to these, the dispersion in the distribution decrease.
In the last chapter, an experimental solution for a more robust evaluation of the area-averaged pressure has been proposed. The method relies on the use of a small passive device formed by an empty cavity with a porous plastic panel on the front face. The pressure acting on the front face communicates with the interior of the tap through an array of holes, where is then measured with a traditional pressure scanner. The device does not have any moving, nor electric component and can be easily realised using CNC machinery or 3D printing technology. The frontal panel can also be realised with rather inexpensive technologies. Since the "averaging" operation is performed by the physics of the device itself, the need of an analytical evaluation of the spatial correlation of the pressure from a single time-history is completely eliminated.
The solution has been tested in two different positions on the building. Moreover, both the stand-alone configuration and the one within the wake of an upwind building have been tested. The results were compared with the ones obtained from the measurement of the pressure field with 72 independent "classical" pressure taps numerically averaged.
The results showed that the peak value evaluated with the proposed device match the one evaluated with the area-averaged array of pressure tap with an error that is almost everywhere lower than . The proposed method has also the advantage that produce a signal whose spectrum match the spectrum of the one of the area averaged pressure up to the maximum sampling frequency allowing the characterization not only of the mean and peak pressure, but it's whole frequency content.

Fig. 1

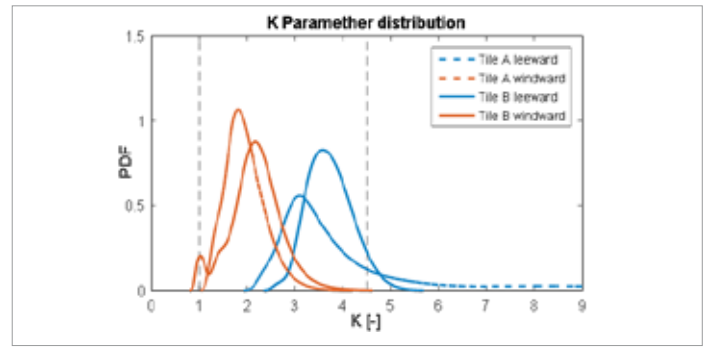


Fig. 2

Fig. 3

VIRTUAL REALITY (VR) DRIVING SIMULATOR FOR ANALYSIS OF DRIVER BEHAVIOR

Dedy Ariansyah - Supervisor: Prof. Monica Bordegoni

The issue of road accident is a global problem that contributes to ill-health and death. Existing studies have identified that human factors are the major contributing factor to road accident. While, poor or aberrant driver behavior often leads to traffic fatalities, much of the human error is not a faulty human, rather the design of the vehicle and road system have been ill-suited to sustain human performance. To achieve road traffic without involving road fatalities or injuries, there is a shared responsibility between the road user and the designers of vehicle and road system. Road users are responsible for their good behavior while using the vehicle and road system, whereas designers need to understand road users' capabilities when they design the vehicle and road system.

Driving simulator emerges as a promising tool for designers to identify potential issues that road users might encounter and make use of this tool to address the appropriate design of road transportation. One important issue that needs to be addressed for the improvement of road safety involving a high traffic incident in urban driving which is often caused by driving with excessive speed or failing to adjust the speed in critical conditions.

The complementary approach to traffic rule enforcement for resolving this issue could be oriented toward the development of road infrastructure that could modify driver behavior but without introducing too much discomfort to the drivers. The road safety intervention could be aimed at providing road design solution that unconsciously influence drivers to adapt safer driving style. Therefore, safety measure of hazardous driving area based on which safety countermeasure can be designed and evaluated is necessary to ensure the effectiveness of the treatment before its actual implementation. Another issue that might hold potential threat to the decrement in drivers' safety is the interaction of driver with Advanced Driver Assistance Systems (ADASs). In today's commercial vehicles, many systems are brought in or embedded into vehicle for advising driver to maintain safe headway distance to the lead vehicle or even supplying information to drive eco-friendly. This interaction could bring negative impact to the driver as processing information from ADASs requires the operating expenses in terms of mental workload and attention withdrawal from the road demand. The dynamic change in driving demand could also potentially impair driver's interaction with ADAS as additional effort is required to maintain the dual-task performance with ADAS. The detection of drivers' cognitive operations underlying the impairment and improvement of driver-ADAS interaction in different conditions is necessary as to identify the design of ADAS interface that is cognitive suitable to sustain driving performance. Furthermore, road traffic is facing a novel management of risk accident due to the increasing number of foreign drivers on the road following the widespread of car-sharing and car rental companies. Foreign drivers are more likely to involve in traffic collision owing to the lack of road regulation knowledge and driving skills, especially for young drivers who represents a higher proportion of accident involvement than older drivers due to the characteristic of youthfulness and high-risk propensity. To pursue a preventive action, concreate initiative must be taken to address the safety issue for this group of the drivers.

This thesis presents the setup of a fixed-based driving simulator integrated with physiological sensors to assess the psychophysiological factors of driver behavior and performance.

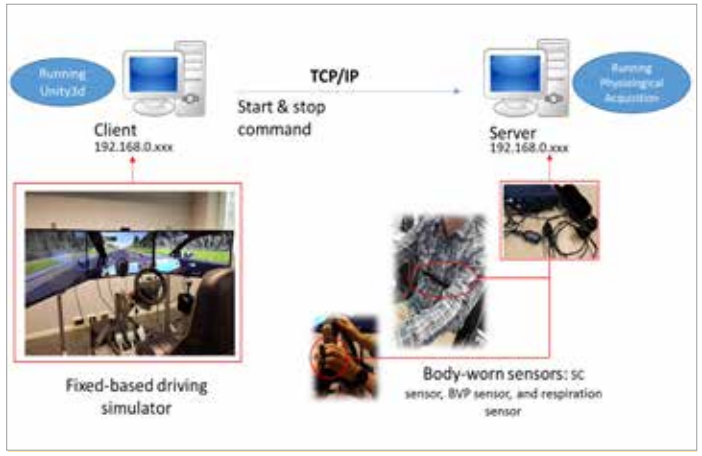


Fig. 1 - System architecture of virtual driving simulator and physiological sensors setup

The aim of this thesis is to develop a fixed-based driving simulator for the analysis of driver behavior and the evaluation of road traffic solutions. The objectives of this study along with the main key findings are summarized as follow:

- *Objective*: to identify and to address the issues of driving simulator development and utilization.
  Key finding: although a fixed-based driving simulator does not simulate complete driving cues and is likely to produce vision-induced simulator sickness, some important parameters in driving simulator setup could be identified in accordance to the purpose of its use.
- *Objective*: to examine whether the driving simulator could be used as an effective tool for designing and evaluating road traffic solutions.
  Key finding: the comparison study with field testing demonstrated that current configuration of driving simulator provides a sufficient well representation of actual driving that could trigger comparable driver behavior and physiological response to the real-life setting which indicate the feasibility of current setup to further investigate its usability as an effective tool for the design of road solutions.
- *Objective*: to investigate the specific physiological indexes that are useful to capture drivers' cognitive operations elicited by the interaction with ADAS for the development of ADAS interface that fits human capabilities.
  Key finding: the analysis of autonomic indexes such as Blood Volume Amplitude (BVA) as an index of sympathetic activity and High Frequency of Heart Rate Variability (HF-HRV) in autonomic space could discriminate different cognitive operations underlying the change in drivers' workload while driving with visual ADAS in different driving conditions (or working modalities), which allows the assessment of ADAS working modality that could enhance drivers' interaction with ADAS.
- *Objective*: to examine the relationship of multiple driving abroad-related factors on risk-taking behavior among young foreign drivers.
  Key finding: risk-taking behavior of young drivers in driving abroad context is not directly correlated with road regulation knowledge but could be modulated by factor such as self-assessment of driving skill.

INNOVATIVE ADAS SYSTEMS FOR AUTONOMOUS VEHICLES

Stefano Arrigoni - Supervisor: Prof. Francesco Braghin
Co-Supervisor: Prof. Federico Cheli

During the last decade global economy is radically and quickly evolving. Several macro-trends have contributed to this, such as an extraordinary period of technological improvement (new emerging technology and a generalized reduction of costs and a boost in computing power of on-board electronics), a renewed attention to sustainability policies (energy saving and pollution reduction), the growing of new emerging markets and a mutation of ownership concept by the costumers (ownership less appealing) just to name the most important ones. This revolution is now involving automotive industry. In addition to that, statistics about urbanization reveals that the process of global urbanization has proceeded rapidly over the past six decades and it is expected to continue, so that by 2050, the world will be only one-third rural.
This is leading toward a series of issues related to transportation mainly involving: pollution, traffic efficiency, road safety, space consuming, access for people that can't drive, service quality and mobility cost.
Experts considers "self-driving vehicles" (SDV) as a proper response to all mentioned issues.
A complete control logic for an autonomous vehicle is an extremely wide and complex task to achieve and it involves multidisciplinary skills from different fields of research (dynamic, control, image processing, signal processing, code programming,...) so that an entire working group is required for its development. In FIGURA 1, a general framework of the main tasks required for autonomous vehicle control design is presented. The scheme is mainly composed by two parts: right block (blue background) represents entirely the overall real environment. It is divided into three sub-blocks that stand for crucial aspects to be considered during control software design. This block can be more generally considered as a logical schematization of the "hardware" vehicle surrounded by the scenario (roads, other vehicles or pedestrians, \dots) and by the set of mounted sensors capable of providing raw data or the sub-systems required in a virtual simulation to properly reconstruct a testing environment.
Left block (green background) represents software implementation of a driverless vehicle. It can be considered as the "human driver" sequence of tasks required in order to drive correctly a vehicle. It can be mainly divided into sequential tasks:

- "Raw data processing", all raw data provided by several sensors need to be processed in order to compute accurate high level information useful for decision making processing;
- "4D environment reconstruction" block is designed in order to reconstruct "World environment" as most accurate as possible starting from processed data. In detail the process uses redundant measures to obtain an accurate and reliable self-localization of the vehicle in a 3D digital map enriched by traffic and behavior laws, where detected obstacles are tracked and their time evolution is predicted (time dimension);
- "Decisional Algorithm" block can be considered the "brain" of the system. Receiving as input the full information regarding surrounding environment as well as driver requests and information (i.e. final destination of the journey, ...), it has to be capable of define a decisional strategy to currently actuate the vehicle in order to fulfill all the requirements. For simplicity, it is defined by two sub-tasks: as a human driver, the controller needs to decide a proper trajectory and driving strategy and, at the same time, it needs to monitor vehicle response and to modulate control actions basing on it.

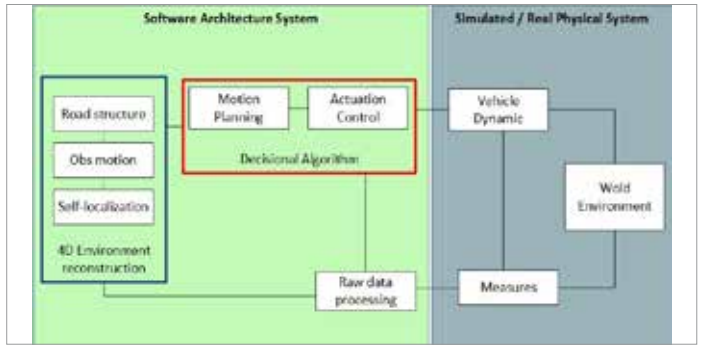


Fig. 1

The main novelty contribution of this research work is represented by the design of a decisional algorithm capable of performing trajectory planning and vehicle control tasks ensuring:

- a real-time feasible implementation
- a sufficient robustness of the solution calculated
- the capability of correctly handle with multiple and moving obstacles in urban-like scenarios.

The required capabilities just introduced can be translated more in detail in a set of specifics evaluated and verified. In particular, real-time implementation means to define a minimum working frequency for the controller that allows to dynamically react fast enough to unexpected (dangerous) situation that can occur. This limit is set around 20 Hz, that correspond to a reaction time of 0.05s: this is limited mainly by considering the working frequency of camera sensors (usually around 30 Hz to which should be added the delay due to image processing).
Robustness is intended mainly as the capability of the controller to always generate a feasible result (even if sub-optimal), to be capable of correctly operate although moderate modeling errors or external disturbances and finally to prevent to get stuck in local minima. Moreover the algorithm is required to correctly compute vehicle control inputs that generate a safe and collision free trajectory in presence of several multiple and moving obstacle.
It's finally required to operate in a urban-like environment. It is characterized by the presence of sharp curves, narrow lines and medium-low driving speed required. Moreover obstacles are expected to be mainly groupable in slow speed and small dimension but unpredictable obstacles (pedestrians, cyclists) and big and fast but more predictable obstacles (other vehicles).
The algorithm proposed by the author is a novel formulation based on MPC approach and solved by mean of a customized Genetic Algorithm-like method (GA) is presented as the main novelty aspect of the PhD thesis.
The controller is able to generate time-continuous control inputs and a feasible evasive trajectory at each time step thanks to the mathematical formulation of vehicle model and cost function, while GA solver prevents the solution to get stuck in local minima and allows high operating frequency. A set of testing scenarios to evaluate capabilities and performances of the controller are performed. In detail, a urban scenario (sharp curves and single line) is considered.
As an example in FIGURA 2 an overtaking maneuver is shown, where green line represents planned trajectory over the predictive horizon, red line is the closed-loop trajectory performed and the black lines are estimated obstacles' motion (red ellipse A with a reference speed equal to 8 m/s).The results confirm the real-time feasibility of the algorithm, its robustness to modeling errors and its capability of correctly handling multiple moving obstacles while driving in a urban environment. Conclusions, critical aspects and future developments analysis are finally presented.

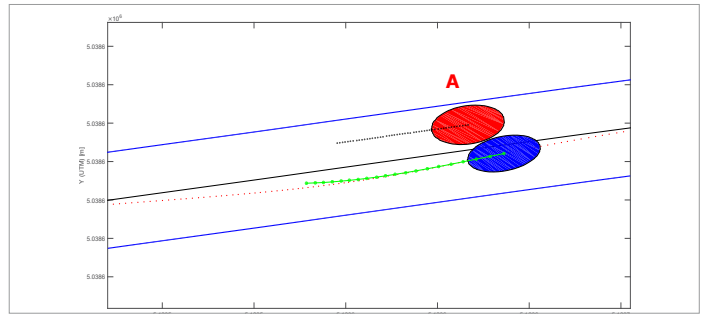


Fig. 2

DYNAMIC CHARACTERIZATION OF SEALS IN TURBOMACHINERY

Filippo Cangioli - Supervisor: Prof. Paolo Emilio Lino Maria Pennacchi

Sealing technologies are widely used in gas compressor, steam and gas turbines to reduce the leakage flow and to separate high-pressure to low pressure regions. The current oil and gas market competitiveness lead the turbomachinery manufacturers to increase the rotational speed and the power output and/or to maximize the efficiency. Sealing clearance reduction has been confirmed as the most cost-effective way to meet today's aggressive turbomachinery requirements.

Labyrinth seals are a common solution in turbomachinery applications because they are easy to be manufacturing and do not require maintenance. Labyrinth seals are good in restricting the leakage flow by dissipating the flow kinetic energy through the tortuous passage, however they do not respond well to the machine dynamics. Labyrinth seals drive to instability, because of the fluid dynamics mainly related to the presence of a non-uniform circumferential pressure distribution. The non-uniform pressure distribution generates dynamic forces on the rotor that may lead to sub-synchronous instability issues.

The influence of labyrinth seals on the stability of turbomachinery is investigated using the standard rotordynamic beam element model of the shaft-line, labyrinth seals are modelled through linearized coefficients, the so-called rotordynamic coefficients. The accuracy of stability analysis is of primary importance during the design phase of turbomachinery, therefore, the correct prediction of the rotordynamic coefficients is critical.

Over the last decades, numerical modeling and experimental characterization of labyrinth seals have been conducted by university and industries. The predictions, compared to experimental evidences, are accurate for a narrow range of operating conditions and labyrinth seal configurations.

In this thesis, a one-control volume bulk-flow model has been developed for straight-through and staggered labyrinth seals, the model shows improvements with respect to the literature, in particular regarding the characterization of the flow conditions within the seal cavities. The bulk-flow model is a control-volume approach to analyse the fluid-dynamics within the seal. The continuity, circumferential momentum and energy equations are solved for each control volume by the perturbation method. Finally, the dynamic forces are calculated by integrating the pressure along the circumferential direction.

Two experimental campaigns have been performed in the high-pressure seal test-rig owned by General Electric Oil&Gas to validate the numerical models. Thanks to this test-rig, it was possible to test inlet pressure up to 500 bar; pressure ratio up to 2.5 and rotational speed up to 15000 rpm. The rotor orbit was controlled by active magnetic bearings (AMBs) with an excitation frequency up to 250 Hz by applying multiple excitation frequencies. Additionally, interchangeable swirler device sets the desired pre-swirl ratio (also negative pre-swirl ratio by inverting the rotational speed) and off-center rotor positions have been tested.

With the increasing demand of efficiency and performance, steam turbines have started to operate near critical conditions of their structural and thermal capabilities. Because thermal, pressure and centrifugal loads may change the nominal geometry of labyrinth seals and consequently also the rotordynamic coefficients associated, a thermo-elasto bulk-flow model has been introduced. Similar to the oil and gas market, the technology trend in the power-generation field is to increase the power and efficiency of turbomachinery. The need of high efficiency leads, among other things, to the introduction of new sealing technologies such as brush seals. Brush seals operating principle is different from that of labyrinth seals. Brush seals can be assembled at very tight or zero radial clearance or even with interference on the rotor. This means that the contact between the rotor and the seal bristles exists, especially in the case of zero clearance or interference. If a contact occurs a hot-spot develops on the rotor and this may cause the vibration to be unstable, resulting in a synchronous instability (spiral vibration).

The development of numerical models to analyse this phenomenon is therefore important to assess the rotordynamic stability during the design phase and avoid excessive vibrations, which may have severe impact on the operability and mechanical integrity of turbomachinery.

Based on the domain swap method proposed in the literature, in this thesis, a model for the analysis of thermally-induced vibrations cause by light-rub of the rotor against brush and labyrinth seals has been developed.

This thesis aims to give an original scientific contribution to the rotordynamics community about the dynamic characterization of seals. Whenever possible, the novelties introduced in the numerical models have been validated with experimental evidences. The existing bulk-flow models for straight-through and staggered labyrinth seals have been improved and validated through dedicated experimental campaigns. These models have been finally adopted by General Electric Oil&Gas in the rotordynamic design internal procedure. A thermo-elasto bulk-flow model has been introduced to consider the effect of the structural deformation caused by temperature, pressure and centrifugal loads on rotordynamic coefficients. Thermally-induced vibrations caused by light-rubs between the rotor and brush seals are numerically investigated by a rather complex model developed specifically for this purpose.

Fig. 1 - Labyrinth seal.

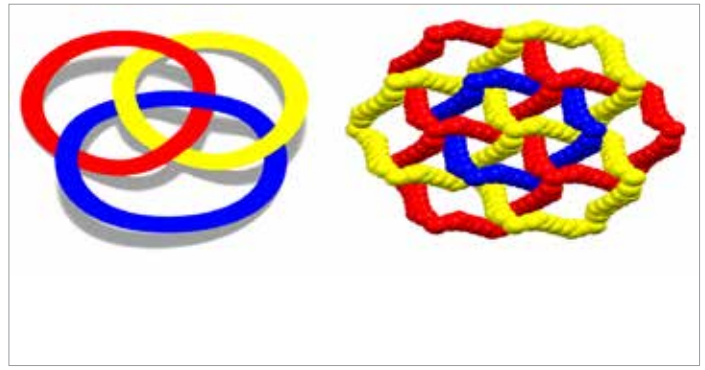


Fig. 2 - High-pressure seal test-rig.

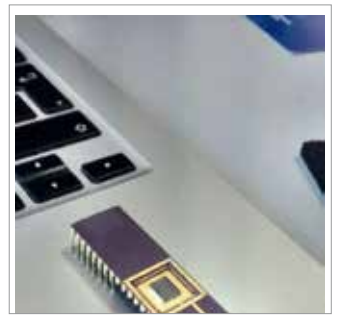


Fig. 3 - Brush seal.

A NEW DAMAGE DETECTION TECHNIQUE

Liangliang Cheng - Supervisor: Prof. Alfredo Cigada
Co-Supervisor: Dr. Giorgio Busca

Many infrastructures and mechanical structures are inevitable to suffer damage along with aging, which has drawn a lot of attention during the research of last decades in terms of the damage localization and quantification of engineering structures for health evaluation. Damage identification based on vibration-based data has been developed rapidly, since the change of physical structure naturally causes a change of system property such as natural frequency, modal damping and mode shape. There exists a variety of vibration-based methodologies for damage detection: by means of the change of natural frequency, the change of mode shape, the change of frequency response function and the change of transmissibility function, and so on. Among these methodologies, measuring the change of transmissibility function is preferable since it not only has a better sensitivity to the damage but also none prior information of the system loading is required. Transmissibility function as one of the most popular methods widely applied for identifying damage. Moreover, it is traditionally defined as response spectrum ratio between two degrees of freedom. During the recent decades, more damage indicators based on transmissibility function have been proposed and their results of damage identification have proved the excellent performance of this approach in terms of the sensitivity than the classical frequency response function (FRF). The author also points out the significance of poles and zeros to localize damage in the dynamic system. More recently, it has been proved that the value of transmissibility function converges to the mode shape ratio when frequency bandwidth is restricted to the system's poles. The convenience and effectiveness of using transmissibility in practice is the basis of making it selected as the main research object in this work. A new conception, namely strain transmissibility function, has been proposed in this study due to the fact that strain is more sensitive regarding to damage in comparison with displacement, which could be proved through the related sensitivity analysis. In addition, the accuracy of damage localisation also relies on the number of sensors. Especially when dynamic test is performed on large structures such as bridges, tunnels and buildings, it is extremely difficult to reach the target of full coverage on the objects. Also, usually a large number of sensors are need and then the idea is impracticable mainly for economic reasons. Fortunately, distributed fiber optics techniques have kept developing rather maturely and they have been applied into various domains which can measure continuously strain and temperature along the structure layout. During the validation of the feasibility of the proposed new conception and approach, a series of simulation studies and the related experiments based on distributed fiber optics have been carried out. However, many researchers mainly concentrate on linear damage case where damage can be considered as the linear reduction of mass and stiffness, apparently, their methodology is unable to detect the change caused by the nonlinear damage. Damage scenarios in engineering structures are manifested as nonlinear behaviours in many cases, which could be deemed as the potential security hazard. Certain types of damage in MDOF systems create a significant nonlinear change instead of a linear one, such as breathing crack (Bilinear stiffness), post-buckled structures (Duffing nonlinearity) and rattling joints (The system with discontinuity), etc. Therefore, the study on nonlinear damage identification is of great importance. Another part of this study focuses on nonlinear damage identification based on the conception of nonlinear output frequency response function (NOFRF). The highlight of this work is the extension of the NOFRF approach to the general input condition and corresponding simulation on a MDOF system clearly demonstrates its availability. In particular, this work also discovers and proves the relationship between NOFRF-based transmissibility function and Output-based transmissibility function under general input condition, which offers a more convenient and reliable strategy for detecting and localizing damaged components, on account of various damaged scenarios, including existence of single damaged component and multiple damaged components. In addition, various loading scenarios are taken into consideration as well, including single-point loading, multiple-point loading and distributed uniformed loading.

The methodology about identifying single or multiple nonlinear components for MDOF system under general input has been put forward. The important properties of transmissibility functions based on different nonlinear order NOFRFs and output have been illustrated and it clearly figures out the relationship between transmissibility functions based on the total system output and the output under different nonlinear order or NOFRFs. Moreover, it is helpful to replenish the knowledge and application of NOFRFs on damage identification under general input. Two separate diverse loading forces (general input with same frequency components, but different excitation intensity) have been introduced in order to localize the nonlinear components. This paper demonstrates the theoretical approach only, corresponding simulations and experiments will be published in the near future.

As for the experiments, two different setups will be carried out: Blade model and steel beam structure. Distributed fiber optics, as a consideration of dense measurement, will be applied into the beam structure which contains huge amount of sensors along one single fiber and be beneficial to localize the damage (nonlinear components) more precisely. There will creating one or more breathing cracks that could be reckoned as nonlinear components.

Key words: transmissibility; strain transmissibility; SHM; damage detection; distributed fiber optics; NOFRF; linear damage; nonlinear damage

SUPER DUPLEX STAINLESS STEELS MICROSTRUCTURAL CHARACTERIZATION AND ITS APPLICATION IN SURFACE TREATMENTS OPTIMIZATION

Andrea Francesco Ciuffini - Supervisor: Prof. Carlo Mapelli

Super duplex stainless steels (SDSSs) consist of γ-austenite and α-ferrite phases. Their microstructure exhibits good combinations of strength, ductility and corrosion resistance, since it takes advantages of the single phased counterparts. The steels not only inherit the mechanical properties of the completely ferritic or completely austenitic alloys, but they also exceed them. Due to their unique combination of properties SDSSs are materials of choice in many industries. Their use has drastically grown in the last fifteen years and no doubt there is a great potential for further volume increase. The growing trend of the SDSSs market is, however, confined by the occurrence of brittle detrimental phases precipitations during hot forming and joining processes. Another undesired feature occurring during these processes is the uncontrolled change of the phase ratio balance (Fig. 1). A good comprehension of their microstructural evolution consequently results clearly crucial to spread their application fields. Moreover, the use of innovative surface treatments, as controlled shot peening, could enhance their properties extending SDSSs convenience with respect to the direct counterparts, promoting their industrial exploitation.

In details, the mechanisms governing the α/γ phase ratio changes during thermal treatments are still not well-defined. Moreover, secondary austenite precipitation processes are still not widely described since the research activities were focused on the detrimental embrittling phases, such as σ, χ, α'. Linked to the γ_2 precipitation mechanisms, interesting not yet exploited nor investigated mechanical properties, such as transformation-induced plasticity processes, can be achieved. These results would be used to achieve an enhancement in SDSSs properties and to perform and tune different surface processes to further increase these results. Moreover, the choice of these technologies has been realized, to highlight the influence of the microstructure on the resulting products, analyzing different aspect of the interactions developed during the investigated processes. The technologies chosen for this research activity are controlled shot peening, which is a mechanical process acting mainly on austenitic phase, and hot-dip aluminizing, which is a thermo-chemical process involving primarily the ferritic phase. Controlled shot peening is recognized to provide an interesting fatigue resistance increase to the target component. This technology has never been applied on new generation SDSSs (Fig. 2). These possess a higher γ-austenitic content, which is more susceptible to strain-hardening inductive processes and would amplify the beneficial effects of this treatment.
Hot-dip aluminizing is a quite new research branch, mainly related to the development of hydrogen technologies and bimetallic components realization, which are promising application fields. Since the novelty of this process, it has never been investigated on duplex stainless steels. This process consists in a thermo-chemical process, involving mainly the ferrite, due to the high affinity of aluminium to this phase (Fig. 3). Further, the thermic input strongly affects the microstructure evolution in SDSSs.
Since all these technologies would strictly interact with the SDSSs microstructure, they would drastically modify the final properties of this steel grade.
On the other hand, the initial microstructure of the worked semi-products would widely affect the behaviour during the processing and on the treated products.
The main objective of this research activity is the attainment of a deeper knowledge about super duplex stainless steels grade and its use to perform different forming and surface processes, to achieve the best combination of mechanical and corrosion resistance properties. Moreover, the collected data would grant to tune the microstructure, maximizing the final properties and emphasizing the beneficial effects obtained through each applied technological process. This allowed the achievement of improvements in the final properties with respect to the use of commercial standard SDSSs. A further significant result is the identification of the mechanisms involved in the applied surface treatments. This enables the use of these results to tune and optimize other technologies, aiming the exploitation of the investigated interactions between the processes and microstructural features.

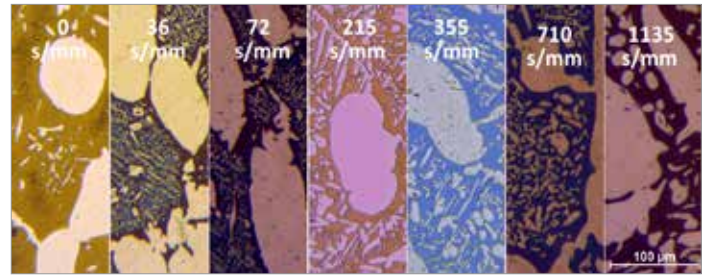


Fig. 1 - SDSSs microstructures.

Fig. 2 - SDSS after controlled shot peening

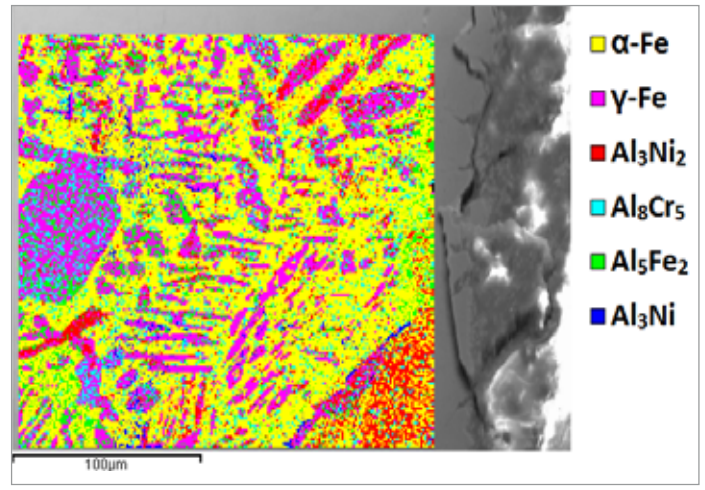


Fig. 3 - SDSS after hot-dip aluminizing.

STUDY OF WHEEL FORCE SENSORS TO IMPROVE SAFETY IN INTELLIGENT TRANSPORT SYSTEMS

Stefano Dell'Agostino - Supervisor: Prof. Gianpiero Mastinu

Intelligent Transportation Systems or ITS means "systems in which information and communication technologies are applied in the field of road transport, including infrastructure, vehicles and users, traffic management and mobility management, as well as for interfaces with other modes of transport". The ITS evolution can be divided into four generations. The first ITS generation, developed during the 90's, is based on infrastructure one way comunication systems. The second generation technology is based on two way comunications. From 2004 to 2005, automation in system management and system operation are the focus of the third ITS generation. The ITS fourth generation has been developed for both the system operations as well as personal mobility solutions. In particular, since 2006, the ITS solutions incorporates vehicle, infrastructure and mobile devices with a multi-modal approach. Multi-modal approach, combine personal mobile devices, vehicles, infrastructure and information networks for system operations as well as personal contextual mobility solutions.
Today, the main changes are related to the advent of Big Data. Within the Horizon 2020 program, the European Commission has specified a number of targets for Europe to be met by the year 2020. Social, environmental and economic challenges are addressed in this program and one of the Societal challenges refers to smart, green and integrated transport.

This program aims at a better mobility, less congestion, more safety and security, for both people and freight transport. Research should focus on developing new concepts of freight transport and logistics and by reducing accident rates, fatalities and casualties and improving security. According to the last European status report on road safety, the deaths and injuries caused by road vehicle accidents have decreased from about 50000 in 2001 to 30000 in 2013 thanks to the European road safety policy. However, there is still room for improvement. A key factor to improve mobility is the implementation of the Intelligent Transportation Systems technologies. Due to the wide range of ITS applications the European Parliament outlined four priority areas for the development and use of ITS.
Those areas are:

- Optimal use of road, traffic and travel data;
- Continuity of traffic and freight management ITS services;
- ITS road safety and security applications;
- Linking the vehicle with the transport infrastructure.

The National cluster 'Trasporti Italia 2020' established the Italian development program for the Intelligent Transportation Systems with the partnership of research institutes, Universities and companies. One of the cluster priorities is the integrated smart sensing for freight transport support. This topic has been addressed by research projects for both the road infrastructures and the vehicle sensor technologies. Politecnico di Milano, as one of the main partners of the cluster, develops advanced measuring systems for automotive applications. One of the developed instruments is a wheel force sensor for Intelligent Transportation systems applications. This project, from the concept design to the prototyping and testing, is presented.
The design process of an advanced measuring instrument, is presented. In the state of the art of tyre road contact forces measurement accurate measuring systems are found but their layout can not be implemented on a standard vehicle. Those sensors require external cables and additional structures outside the vehicle and the cost of a wheel force sensor is too high.
As a result, further studies are needed for the use of tyre force sensors on standard vehicles.
The objective of this thesis is to find a trade-off between a low cost sensor, a standard vehicle layout and a sufficient accuracy.
Thirteen different sensor configuration have been evaluated, considering the sensor performance and the configuration cost.

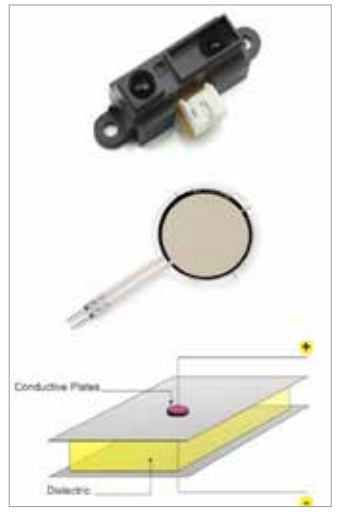


Fig. 1 - Tested sensors: a) optical triangulation; b) piezo-resistive; c) capacitive.

Figure 1 show three of the proposed sensors. The best performance has been obtained with the capacitive sensor. This solution has been optimized, considering the dielectric material of the capacitor and the capacitor size as design variables.
The dielectric material has been selected through an Analytical Hierarchical Process. The capacitor size influence on the capacitive sensor measurement has been studied through a FEM model. Other aspects of the capacitive sensor design as the A/D converter and the signal shielding have been considered for the prototype integration. Figure 2 shows the static tests results.

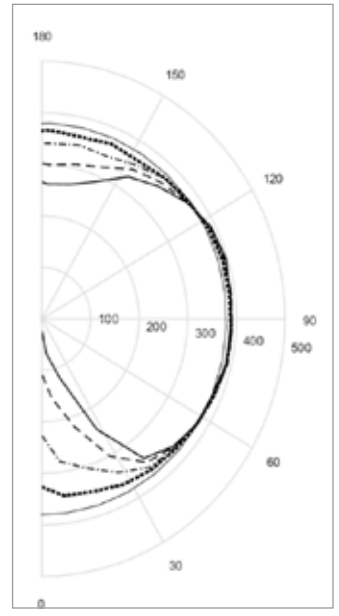


Fig. 2 - Capacitive sensor signal with respect to wheel angular position. the load is applied at 0°

The on-board test on the prototype (Figure 3) validate the wheel force sensor technology in a relevant environment. Errore: sorgente del riferimento non trovata shows the technical specification of the prototype. The wheel force sensor has been patented though, it can not be described in the detail.

Max Load	20000 N
Resolution	100N
Sample rate	400 Hz
Power source	battery

Tab. 1 - Wheel Force Sensor technical specification

Fig. 3 - Wheel Force sensor prototype

DESIGN OF A 6-DOFS PARALLEL KINEMATIC MANIPULATOR FOR HARDWARE IN THE LOOP SIMULATIONS: SYNTHESIS, CALIBRATION AND CONTROL

Enrico Fiore – Supervisor: Prof. Hermes Giberti

The continuously increasing request of electrical energy in the last few years gave an important incentive to the study of renewable energy sources. In this perspective, one of the most promising fields is represented by offshore wind farms. For this reason, some complex and deep studies on the design and qualification of wind turbines must be performed and CFD simulations can be a good starting point. However, in order to validate numerical codes and the results of CFD simulations, experimental tests are fundamental, especially in a controlled environment such as the wind tunnel. Politecnico di Milano is directly involved in an Horizon2020 project called LIFES50+, whose purpose is the analysis and qualification of 10 MW wind turbines and of the floating substructures they are housed on. In order to conduct reliable experimental tests on the scale model of an offshore wind turbine, it is necessary to evaluate the combined effects of the aerodynamic and hydrodynamic phenomena involved. A 6-Degrees of Freedom (DoF) parallel kinematics robot has been designated as the responsible to reproduce the hydrodynamic effects of the floating substructure on the wind turbine scaled model. The wind tunnel tests will be based on a hardware-in-the-loop approach and will use a six axes load cell installed between the robot and the scaled wind turbine model to measure the aerodynamic forces. These forces represent the inputs for a mathematical model describing the motion of the floater, which is computed in real-time. The resulting movement will be fed to the robot in order to make the wind turbine model follow the desired trajectory, thus closing the loop. This work describes the entire cycle of the design of the parallel kinematic manipulator shown in Fig. 1, starting from the definition of the technical specifications, till the deployment and the development of the control logics that govern its behavior.

The work has been structured in three parts:
- PART I: this part starts by describing the context in which the robot is supposed to be applied, defining the requirements the robot is supposed to satisfy and the constraints imposed by the application and the surrounding environment. An overview of the characteristics of both serial and parallel manipulator is presented, putting in evidence which are the pros and cons of the two typologies of robots. Once identified the robotic architectures that are best suited for fulfilling the task, a description of the forward and inverse kinematics problem is presented, in addition to the velocity and kineto-static analyses. These analytical instruments represent the foundation for all the subsequent steps needed to arrive at the realization of the manipulator. The discussion continues presenting the developed tools employed to delineate the main characteristics of the robot. It is worth to underline that the described tools have a general validity, and thus can be used to design a generic parallel manipulator for a generic application. The first tool is an optimization tool that allows to determine which of the candidate robotic architectures is the best suited for the application and which are the geometric parameters that allow to reach the desired goals while respecting the existing constraints. The next tool wants to provide a solution to the problem of sizing the mechanical components and the actuating system for those manipulator involved in applications in which the operating conditions are not known in advance (e.g. simulators). This tool relies on a statistical approach based on the Monte Carlo Method. The last tool has the purpose of assessing the structural properties of a robot allover its workspace. In fact, the performances of a parallel manipulator strongly depend on its pose, and for some applications in which a high accuracy is required, it is necessary to guarantee a sufficiently rigid and robust structure regardless of its configuration.
- PART II: the second part applies the tools previously defined to the specific case of the LIFES50+ project. First, the geometric parameters of the designated robotic architecture are computed. The robot will become an integrating part of the wind tunnel. For this reason, it is impossible to properly setup the control algorithms without stopping the wind tunnel for weeks or even months. In the light of these considerations, a low-cost scaled version of the robot is realized using 3D-printing technology. This reduced scale version is designed in such a way to be as much similar as possible to the real scale version. For both the robots the tool based on the MCM is employed to properly size motors, transmission units and all the other mechanical components. In order to ensure reliable and meaningful results at the end of the HIL tests, it is necessary that the aero-elastic model of the turbine preserves its structural properties, or, in other words, it is necessary that its normal modes are not affected by the presence of the robot. The modal analysis tool comes in handy since it allows to verify that the mechanical components of the robot are designed in such a way that the robot can be regarded as a rigid structure in the desired frequency range, without modifying the properties of the turbine.
- PART III: the last part focuses on the control logics developed on the scaled version of the robot, since at the time of writing of this thesis the components of the real scale robot are being manufactured. In any case the control architecture is the same for both robots, and so all the developed algorithms can be easily ported from one robot to the other. First of all, a description of the employed controller environment is provided. The implemented state machine logic is then presented together with the different modalities in which the robot can be operated. Next the external reference control modality is shown. In this modality the robot follows a trajectory specified by an external agent, as in the case of the mathematical model of the wave motion. Lastly, the admittance control is described, that is an experimental tool to test and optimize the methods developed for the external reference control. In addition, a safety logic to enforce the robot to remain in its admissible workspace is presented.

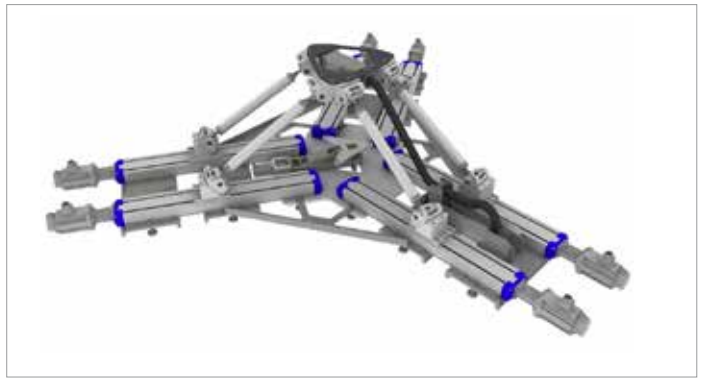


Fig. 1 - Figure 1 Rendering of the parallel kinematic manipulator to be used for the HIL tests within the wind tunnel of Politecnico di Milano

DIRECT LASER INTERFERENCE PATTERNING: A NOVEL APPROACH WITH SCANNER OPTICS

Valentina Furlan – Supervisor: Prof. Barbara Previtali

Inspired by nature, patterns are able to improve surface properties ranging from problem of adhesion to light management or cell interactions. Different methods were investigated and were used in order to realize patterns with different scale dimension on different substrates. These methods, with the exception of direct laser techniques, present disadvantages of multiple-steps and low fabrication speed.
A new approach to use directly a laser beam on a surface in order to produce a texture is Direct Laser Interference Patterning (DLIP). DLIP is a beam shaping method, which uses interference and ablation phenomena to realize micrometric and sub-micrometric structures, overcoming limits of other approaches. DLIP permits a good control on pattern shape and pattern dimension, which can be applied with different optical set-ups either simple or much more complex. Although the industrial interest in laser surface patterning it is possible find only few examples of complete laser head for DLIP treatment. Moreover, considering the application field, also the material choice is crucial in surface functionalization. Magnesium alloys attracts interest in different industrial areas due to their good mechanical properties and low weight as well as elevated biocompatibility and biodegradability. Nevertheless, the high corrosion rate of Magnesium constitutes a limitation in its usage. This condition involves the necessity of material treatment in order to satisfy the requirements related to a specific field.
In this work a different approach to realize DLIP treatment on large areas is proposed. The novelty aspect is the combination of an interference set-up with a scanner head, which is used to increase productivity and define the process feasibility on large area, considering a challenging material.

The work was divided in three steps (as shown graphically in Figure 1). In the first one, DLIP process was analysed considering traditional set-up employing a Mach-Zehnder interferometer. The focus was put on the use of an industrial laser source with a ramp pulses train in emission profile, which affected the process feasibility and the line-like pattern quality. Another critical issue was the use of a magnesium alloy, characterized by a low melting point and high thermal conductivity. This condition constituted an additional problem during the interaction between material and interfering beams. In fact, the feasibility window revealed narrow range of conditions able to realize well defined line-like pattern. Otherwise, patterns with a features size in the sub-micrometric range were obtained, with a minimum line-like pattern period of 0.6 µm. The improvement of pattern quality was proposed and realized.
The second phase of this research was focused on the concept and development of a new DLIP laser head, which was composed by a Michelson-Morley interferometric set-up and a scanner head equipped with an F-theta telecentric lens. The innovative aspect is related to the use of a scanner hand in order to realize interference-beams handling on the work plane. Using this configuration, the image of interfered beams with spot energy redistribution can be managed by galvanometric mirrors and handled at the target plane. Collimated interfered spots were scaled by an F-Theta lens, reproducing the same image at the target plane, with a consequent pattern size reduction. The introduction of the F-Theta lens, which is a complex element, was managed with a model, considering the fact that the interference beam angle was transformed by the lens in a spot displacement at the target plane. For this reason, the new DLIP head was modelled as a function of laser and optical parameters. The model was able to help in parameters modification as a function of desired pattern periods, potentially achieving sub-micrometric dimension.
The interesting aspects of this new solution are the flexibility in terms of pattern period and in its compactness. It is relevant to observe that the new set-up is potentially automatable considering motorized mirrors for the Michelson-Morley interferometer. Moreover, the new-DLIP is potentially applicable to different kind of laser sources, with different laser wavelength and pulse duration.
The validation of the new DLIP concept was performed. Also in this case an industrial nanosecond lasers source was used, testing different conditions on the same magnesium alloy. DLIP by scanner optics was investigated considering two different scanner movement approaches. The first one based on "continuous galvos movement" strategy and the second one on a "point by point" strategy. Two feasibility maps were obtained for the considered strategies. Results revealed areas where process parameters were able to produce well-defined surfaces.

Considering the final goal of this Ph.D. thesis was surface texturing realization, the capability of this new system on large area fabrication was also demonstrated (Figure 2). Line-like textured surfaces were obtained for each strategy and a comparison with the traditional approach was proposed. The comparison revealed promising results for DLIP. Production time obtained by the DLIP technique are consistently decreased in comparison with other direct laser methods with ns and fs laser sources, confirming the achievement of the purpose of this research.

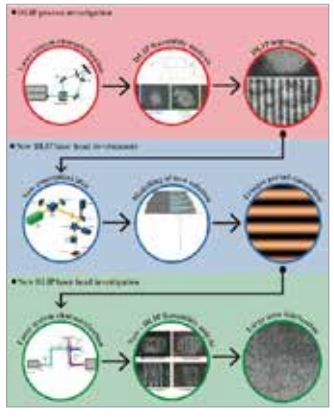


Fig. 1 - Figure 1 Outline of Ph.D. work

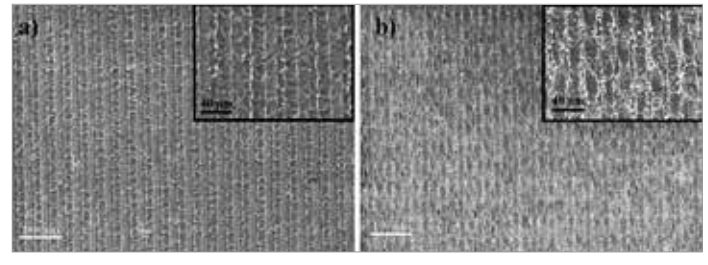


Fig. 2 - Large area textured surfaces: a)"continuous galvos movement" strategy, b)"point by point" strategy

EXPERIMENTAL CHARACTERIZATION AND MODELING OF THE MECHANICAL BEHAVIOR OF PARTICLEBOARD

Riccardo Galeazzi

Supervisors: Prof. Andrea Bernasconi, Prof. Roberto Corradi

Introduction

In this PhD thesis, different modelling techniques and experimental methods were employed to study the mechanical behavior of particleboard in perspective of reducing its weight. Particleboard is a wood-based material made of particles of recycled wood bonded together with urea-formaldehyde adhesive. This thesis is focused on the estimation of elastic constants of actual particleboard considering it similar to sandwich structure and modelling at macro and micro level, aiming at understanding the relationship between the properties of the constituents and those of the final product, particularly under bending loads. To reach this goal, the experimental techniques applied to particleboard to generate the data used in macro and micro approaches are presented: Three points bending test (TPBT) and Iosipescu test (IT). To collect the data to perform the particleboard's micro-modelling, measurements and imaging methods are exploited, namely Micro Computer Tomography (Micro- CT) and Digital Image Correlation (DIC).

Objectives

Figure 1 reports the objectives of this PhD work.

Results

Particleboard vertical density profile by Micro-CT and image analysis was derived. After elastic constants determination considering particleboard as a sandwich and comparing the results with Iosipescu and Three Points Bending Tests coupled with Digital Image Correlation, the relationship with density was derived also (Figure 2).

The micromechanical model developed in this thesis is a FE model of Representative Volume Element (RVE) of the particleboard, which will lead the evaluation of the elastic constants at the macro-scale by homogenization. Input data to FE Micromodel are: (1) Panel's zone core selection; (2) Particles dimensions, orientation distribution and thickness; (3) Volume fractions of constituents; (4) Adhesive mechanical properties; (5) Wood mechanical properties and (6) RVE dimensions, generation algorithm (stacking). G_{13} Shear Modulus of the particleboard are reported in Figure 3.

These relationships will be useful to predict the particleboard's elastic constants in the perspective of the reduction of the panel's weight acting on its core by changing the production process parameters or raw material involved.

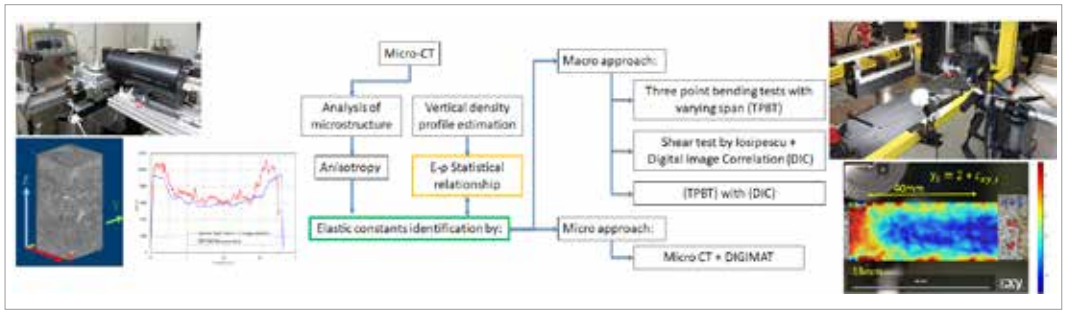


Fig. 1

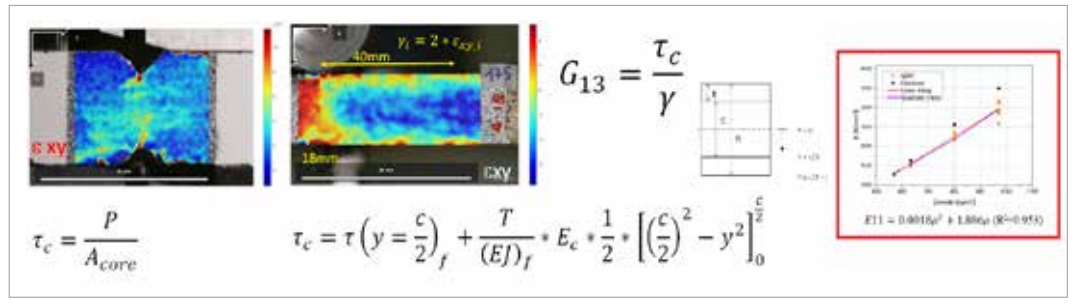
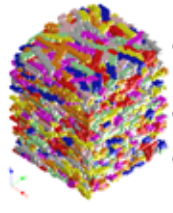


Fig. 2



Board Tick. [mm]	Iosipescu + DIC [MPa]	Iosipescu + DIC without notches [MPa]	TPBT +DIC [MPa]	Classical Sandwich Model [MPa]	RVE Homogenization [MPa]
38	105	125	219	137	-
18	144	222	225	223	175

Fig. 3

STRUCTURAL INVESTIGATION OF CULTURAL HERITAGE THROUGH FEA ON REALITY-BASED MODELS ORIGINATED BY 3D DIGITIZATION

Sara Gonizzi Barsanti - Supervisor: Prof. Gabriele Guidi

For research purposes, documentation needs, preservation and conservation issues in archaeology and Cultural Heritage field, it is very important to appropriately record, document and survey artefacts and sites: indeed, an accurate and complete 3D digital documentation is a prerequisite for further analyses and interpretations. In modern times, atmospheric agents, the growing of the urban drift and of the density of constructions, bombing during the two world wars, the negligence during the centuries, as well as the current situation of political instability and danger in certain areas have all contributed to damage and strongly influence stability of our Heritage; it is, therefore, fundamental to define a proper methodology to preserve our Cultural Heritage. In order to achieve diagnostic studies aiming at understanding the level of decay of Cultural Heritage and at selecting the appropriate preservation methods and materials, a scientific base for allowing correct interventions would be fundamental. However, it is always difficult to predict how a historical object or structure, built thousand years ago, will suffer for environmental agents such as earthquakes, pollution, wind and rain, or human factors like constructions in the surroundings, vehicular traffic, or heavy tourism. Conservation of Cultural Heritage is a key topic and structural changes and damages can affect the structural behaviour of Cultural Heritage artefacts and buildings. Although the use of technologies can help in preserving, conserving and restoring ancient structures, it is mandatory to find the most appropriate and effective pipeline to produce the correct analysis. The analysis of the structural behaviour of a Cultural object can be made by using Finite Element Analysis, a well-known technique used in engineering for modelling stress behaviour of objects and structures. The typical workflow of such analysis involves the use of CAD 3D models made by Non- Uniform Rational B-splines (NURBS) surfaces, which represent the ideal shape of the object to be simulated (Höllig, 2003). The major FEA packages have meshing modules capable to transform a NURBS model, made only of its exterior surfaces, to a volumetric mesh which, differently from a surface mesh typically generated with 3D capture methods, has nodes distributed both on the exterior surface and in the interior volume, connected each other by elementary volumes such as tetrahedron, pyramids, prisms or hexahedral. This workflow is appropriate in the mechanical field, where a physical element to be simulated is very close to its ideal drawing within strict tolerances. Conversely, when applied to 3D models of Cultural Heritage (CH) objects or structures, often altered by the time passed since their original creation, the representation with a schematic CAD model may introduce an excessive level of approximation leading to wrong simulation results. Nowadays, 3D documentation of CH has been widely developed through active sensors or passive approaches like photogrammetry, but the models, formed by the exterior surfaces of the objects captured at high resolution and therefore represented by millions of polygons, are not suitable for a direct use in FEA. The mesh has in fact to be converted from superficial into volumetric, and the density has to be reduced since the computational complexity of a FEA grows exponentially with the number of nodes representing the simulated object. Few preliminary experiments have been done on real CH structures digitized with active or passive methods, whose models have been processed for simulating stress behaviour and predicting damage to artefacts considered critical within the field of conservation. The results are very promising but a few issues have been made evident: i) the way for obtaining a volumetric mesh suitable for FEA from the raw 3D data is not yet clearly defined and may greatly influence the final result, ii) the balance between geometric resolution and confidence level of the simulated results is often not compliant with the shape of a 3D model originated by a 3D acquisition process. This thesis presents a new method based on a strong simplification of the mesh associated to a topological rearrangement of it (Figure 1).

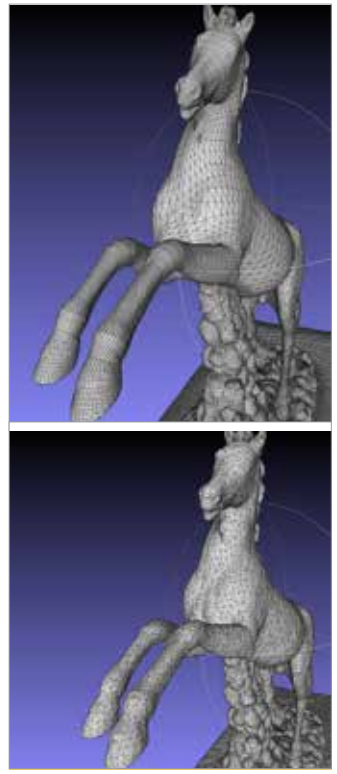


Fig. 1 - Comparison among triangular decimation and retopologized models: triangular decimation of the statue of a Horse in the Uffizi gallery (a) retopologized model of the horse (b). The horse was simplified from more than 1.1 mil polygons to 35K.

Such process aims at generating the most accurate 3D representation of a real artefact/ scenario from highly accurate 3D digital models derived from image-based and range – based techniques, maintaining the accuracy of the high – resolution polygonal models in the solid meshes that have to be created for FEA. In addition, the proposed process keeps into account the suitability of the simplified mesh to be converted in a set of NURBS surfaces through an automatic procedure.

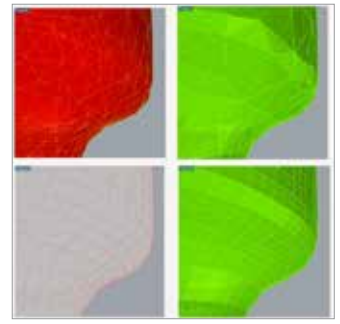


Fig 2 - The comparison between a simplified triangular mesh and its corresponding NURBS (a) and the retopologized mesh with its corresponding NURBS (b). The meshes are represented in red (left side of the images) and the NURBS in green (right side of the images).

This allows producing volumetric models of a Cultural Heritage object or structure maximizing the closeness of the resulting NURBS model with the acquired one, and in the meantime minimizing the number of NURBS patches required for describing it. The aim of the thesis is to provide a geometric process to create models suitable for FEA. The structural analysis presented are a completion to establish the validation of the methodology and to check if the models are suitable for being investigated using the common FEA pipeline (Figure 2). For this reason, the analysis presented are preliminary.

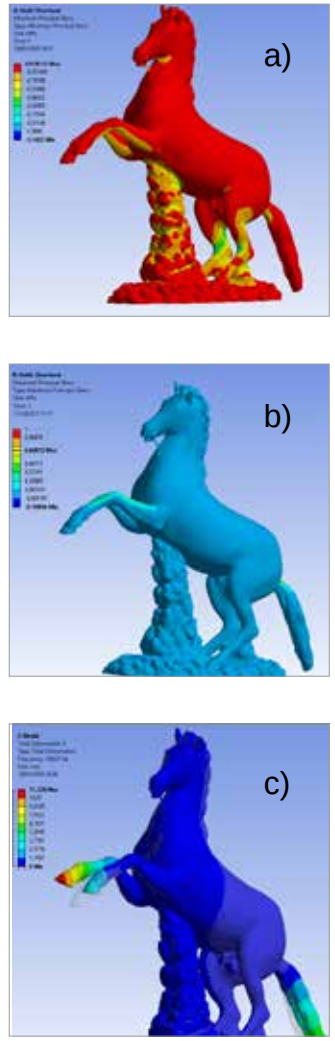


Fig. 3 - The Finite Element Analysis on the statue of the horse: (a) Minimum Principal Stress b) Maximum Principal Stress applying and gravity; (c) Modal Analysis to evaluate the natural frequencies of the statue.

INTEGRATED CONTROL OF ACTIVE VEHICLE CHASSIS CONTROL SYSTEMS

Arash Hosseinian Ahangarnejad - Supervisor: Prof. Stefano Melzi

The principle of integrated vehicle dynamics is investigated in this thesis by proposing a new control scheme to coordinate active aerodynamics subsystems, active rear steering, and hydraulically interconnected suspension. A nonlinear vehicle model is utilized by employing VI-CarRealTime commercial software for this study, incorporating nonlinear tire model. This model consists of 14 degrees of freedom that include longitudinal, lateral and yaw motions of the vehicle and body roll, pitch and heave motions relative to the chassis about the roll, pitch and heave axis as well as the rotational dynamics of four wheels. The vehicle dynamics are analyzed for the entire handling region, and three distinct control objectives are defined, i.e., safety, performance, and comfort which correspond to yaw rate tracking, sideslip and roll motion bounding, respectively.

In this thesis, different subsystems are developed in order to improve safety, performance, and comfort of the vehicle.

Active Aerodynamics Control (AAC) subsystem is designed based on the response of vehicle in cornering maneuvers at high speeds. This control logic monitors the states of the vehicle to correct vehicle behavior by altering load distribution of the vehicle.

Active Rear Steering (ARS) is utilized to track the yaw rate reference and bound the sideslip motion of the vehicle.

Electronic Stability Control (ESC) is developed in order to increase the safety of the vehicle.

Hydraulically Interconnected Suspension (HIS) is employed to reduce roll motion and lateral load transfer.

Active Anti-Roll Bar (AARB) is designed to increase the comfort of the vehicle, reduce the lateral load transfer and enhance the safety and performance of the vehicle.

Torque Vectoring system (TV) is used in high-performance vehicles in order to enhance traction and cornering ability.

Active Suspension system (ASS) is employed to be able to change the longitudinal load distribution of the vehicle to overcome the understeer and oversteer situations in transient situations.

The effectiveness of each standalone chassis control system is assessed for the different range of handling via various maneuvers. It is proved that each controller has a capability of improving vehicle handling in the certain range of handling where a passive vehicle cannot.

After analyzing and investigation, four subsystems are selected in order to develop integrated vehicle chassis control system.

In the first part, three controllers (ARS, TV and HIS) are integrated based on two methods: an optimal control and a fuzzy logic approach. These proposed integrated control systems are evaluated by comparing passive, each subsystem and combined control.

The second part is related to the integration of four controllers (AAC, ARS, TV and HIS) based on a fuzzy logic approach. The results demonstrate that the proposed integrated scheme can optimize the overall vehicle performance by minimizing the objective conflicts of the subsystems and increasing the functionalities of individual subsystems.

OPTIMAL POWERTRAIN DESIGN AND CONTROL OF AN ELECTRIC RACE CAR

Yu Huilong - Supervisor: Prof. Francesco Castelli Dezza

Co-Supervisor: Prof. Federico Cheli

In order to face the growing challenges from air pollution, dependence on fossil oil and greenhouse gas emissions, electric vehicles have attracted unprecedented amount of global attentions from the governments, academia, industry, public and environmental organizations. Electric racing becomes more popular under this background: a new championship called Formula E has been held for three years since 2014. An upcoming championship named Roborace in 2017 will be the first global championship for autonomous electric race cars, which will open a new page of racing. Electric racing is undoubtedly a good platform to draw the attentions of the public on electric vehicles and also for testing and improving the most advanced design and control technologies. Compared with conventional internal combustion engine vehicles, electric vehicles can have very flexible powertrain topologies, which can be 1-motor, 2-motor and 4-motor driving with different mounted positions, and the transmissions can be single-speed or multi-speed. From the design point of view, the selection of the powertrain layouts, the motors and transmissions can affect the dynamic performance of the electric vehicles directly. As for control, different steering, accelerating and braking operations will result different trajectories, velocity profiles and lap time. Thus, the advanced design and control technologies are always expected.

Recognizing the limitations of the conventional powertrain design approaches, this work is dedicated to achieving further improvements by proposing innovative optimal design approaches of the electric powertrain, with an electric race car as the platform. In order to test the performance of a designed powertrain, a corresponding control strategy should be developed. However, there are various kinds of control approaches for the electric vehicles, and accordingly, different control strategies may result in different results with the same designed powertrain. Considering this, the optimal control of the electric race car is coupled into the optimal design problem. The final results includes both the optimal design and control solutions for different powertrain layouts.

In order to represent the vehicle behaviour for cornering, braking, acceleration and comfort performance studies for four wheel driving vehicles with independent suspensions more accurately, a 14-DOF vehicle model is necessary. In this work, a 14-DOF vehicle model together with a suspension model considering the details of toe angle, camber angle, anti-roll force and suspension forces, are developed based on Lagrangian dynamics. To accurately predict the behaviour of a vehicle, it is also required to estimate the external forces acting on the vehicle as precisely as possible. An empirical tire model based on the well-known Magic formula equations is

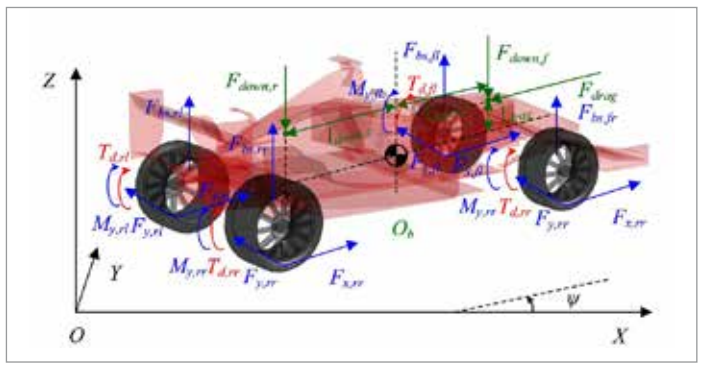


Fig. 1 - Forces and Torque acted on the 14-DOF vehicle model

programmed to calculate the tire forces. In particular, the tire model developed in MATLAB supporting inputs of the standard '.tir' tire data file. In order to evaluate the effect of design parameters of the motor and the transmission to the lap time of the race car, the mass model of the motor and transmission mainly concerning the dependence of the mass and output torque of the powertrain on the design parameters are derived. A virtual driver model is also devised to track a given trajectory depicted in curvilinear coordinate system based on the proposed control logic, and the obtained results are served as the initial guess of the optimal powertrain design and control problem. Heavy computing workload is a common issue in large scale optimization and optimal control problem. In order to improve the computational efficiency, all of the mentioned models programmed supports matrices operations. The entire vehicle model is validated with a well-known vehicle dynamics simulator 'VI-CarRealTime' developed by VI-Grade.

After a detailed reviewing of the numerical approaches for optimal control problems, a MATLAB software package for General DYNamic OPTimal control problems (abbreviated as GDYNOPT) based on direct collocation methods is developed. GDYNOPT is implemented different transcription methods including both the local collocation and global collocation approaches, differential methods including forward, central, complex step and analytical differential methods. Moreover, it has the features of automatic scaling based on linear scaling and a proposed average gradients scaling approach, sparsity and supporting parallel computation.

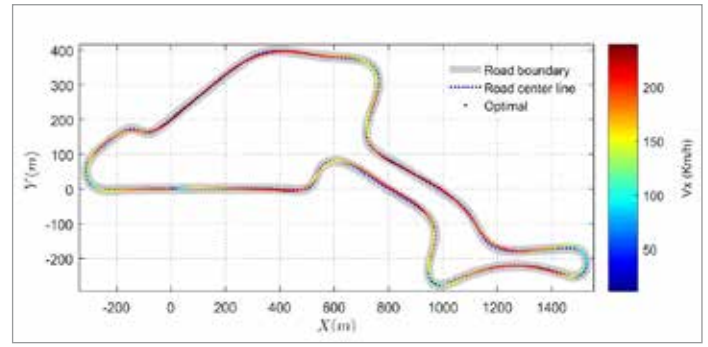


Fig. 2 - The obtained optimal racing line

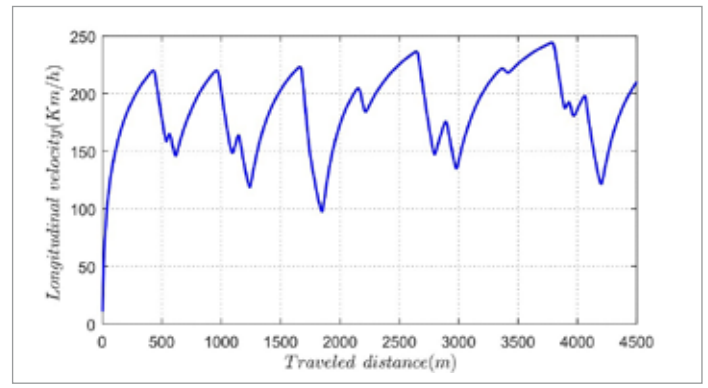


Fig. 3 - The obtained optimal longitudinal velocity profile

The optimal powertrain design and control problems of the 1-motor driving, 2-motor and 4-motor driving topologies based on the developed entire vehicle model are formulated and solved with GDYNOPT based on a direct transcription method for the first time with reference to the existing literature. In addition, an innovative approach is proposed to smooth the control trajectories. The optimal powertrain design parameters, control arcs and the optimal racing lines are obtained and analyzed with different number of collocation nodes.

The obtained optimal design parameters in this work can be used as the reference for the motor and transmission design of electric race cars, while the optimal control results can serve as the benchmark to develop and evaluate the closed loop control strategy. In addition, the obtained racing line and steering wheel angles can be used to train the race car driver in a car simulator. The methodology proposed in this work can also be applied in the design and control of the common type ICE vehicles, EVs and HEVs with different driving profiles and objective functions.

RAPID TOOLS IN SHEET METAL FORMING PROCESSES

Lorenzo Iorio - Supervisor: Prof. Matteo Strano

In the sheet metal forming industry the rigid metallic tools setup are the most common configurations used to plastically deform blanks or tubes (i.e. deep drawing and rotary draw bending), especially in the big batches productions. The use of metal rigid tools setup ensures robust process performances in terms of repeatability of the final tolerances of the components, thanks also to their high wear resistance. Furthermore, the numerous information available in scientific and industrial literature, in terms of design guidelines and numerical modelling, speed up all the initial phases of the process design. If the rigid tools could represent the best solution in terms of process accuracy and reduced time developments, the main disadvantage of the rigid metal tools can be researched on the elevated cost of the manufacturing operations, which have a great impact on the total costs of the process especially in small-medium industrial productions.
In order to reduce the tooling costs, rubber or flexible tools, with general purpose shape, have been coupled together with one rigid metal tool, die or punch (i.e. flexforming and rubber pad forming), in order to enforce repeatable geometry of the stamped parts. The use of a general-purpose rubber tool coupled with a metal one allows reducing the tooling costs around the 50% with respect to a total rigid metal tools configuration, because only the total rigid metal tool must be manufactured each time new product must be stamped. Esthetical defects, like scratches on the component surface, are generally avoided thank to intrinsic auto-lubricating properties of the rubbers materials. If these advantages make the rubber tools as an attractive solution for the industrial production scenario, it should be noted that the rubber tools are not suitable for hot-forming processes (typical used in automotive industry), because at temperature approximatively of 80°C the mechanical behaviour of the rubber material tends to degenerate. Furthermore, the production rate of the processes based on rubber tools is very low, because elevated strain rates reduce the rubber tools life. The concept time phase of a process with rubber tools is normally very long because very few information and guidelines about design methodologies and numerical modelling are available in scientific and industrial literature, maybe due to their low diffusion in the industrial scenario. The behaviour of the rubber tools is not easy to be predicted, because the simulation models of a rubber forming process often need to be validated with experiments, which require a lot of resources in term of time and costs.
From the considerations made above, it follows that the rubber tools setup can be suitable for small batches production, especially when small precision and components with simple features are manufactured.
Resuming the considerations made above, the rigid and deformable tools seem to be opposite solutions in terms of achievable production volume, final accuracy in terms of tolerances on the stamped parts, production costs and design time. These opposite characteristics suggest that another solution could be investigated in order to reach the best compromise in terms of time and costs, especially in case middle production volume and restricted interval of tolerances are required.
Since from the advent of rapid prototyping technologies, the rapid tools method has always been used in the production of prototypal tools setup, made by polymers, intended for the manufacture of pre-series products.
Over the years, the polymer materials have been subjected to a lot of attention from the applied research, especially with the tremendous growth of additive manufacturing technologies observed in the last few years. The development of reinforced plastic materials with high performances gave a reborn attention on rapid tooling technologies as a possible cost-efficient and innovative solution for the improvement of the traditional sheet metal forming processes
The main objective of this doctoral thesis is to investigate potentiality of rapid tools, made by different polyurethane materials, in three representative cold sheet metal forming processes, in order to formalize some guidelines based on direct experiences grown up by the collaboration of research laboratories and industries.
In the first chapter of this thesis a general introduction about the rigid and rubber tools setups has been presented in detail with the analysis of the cold sheet metal forming processes most diffused in the companies encounter during the period of this doctoral research. The analysis of the sheet metal forming processes with metal and rubber tools allowed to identify the advantages and disadvantages of these two macro categories of tools setup intended to outline the necessity of the investigation of new tools setup solution. This new solution has been identified in the rapid tools by the presentation of an investigation of possible innovative materials suitable for tooling purpose. After the identification of the rapid tools as a possible alternative solution to the traditional tools setup, the state of the art and the description of the technologies able to manufacture them has been presented.
In the second chapter a review of polymer materials has been performed in order to define their classification and the attended mechanical behaviour. Afterwards, the complete description of the performed tensile and compression tests, need for the characterization of the materials used in the case studies, has been described.
After the characterization of the materials, the simulations of the compression tests have been performed in order to tests the capability of the FEM software PAM-STAMP in predicting the deformation of the characterized polyurethane materials.
In the third chapter, the application of the rapid tools setup has been studied in sheet metal stamping process. Two case studies with different shapes, have been analysed experimentally, by the execution of experiments, and numerically, by the development of simulation models able to predict the final geometry of the stamped components. A compensation algorithm has been presented, together with a small state of the art of possible compensation methodologies, in order to correct the geometrical errors obtainable from the use of the rapid tools in the stamping process. Finally, fatigue tests on the polyurethane materials used in the experiments have been conducted, in order to evaluate the possible tools life at similar conditions of the stamping tests performed in the two case studies.
In the fourth chapter, the application of the rapid tools in the sheet metal air bending process has been presented. A modular bending die with polyurethane inserts has been designed and compared with other traditional commercial die configurations made by meta, nylon and rubber. A big experimental plan has been designed and conducted in order to evaluate and compare the performances of the rapid tools with respect to the commercial solutions. Afterward, a numerical simulation model able to predict the process results has been presented for analysing the stress and strain maps on the rapid tools in order to evaluate the tools life, according with the tests performed in the previous chapter, and possible improvements for future developments.
In the fifth chapter, a possible rapid tools implementation has been presented for tube rotary draw bending process. A simulation model with a polyurethane tools setup will be compared with a simulation model implemented and validated by the author in the thesis presented during the bachelor degree. The FEM model has been used for improve the polyurethane tools setup with some prototypal proposal which can be taken in account in the future developments.
In the conclusions section, all the achieved results, maturated experiences and possible future developments will be resumed.

DESIGN OF INNOVATIVE INERTIAL MEMS SENSORS FOR THE MINIMIZATION OF QUADRATURE ERROR

Mohammad Izadi - Supervisor: Prof. Francesco Braghin

Micro Electro Mechanical Systems(MEMS) industry has been growing at a spectacular rate during the last couple of decades. Among diffrent devices, a significant part of market comprises the inertial MEMS, which mainly consists of accelerometers and gyroscopes. The growing trend of inertial MEMS application is mainly driven by the growth of mobile devices market. Potential growing opportunities are expected by the evolution of sensors for wearable electronics, mobile health-care, and Internet of Things (IoT). Achieving leadership position among suppliers in the global inertial MEMS market is highly competitive. Persisting development to further reduce the size and unit cost of the sensors, with reduced power consumption and high performance is highly demanded. The aim of this research is to increase the consumer market opportunities of the MEMS gyroscope. Firstly, improved performance in terms of reduced quadrature error is desired, which result in improved Signal to Noise Ratio (SNR). Moreover, by reducing the die size the higher applicability of the sensor for mobile devices is achieved with reduced unit cost. One the most important sources of bias in vibratory gyroscopes is the quadrature error, which is related to the undesired displacement of the mechanical resonator along the sensing axis, due to unavoidable imperfections of the structure. In fact, quadrature error is the component of the output signal which is in 90° phase shift with respect to the Coriolis signal component and its influence depends on the accuracy of phase setting of the demodulator. In practice, the quadrature component might exceed the maximum Coriolis signal up to three orders of magnitude.

This thesis presents the strategies to design mechanical structure of MEMS vibratory gyroscopes with quadrature error compensating capabilities. The focus is on the mechanisms along the out of plane sensing direction of the surface micromachined gyroscopes.

The main responsible mechanism of out of plane quadrature error generation is known to be the skew bending of the flexible beams, resulting from the cross-section distortion, due to non-uniform etching of vertical sidewalls during the DRIE process. In this thesis, another important source of anisoelasticity of the structure, which is caused by the non-uniform etching along the longitudinal axis of the flexible beams is represented. Consequently, a computationally efficient modeling approach capable of reproducing the imperfections of the mechanical structures of the MEMS gyroscopes is developed, which allows to highly improve the design and analysis of the new devices layout to achieve optimized structures with improved performances.

Two main approaches are followed to achieve self-compensating quadrature error mechanical structures. The first approach is based on quadrature force absorption by the aid of carefully designed flexible elements and the second strategy is to manipulate the dynamic modes of vibration of the structure, in order to decouple the Coriolis excited modes, from the quadrature components mainly induced by the anisoelasticity mechanisms. A3-axisgyroscopedesign(GkPAR) based on first approach with highly reduced quadrature error is achieved. The modes decoupling solution concept is also developed on a single axis primary layout(GkFrog) demonstrating high potentials for quadrature nulling. The final goal of research is to realize 3-axis gyroscope with low power consumption and unit cost, highly applicable to mobile devices, by the aid of a well-designed mechanical architecture in a compact area with reduced quadrature error. A final layout of 3-axis gyroscope with promising improvement, compatible with STMicroelectronics process technology is designed and prototyped.

TYRE-SOIL INTERACTION FOR OFF-ROAD VEHICLE APPLICATIONS

Ramadhani Omari Kivugo - Supervisor: Prof. Francesco Braghin

Agricultural and other off-road tyres primarily have to satisfy different operational requirements, such as better traction performance, limit slip sinkage, limit soil compaction andsupport weight of the machine. These requirements strongly depend on the soil characteristics-ROAD tyres primarily have to satisfy differents operational reand tyre tread design.

Little attention has been devoted to discrete element method (DEM) model that can be used to predict the traction performance as a function of tyre tread design with respect to to soil characteristics considering the effects of discontinuous behaviour of terrain during interaction. An early attempt to predict the tyre-soil interaction has been done by modelling terrain as a collection of deformable layer springs and tyre as deformable ring with tread geometry.

Moreover, recently attempts in numerical and discrete element models have been studied and developed, these models can predict traction performance, stresses and sinkage of wheel, but have the weakness of predicting the effects of build-up and cleaning which rise due to discreteness deformation of terrain during interaction.

Given the fact that, deformation of terrain is discontinuous in nature during interaction which rise to bulldozing effects, build-up and cleaning phenomenon and these mostly affects performance of wheel and off-road vehicles, then modelling terrain as assemblage of rigid colliding bodies must be studied and developed to predict those effects with respect to soil rheology.

In this work a multi-body dynamic software chrono::engine based on discrete elements method for non-smooth contact detection and computational and Bekker-Wong semi-empirical methodology has been used to model tyre-soil interaction to study the effects of terrain deformation with respect to wheel performance during interaction. This has been achieved by using C++ multi-body library in the software for modelling single tyre-soil interaction simulation model.

Simulations of tyre-soil interaction has been carried out with this model to study the influence of soil particles characteristics such as particle size, friction, cohesion force, mass/size distribution, shape and tyre tread design parameters such as lugs angle, type, height and spacing on interaction parameters such as wheel slip, traction, slip sinkage, slip velocity and forward velocity.

From the interaction parameters estimated with the model, terrain parameters such as sinkage exponent, deformation modulus, cohesion dependent parameter, internal friction dependent parameter and internal friction angle were aslo able to be estimated based on terramechanics underlying principles. Through these the terrain was able to full defined in terms of its parameters. Also, sensitivity and performance analysis has been carried out with the model considering terrain properties.

Finally, semi-empirical soft terrain model has been developed in this model. This terrain model is an alternative to granular terrain, in which soil properties depends on Bekker-Wong parameters. The model improves computational time and sinkage estimation accuracy and simulation time as in granular terrain. These two terrain models used in this simulation model gives reliable results of interaction parameters and contact pressure during interaction. The model has been validated with experimental and numerical data available in literature and guarantees an error less than 10% for traction force with respective slip.

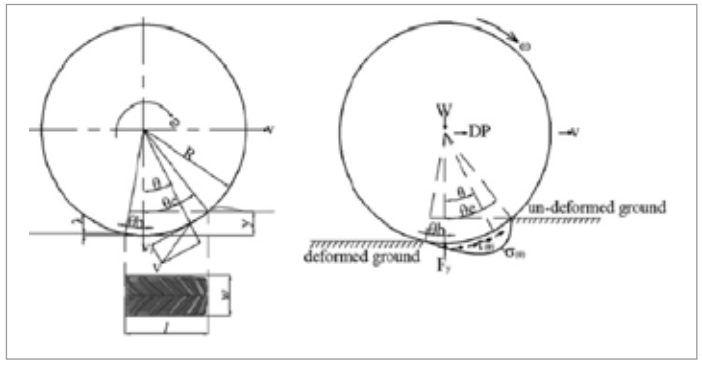


Fig. 1

$$s = \frac{R\omega - V}{R\omega}$$

$$Vj = R\omega\left(1 - (1-s)\left(1 - \frac{y}{R}\right)\right)$$

$$p = \left(\frac{k_c}{b} + k_\phi\right) y^n$$

$$\tau = (c + p\tan\phi)\left(1 - e^{-\frac{j}{k}}\right)$$

$$F_T = Rb\int_{\theta_b}^{\theta_e} \tau(\theta)\cos(\theta)\, d\theta$$

$$T_w = R^2 b\int_{\theta_b}^{\theta_e} \tau(\theta)\cos\theta\, d\theta$$

$$W = Rb\left[\int_{\theta}^{\theta_e} p(\theta)\cos\theta\, d\theta + \int_{\theta}^{\theta_e} \tau(\theta)\sin\theta\, d\theta\right]$$

Mathematical Formulas

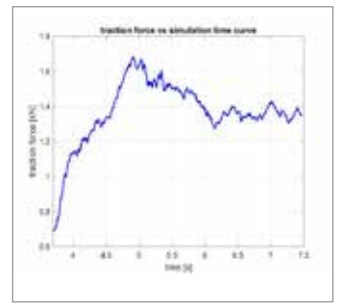


Fig. 2

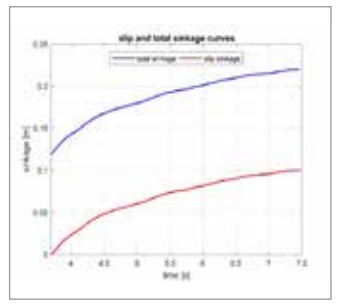


Fig. 3

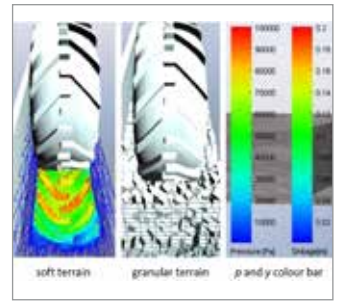


Fig. 4

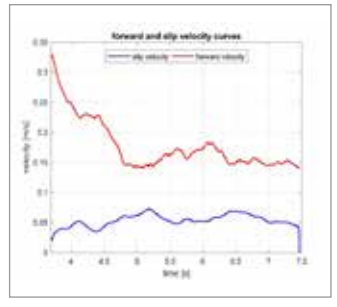


Fig. 5

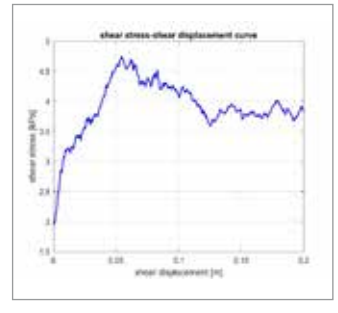


Fig.6

DEVELOPMENT AND APPLICATION OF VISION-BASED MEASURING TECHNIQUES IN DYNAMIC APPLICATION

Rui Liu - Supervisor: Prof. Emanuele Zappa

Novel non-contact measuring techniques have been widely applied to measure the motion of different targets. In this work, the measurement of the angles of helicopter blades during flight is the goal to further develop strategies for the reduction of the emitted noise. Vision-based measuring technique as the best solution is developed and applied, compared with the traditional contact measuring techniques and other non-contact measuring techniques.

There are two approaches for the angle measurement, hub-mounted approach and beanie-mounted approach.

For hub-mounted approach, the critical point is to develop a novel vision-based measuring technique for the narrow space application. A single camera system is developed. Geometrical relationship model avoiding the spatial reconstruction is proposed to realize the motion recovery of the blade. In order to improve the accuracy of the measurement and solve the constraint of narrow space measurement, iteration algorithm and self-adaptive algorithm is proposed. Simple flapping test is conducted to verify the basic idea of the model. A group of numerical analysis demonstrates the model is robust to different noise level and complex motion conditions. Due to the limitation of the assumption of the model, the beanie-mounted approach without narrow space constraint is considered in the following.

For beanie-mounted approach, 2D laser triangulation and vision-based measuring techniques including a single camera and stereo camera are considered in the preliminary selection. The basic measurement principle is determined based on tracking the special feature of the blade and the angle of the blade is recovered from the spatial coordinates of the feature by means of solving the inverse problem. AgustaWestland AW139 helicopter is the target for the measurement system and is applied to simulate complex motion of the blade. The stereo camera system shows better performance than the other two solutions and satisfies the discrepancy of the lag-flap-pitch angle is lower than 0.3º. Therefore, the stereo camera system is considered as the feasible solution for the final real flight test.

For the stereo camera system, the pattern of the object with eight black blobs is designed to be attached on the surface of the tension link, which connects the blade and the hub of the helicopter. The angle of the blade is estimated by means of tracking the eight blobs and solving the inverse problem. The singular value decomposition (SVD) algorithm is applied to solve the inverse problem. The experimental results demonstrate SVD algorithm is robust on the translation of the target due to the deformation of the structure in harsh dynamic condition. Moreover, the numerical analysis proves SVD algorithm is also robust on different noise levels.

In order to measure the angle of the blade, a calibration procedure to estimate the rotor translation parameters between the stereo camera system and the blade rotation system is required. Generally the conventional calibration method is to set the blade at the zero position, which means lag angle, flap angle and pitch angle are zero. However, it is difficult to satisfy this condition in the real application. Therefore, an advanced calibration procedure is developed. That is giving arbitrary and known blade angles as the calibration position, the rotor translation parameters are estimated. A simple test rig is developed to validate the method. Before the final flight test, a series of laboratory tests are conducted to confirm the parameters and the qualification of the full scale measurement system with a helicopter beanie, including stereo camera, lighting device, data acquisition and trigger distributor unit. The results of modal tests, rotation tests, vibration tests, sunlight sensitivity tests and accuracy tests with pattern size optimization determine the measurement system can be applied in the dynamic condition. Finally, the measurement prototype system coupled with the helicopter is evaluated in an extensive flight test measurement during the real flight (see Figure 1). First, in order to realize 35Hz sampling frequency, a novel data transmission method is applied to save the bandwidth. Only the positions of the blobs in the image instead of the full image are extracted by means of the pre-image processing. Meanwhile, the position of each blob is decomposed into four numbers by means of hexadecimal format. Second, data synchronization between the left camera and the right camera are required. The time stamp of receiving the data of each camera is recorded. If the difference of the time stamp between the two cameras is less than 10ms, the two data are considered as a pair of images. For the triangulation algorithm of stereo camera system, eight blobs in the two images must be made pair of correctly. An advanced matching algorithm is developed, and it works well for both small pattern and big pattern. Another critical issue is the harsh measurement condition in real fight is more complex than that in the laboratory condition. Some blobs are probably missing due to the unstable lighting conditions. In order to solve the problem, the advanced prior knowledge algorithm is developed. That is to assume all the blobs in the first known image are correct. Therefore, the wrong blobs in current image can be identified and refused to compute the angles of the blade. Another advanced estimation algorithm is proposed to estimate the correct positions of the wrong blobs, and the correct positions of the eight blobs are input for next image to detect wrong blobs. Finally, more than 1 hour continuous measurement (see Figure 2) shows the qualification of these algorithms and also the results of the measurement are acceptable, compared with the contact measurement system MovPal. The results show there is a slight discrepancy between the stereo camera system and MovPal system. The translation resulting from the deformation of the structure in dynamic condition is analysed, and several millimetres of the translation are presented. Considering the Movpal system is sensitive to the displacement and the fatigue problem of the Movpal system probably occurs in the long time flight, the stereo camera system is believed as the best candidate in this field.

Fig. 1 - The measurement system integrated with helicopter main rotor

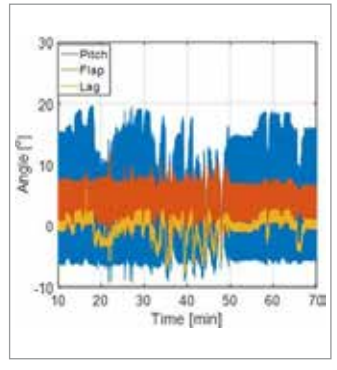


Fig. 2 - The lag-flap-pitch angles of the blade as the time during the real flight

USING BIO-INSPIRED DESIGN ELEMENTS IN THE FABRICATION OF CELLULAR MATERIALS WITH SPECIAL PROPERTIES AND FUNCTIONALITIES

Mohammad J. Mirzaali

Supervisors: Prof. L. Vergani, Prof. M. Strano

Building blocks of cellular biological materials are mainly limited to few numbers of biopolymers (protein and sugar-based polymers) as the soft phase, minerals and ions as the hard phase and cross-linking agent to integrate these materials. In addition, there is limited amount of geometrical, morphological and topological arrangements in the microstructure of natural substances also known as essential design elements.
Some of the most fundamental design elements are functionally gradient, randomness and multiple length-scale hierarchies at different length levels.
Besides, particular shapes can be observed in the biological materials such as tabular, circular, honeycomb or re-entrant forms.
Despite these limited number of variations in material constituents and microstructural organizations in nature, biological materials offer a wide range of mechanical and functional properties as a result of proper, smart and optimized combination of chemical composition and microstructural design features to satisfy specific functions and design motifs.
Modern engineering materials with specific functionality and properties have always been on demand for various medical and industrial applications. Learning from nature, via biomimetics, has still been considered as a powerful tool to understand fundamental characteristics responsible for their attractive properties and functionalities. This has led to the fabrication of advanced engineering materials through the history. Biomimetics approaches aim to study biological substances and synthesize and imitate similar structure/ elements, systems and models of nature in order to fabricate advanced artificial human-made products with particular functionalities and properties. To mimic these unique features in a synthetic material, it is essential to implement proper combinations of existing manufacturing processes. However, to date there is no unique manufacturing method that can merge all these design features such as multi-scaling, heterogeneity, anisotropy, gradient, and hierarchy in de-novo materials. Therefore, development of new manufacturing methods for such an implementation is of high interest.
Recently, due to the new development in manufacturing techniques, studies related to the creation of bio-inspired materials have gained a numerous deal of attention. These needs are appreciated by scientist and engineers working in the area of material science, mechanics, architecture, and biology. Improving mechanical properties and functionalities have always been regarded by material scientists, mechanical engineers, and architects because of its applicability in industry. Bio-inspiration is also crucial for the design of new scaffolds, and (patient-specific) implants as it is required to accurately mimic the microstructure of tissues in order to have appropriate tissue regeneration.
Within different studies in this thesis, we aimed to take into account the most important design elements in natural materials, i.e., functionally gradient, randomness together with special shapes found in natures and implement those features in the fabrication of new advanced materials. In each study, we targeted certain mechanical or functional properties using the current manufacturing techniques. Different studies in this thesis are summarized as following:

Firstly, we reviewed the state-of-the-art of bio-inspiration in material science and engineering. We also reviewed some of the key design elements in natural materials and provided few examples of the previous works on this area. A brief summary of outline of the thesis, and summarizing the content of other chapters are also provided at the end of this part. All materials in chapters 2 to 5 are taken from published documents in peer-reviewed journals.
• In the first study, we investigate the application of conventional foaming processes in the production of new closed-cell aluminum foams which their microstructures are mimicked to the ones of microstructures of trabecular bone. For that aim, we modified the current technique in order to design, manufacture and test two different types of bone-inspired aluminum closed cell foams. We also compared the microstructural feature and mechanical properties of that bone-inspired aluminum closed cell foams with bone samples. (Manuscript detail: M. J. Mirzaali, V. Mussi, P. Vena, F. Libonati, L. Vergani, M. Strano, Mimicking the loading adaptation of bone microstructure with aluminum foams, Materials and Design, doi: 10.1016/j.matdes.2017.04.039.)
• In the second study, we introduced patterned randomness as a strategy for independent tailoring of the elastic properties of soft metamaterials, i. e. the elastic modulus and Poisson's ratio. As the randomness is one the features that can be found in the biological substances, the results of this study show how randomness in general and patterned randomness, in particular, can be served as design strategies to reach various mechanical properties in soft mechanical metamaterials, i. e. elastic modulus and Poisson's ratio. For this goal, we designed, tested and manufactured several samples and computational models to predict the topology-property relationship in a wider range. For the manufacturing of these structures, we used in-direct manufacturing technique. (Manuscript detail: M. J. Mirzaali, R. Hedayati, P. Vena, L. Vergani, M. Strano, A. A. Zadpoor, Rational design of soft mechanical metamaterials: Independent tailoring of elastic properties with randomness, Appl. Phys. Lett., 111, 051903 (2017); doi: http://dx.doi.org/10.1063/1.4989441.)
• In the third study, we introduced functional gradient in soft mechanical metamaterials in order to predict predefined boundaries under mechanical stimuli. For this purpose, we designed, manufactured and tested few prototypes which later have been used for the validation of computational models. Then, we used computational results to predict pre-defined random shapes using forward-maps approaches. We also showed how these materials can be used for the approximation of boundaries of real objects. (Manuscript detail: Mirzaali, M.J., Janbaz, S., Strano, M., Vergani, L. and Zadpoor, A.A., 2018. Shape-matching soft mechanical metamaterials. Scientific Reports, 8(1), p.965.)
• In the last study, we studied physics of crumpling of porous sheets. We proposed crumpling as a fast and easy fabrication technique for manufacturing crumpled-based bio-materials due to their robust mechanical properties. We also compared the process of crumpling of sheets without a hole, with the one with 2D porosity and investigated how holes can affect this process. The method of crumpling can also be considered as a powerful method for converting 2D surface functionalization to 3D. (Manuscript detail: M. J. Mirzaali, M. Habibi, S. Janbaz, L. Vergani, A. A. Zadpoor, Crumpling-based soft metamaterials: the effects of sheet pore size and porosity, Scientific Reports, 7, Article number: 13028, 2017, doi:10.1038/s41598-017-12821-6.)

INTRODUCING INNOVATIONS IN THE EYEWEAR DEVELOPMENT PROCESS

Aurelio Montalto - Supervisor: Prof. Monica Bordegoni
Co-Supervisor: Dr. Serena Graziosi

This thesis arises from a collaboration between the university and an eyewear company, with the purpose to develop methods and tools to support the development cycle of cellulose-acetate frames.
The main problem in eyewear is the wide product variability, which negatively impacts on the industrial efficiency. For example, the fulfilment of some frame angles (i.e., face-form, pantoscopic, and opening-temple angles) is fundamental to ensure both the functionality and the aesthetics of a frame. The continuous variability of these values and, of the frame geometries, together with the lack of knowledge about how this variability affects the design and manufacturing processes of the frame, make difficult the fulfilment of the settled requirements: the final shape of the product (and consequently, the final value of the frame-angles) is not easily predictable. The company overcomes this issue through redesign cycles and reiterated tunings of the manufacturing process until the values — set for these angles — are satisfied. Also, the absence of reconfigurable tools — typical for mass-customisation manufacturing — induces the company to design, manufacture, and finally store ad-hoc tools for each frame-model, generating a waste of resources. The thesis aimed to find efficient solutions for addressing the following two industrial problems: first, avoiding design-and-manufacturing iterations to fulfil the settled design requirements of frames; second, introducing reconfigurable tools for the manufacturing of spectacle frames. A systematic approach was needed to deal with these issues: first, the industrial context had to be analysed, identifying the causes of the problems; then proper strategies had to be developed; finally, tests had to be carried out to verify the solution effectiveness.
A formalisation of the current industrial practice was first performed, to better contextualise the problems and understand the eyewear peculiarities. This step was carried out through personnel interviews in the company, modelling the entire development process of acetate frames through the IDEF0 methodology. The problem causes were identified by a systematic acquisition of data through an automatic inspection system (Fig. 1), specifically developed to acquire the values of the frame-angles during different production phases. The acquired data highlighted problems occurring both during the design and manufacturing processes (especially during the thermoforming phase of spectacle fronts, named "meniscatura") of frames. Consequently, solutions had to be developed considering both aspects. Concerning the design process, a knowledge formalisation was performed to combine aesthetic and engineering specifications, analysing how the frame angles modify the design and generating an abstract model of the frame (i.e., an archetype) based on mathematical relations. This abstract model was finally translated into a design tool for stylists and engineers (i.e., a spreadsheet, see Fig. 2). With reference to the manufacturing process, tests were performed to investigate the possibility to manufacture frames with higher precision. The most important settings of the "meniscatura" phase (i.e., the front thermoforming) were identified through experimental tests, to ensure the correspondence between designed-and-manufactured frames. The effectiveness of the developed approaches was tested with the company, designing and manufacturing new frame models: the predictability of the frame shapes — like as the frame angles — were verified, confirming the validity of the two implemented approaches and, solving the first industrial problem. The second industrial problem was addressed introducing reconfigurable manufacturing tools. Indeed, on the basis of the previously acquired knowledge and taking as an example the meniscatura mould, a new strategy was proposed to transform a standard thermoforming mould into a reconfigurable one, using ad-hoc and re-usable modules (Fig. 3). In addition, all ad-hoc parts have been automatically designed through dedicated scripts. Finally, the new mould configuration was tested in a virtual environment. All research activities demonstrated that fostering a strong product knowledge formalisation — also through mathematical relations — could be a valuable strategy to better manage the development of new products. It is noted that this strategy is effective also in those industrial fields characterised by creativity and wide product variability.

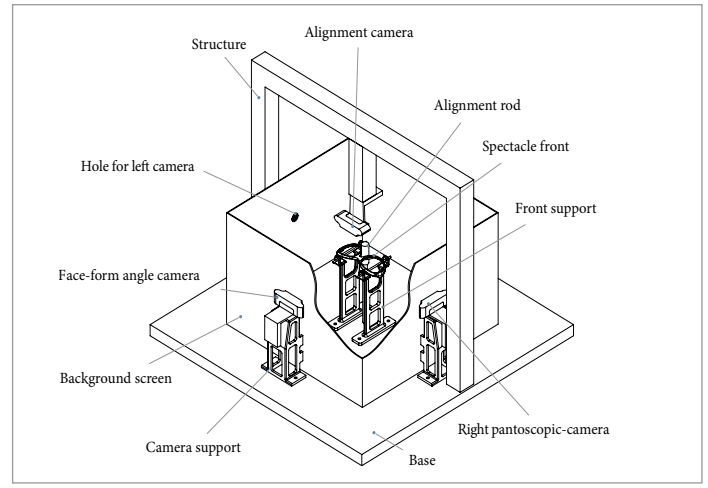


Fig. 1 - The system developed for measuring the face-form and the pantoscopic angles of spectacle frames. The measurements are performed through the automatic analysis of images taken through four commercial webcams. (Image source: "A. Montalto, S. Graziosi, M. Bordegoni, and L. Di Landro. An inspection system to master dimensional and technological variability of fashion-related products: A case study in the eyewear industry. In: Computers in Industry, 83 (2016), pp. 140–149").

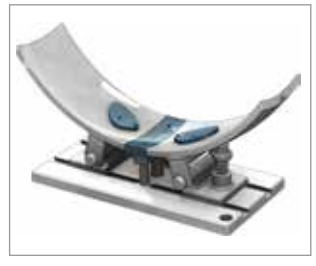


Fig. 3 - Conceptual model of the reconfigurable and re-usable meniscatura mould to support the geometric variability of fronts. The grey modules are standardised and re-usable for different frame-geometries. The blue parts are automatically designed through specific scripts and they are in charge of managing the geometric variability of spectacle fronts.

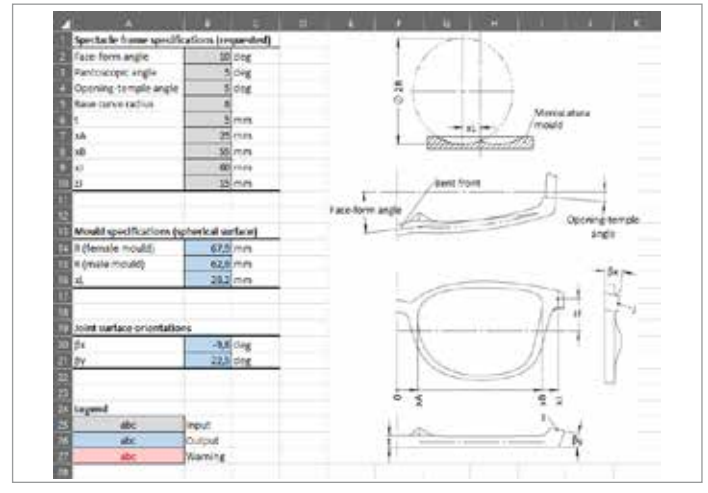


Fig. 2 - The new frame model has been translated into a mathematical model and then implemented into a spreadsheet. This spreadsheet can be seen as a design tool for guiding the design process of new frames, helping to fulfil the settled requirements. (Image source: "A. Montalto, S. Graziosi, M. Bordegoni, and L. Di Landro. Combining aesthetics and engineering specifications for fashion-driven product design: A case study on spectacle frames. In: Computers in Industry, 95 (2018), pp. 102–112").

FROM STRUCTURAL REPAIRS TO ADDITIVE MANUFACTURING; EXPLORING NEW CHALLENGES FOR COLD SPRAY

Klára Petráčková - Supervisor: Prof. Mario Guagliano

Cold spray, a member of thermal spray family, uses converging-diverging nozzle to generate supersonic gas stream, which accelerates powder particles towards high velocities ranging between 200 - 1200 m/s (Fig. 1). At such high velocities, the particles impact substrate and adhere to through plastic deformation. As oppose to the other thermal spray methods, during which the deposited material melts, the main feature of the cold spray is the solid-state nature of particles' deposition. Thanks to this, cold spray possesses many advantages mainly related to the avoidance of deleterious effects due to high temperatures. Cold spray has developed into a reliable industrial technology with many application, amongst which repair of aerospace components is particularly distinguishable thanks to enormous savings brought. Cold spray is used for repairing non-structural parts made of Al, Mg and Ti alloys, for which repair requirements are simpler and less strict than for components carrying load.

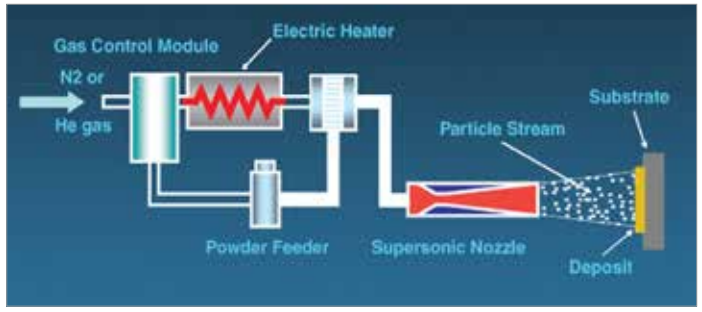


Fig. 1 - Cold Spray system

As the cold spray technology evolves, coating properties are enhanced and extension of its application to parts transmitting loads does not sound unrealistic anymore. Structural restoration requires new testing procedures to be developed to prove that repaired components fulfill high safety requirements in aerospace. Some publications indicated that 50-90% of failures are due to cyclic load. Thus, it is of primary importance to assess whether the repaired parts retain the same fatigue properties as the base material.

Potential of cold spray for the structural repair is demonstrated using coatings made of F357 aluminum alloy, a casting alloy widely used in aerospace.

The coating underwent set of standard tests as well as newly developed fatigue test. With optimal spray parameters, coating deposition on substrate with smooth surface resulted in relatively good bonding, which can be further improved by application of grit blasting on substrate's surface. However, no enhancement of adhesion was obtained for shot peened surface. Process temperature, which was set to either 450°C or 550°C, was shown to influence adhesion and cohesion strength but it does not influence residual stress in the coating. To assess cold spray perspectives for additive manufacturing, flat tensile specimens were machined from coating and tested in as sprayed and heat treated (solution treatment and aging) condition. Tensile properties of the coating after the treatment correspond to properties of the cast F357-T61 aluminum alloy. Two novel specimens to assess behavior of the coating under cyclic load were proposed and successfully tested. Both specimens are designed for axial fatigue test, which is the most conservative and straightforward method. In the case of the first specimen, relatively thick layer of the coating is deposited circumferentially, which allows to generally assess performance of the coating with respect to standardized specimen produced from bulk material. The coated fatigue specimen reached 94% of the fatigue limit of the base material. Second fatigue specimen contained a spherical cavity inducing stress concentration factor of 1.5, which is filled using the cold spray and tested. Calculated fatigue limit yielded 94% of the fatigue limit of the base material. Neither of the fractured fatigue specimen did not reveal crack initiation in the coating or at the interface. Based on the experimental results, it can be concluded that the high pressure cold spray technology can be successfully applied also to the parts subjected to cyclic loading.

Another problem represents oxidation of cold spray powders made from aluminum and aluminum alloys so frequently used in aerospace. Aluminum and aluminum alloys react with oxygen under atmospheric conditions and oxide film forms easily on the powder particles during storage and handling. Experimental studies demonstrated that oxide surrounding the particle hinders plastic deformation and breakage of the oxide film consumes significant part of the impact energy. Results of parametric numerical study to determine effect of the thickness of oxide layer surrounding alumina particle on its deposition are presented in this work. Comparison of three particle impact models, no oxide and oxide layers with thicknesses of 0.2μm and 200μm, shows that the even the thin oxide layer prevents jetting of the particle and, depending on its thickness, also the flattening of the particle. While, no oxide cleaning was observed in the case of the thick layer, some cluster of oxide accumulated at the edge of the contact zone. Thus, the oxide cleaning mechanism, which is believed to be responsible for intimate contact of the substrate and the particle allowing the metallurgical bonding, was not confirmed by the presented numerical simulations. However, it was shown that bonding is obstructed by thick and rather continuous oxide layer in the middle of the contact zone.

With increasing demands on structural integrity of the coatings, fracture properties and prediction of crack initiation and propagation grow in importance. This is addressed by development of numerical model to predict damage in the cold sprayed coatings. The model was based on cohesive zone approach, which combines experiment and numerical simulation to study crack initiation and propagation. The numerical work is based on the cohesive elements governed by a bilinear traction-separation law, which is suitable to simulate brittle fracture of cold spray coatings, the experiment approach determines the material parameters (so-called cohesive) needed as the input of the model. In the presented work, experimental procedure to determine cohesive parameters includes micro tensile test and compact tension test specimen made of thick 7050 aluminum alloy coating and adhesion test specimen and modified compact tension test specimen to determine cohesive properties at the interface between F357 aluminum alloy coating and the same material substrate. Required cohesive parameters are estimated based on the testing and trial-error fitting procedure. Good agreement between numerical and experimental results was obtained demonstrating that the presented cohesive law can simulate the damage in the cold sprayed coatings with reasonable accuracy.

MULTIDISCIPLINARY DESIGN OF ELECTRIC VEHICLES BASED ON HIERARCHICAL MULTI-OBJECTIVE OPTIMISATION

Kesavan Ramakrishnan

Supervisors: Prof. Gianpiero Mastinu, Prof. Massimiliano Gobbi

The design optimisation of in-wheel motor (IWM) electric powertrain is an interdisciplinary problem with multiple objectives functions. In order to solve such complex problems holistically, the objective functions should be handled simultaneously. Multi-objective optimisation (MOO) techniques can be employed to obtain the Pareto-optimal set which gives the best possible trade-off solutions between the objective functions. In order to effectively optimise the complex systems, MOO techniques are combined with Analytical target cascading (ATC) approach. In the case of the IWM electric vehicle optimisation, the Pareto-optimal solutions are derived between fuel economy, acceleration, and comfort. Based on the desired characteristics of a vehicle, the optimal design solution can be adopted from the Pareto front.

Mathematical model: A complex problem can be partitioned into multiple manageable subsystems based on their functionalities and can be solved by exploiting dedicated modelling tools and optimisers. The ATC approach ensures synergy between the optimal solutions. The mathematical formation of ATC algorithm is given as,

$$\begin{aligned} \min_{\bar{x}_{ij}=\{x_{ij},\, t_{ij},\, r_{ij}\}} \quad & f_{ij}(\bar{x}_{ij}) + \phi_{ij}(c_{ij},\, v_{ij},\, w_{ij}) \\ \text{subject to} \quad & h_{ij}(\bar{x}_{ij}) = 0 \\ & g_{ij}(\bar{x}_{ij}) \le 0 \\ \text{where,} \quad & \phi_{ij} = v_{ij}{}^{T} c_{ij} + \left\| w_{ij} \circ c_{ij} \right\|_2^2 \\ & c_{ij} = t_{ij} - r_{(i+1)j} \end{aligned}$$

where f is the objective functions vector of j^{th} subsystem at i^{th} level, t_{ij} is the target linking variables vector from the top level, $r_{(i+1)j}$ is the response linking variables vector from the bottom levels, Φ_{ij} is the consistency constraints vector which relaxes the equality constraints ($c_{ij} = 0$) between the targets and responses using augmented lagrangian function, h_{ij} and g_{ij} are the equality and inequality constraints vectors respectively, and x is the local design variables vector. The Lagrangian multiplier (v) and penalty weights (w) are updated linearly in the successive ATC iterations as in

$$v^{k+1} = v^{k} + 2w^{k} \circ w^{k} \circ c^{k}$$
$$w^{k+1} = \beta w^{k}$$

where k represents the number of iteration. The factor β should be $2 < \beta < 3$ for fast convergence of the problem. The convergence criteria is set at the top-level as $||c^{k}|| < \varepsilon_1$ and $||c^{k}-c^{k-1}|| < \varepsilon_2$.

Optimisation problem formulation: The electric vehicle optimisation problem is partitioned into two levels where the top level consists of vehicle model along with the electric motor and power electronics models. The bottom level contains battery and suspension models. At the vehicle level, the objective functions are the energy consumption in a given range target as per NEDC (E_c) and driving performance. The design variables are axial and radial scaling ratios of the electric motor, the rated voltage, and the total number of battery cells. The constraints are defined on the acoustic performance of the machine, energy content of the battery and the maximum allowable motor power (P_{in}). In the battery model, the cells are arranged in a balanced scheme to enable uniform utilisation of the cells. The number of cells in series (N_{sc}) and parallel (N_{pc}) are taken as the design variables, and they are optimised for the consistency constraints (Φ) on the linking variable N_{bc}. In the suspension model, the objective functions are discomfort, road holding, and working space. The spring stiffness and damping ratio are considered as the design variables.

As a first step, the vehicle model at the top level is optimized and the value of N_{bc} is cascaded down to the battery model as a target. The motor input power requirement P_{in} is treated as a shared variable. Similarly, the sprung mass (m_1) and unsprung mass (m_2) of the vehicle which are calculated from the optimized design variables k_a, k_r, and N_{bc} are passed to the suspension model. The subsystem models verify if the targets from vehicle model can be achieved without violating the local constrains and design objectives. The response linking variables are updated and sent back to the system model for the subsequent optimisation routine.

Results: Pareto-optimal results are plotted in Figure 1 between energy consumption and the inverse of gradeability limit (GL), which converts the GL to a minimisation function. Equivalent acceleration is also shown in the second x-axis. Similarly, the Pareto-optimal front of the suspension system between discomfort, road holding, and working space for specific values of m_1 and m_2 is given in the Figure 2.

The performance of proposed ATC based methodology is compared with the All-in-one (AiO) optimisation in terms of accuracy and calculation time. Two different AiO models are considered for this comparison study. In the first model, the vehicle mass is fixed and it does not change with motor and battery sizes. In the second model, the motor and battery sizes are used to estimate the vehicle mass. When the gradeability or acceleration demand is high, the motor size must be scaled up to achieve the required torque. This results in increased vehicle mass and energy consumption. On the other hand, when the gradeability or acceleration requirement is low, the actual energy consumption will be lower than the estimation of fixed vehicle mass model. In order to solve the second model, evolutionary algorithm is necessary as it involves discrete design variables (N_{pc} and N_{sc}). A simplified multi-level optimisation model is built considering only the vehicle and battery models to generalize the models between ATC and AiO approaches. The acoustic performance evaluation and the suspension model discussed are not included as it is difficult to manage fives objective functions together in the AiO formulation.

The Pareto optimal sets from the proposed hierarchical method and AiO approaches are compared in the Figure 3. As it can be observed, the proposed method gives accurate results as that of AiO with varying vehicle mass. Its calculation time (440s) is significantly lower than the evolutionary methods.

From the given results, it can be suggested that the proposed optimisation algorithm is quite useful in the early design stage of complex systems such as the in-wheel motor electric vehicle in achieving efficient solutions with reasonable calculation time.

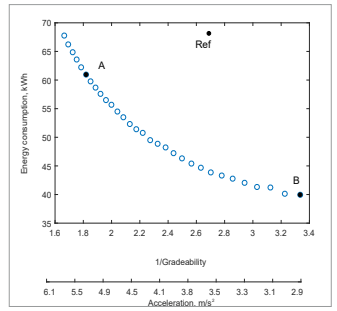


Fig. 1 - Pareto-optimal set between energy consumption and the inverse of gradeability limit.

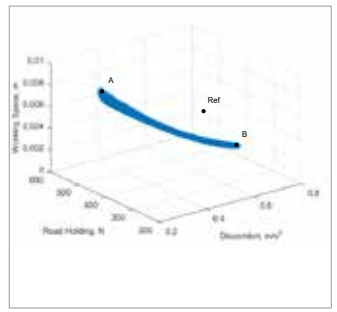


Fig. 2 - Pareto-optimal set of the suspension model

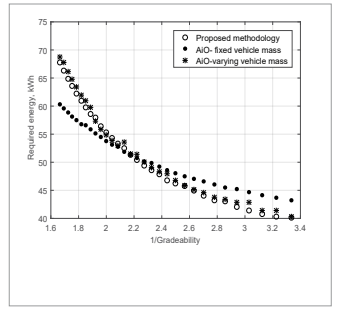


Fig. 3 - Comparison of Pareto optimal sets obtained from AiO optimisation models and proposed methodology

ACTIVE KINEMATICS SUSPENSION FOR A HIGH PERFORMANCE SPORT CAR

Isabel Ramirez Ruiz - Supervisor: Prof. Edoardo Sabbioni
Co-Supervisor: Prof. Federico Cheli

The challenge to design the rear suspension of a rear wheel drive sports car has always been to optimize the position of both wheels and therefore the contact patch of the tires, in order to obtain the maximum possible limit acceleration. To reach these targets, all the more prestigious vehicle companies have greatly improved the kinematics and compliance of the front and rear suspension, together with the tire characteristics (Fig.1).
Normally, the improvements have been obtained working on existing suspensions, without adding any active systems that are able to change the suspension kinematics and compliances. The only exception has been a 4 wheel steering system studied in the 80s, which is an active system that is able to change the toe angle of the rear suspension wheels.
The research undertaken in this thesis presents an innovative active system which allows the control of the vehicle rear suspension wheels by varying the camber angles through the suspension geometry. This enables a more complete control of the tire contact patch which can then further optimize the overall dynamics of the vehicle. This includes improved vehicle steady and dynamic limit stability and faster transient reaction through optimized lateral and longitudinal traction forces. The driver´s benefits are improved safety and higher driving feeling.
The concept of variable camber suspension comes from the idea of enhancing tire performance with optimized camber angles, depending on vehicle behaviour. Experimental results in the tire manufacture bench flat track reveal that cornering force is strongly dependent on camber angle. Overall an increase of tire lateral force of between 15-20% is expected in the sport vehicle, with an increase of negative camber up to -5°. Nevertheless, an adequate control strategy must be developed based on the vehicle dynamics to reach the optimum combination in the linear and nonlinear range of the camber angle of each rear wheel.
The main objective of the thesis is to prove in a virtual environment, supported by road tests, that the use of the systems mentioned above could greatly improve vehicle dynamics for handling behaviour and steering feeling.
It will be shown that the rear camber active system has a clear advantage over the conventional setup of the luxury sport car, which enables a very fast steering reaction and at the same time a very stable vehicle.
One of the main focuses of this work is the optimisation of the control algorithms in order to find the optimal handling behaviour and steering feeling. The virtual analysis of the vehicle is done with the aid of different vehicle dynamics models (multibody models) and other application software (Matlab, Simulink and Amesim) to describe the control logic to implement in the ECU of the prototype car. The driving behaviour of the target vehicle will be virtually defined on the basis of the solid real and virtual driving experience of the automotive company of the prototype car, and it will be demonstrated that the presented active system can reach the target compared to the behaviour of a similar vehicle without active systems. All benefits of other active systems (electronic differential E-Diff and continuous damping control CDC) of the prototype car should be kept and readjusted in order to achieve higher targets of vehicle dynamics.
Because it is necessary to integrate a sophisticated vehicle control logic, a 'High-hierarchy control unit' (Fig.2) should supervise all subsystems (camber, vertical control damping, electronic differential, traction control and aided braking control) to create the control philosophy of the full vehicle. In particular, the camber variation response will be adapted to changes in the environment such as temperature, ground conditions, and vehicle characteristics. One model with real time performance, called the "preview model", should be able to preview as accurately as possible the real behavior of the driving car. After that, it will choose the best positional value to apply to the rear wheels' camber actuators. Simultaneously a complete network of real sensors on the vehicle (suspension strokes, three axles gravitational accelerometer, gyroscope and GPS) will be needed, together with an opportune calculation of the vehicle side slip angle state, in order to compare it to the one calculated by the preview model. The vehicle logic will operate first the corrections to the preview model characteristics in a kind of auto learning, and will update in a second step the preview model, in order to allow it to consistently give better corrections of camber positions so that the results of the requested vehicle response can be obtained.
The preview model is a simplified 15 degrees of freedom vehicle dynamics model based on suspension geometry and the compliance description in the look up tables. The complete model includes the detailed model of the rear electromechanical actuators, with the electrical characteristics of the brushless motor and power electronics.
The model for the vehicle state estimation by on board sensors is able to calculate the wheel's normal, lateral and longitudinal forces from the static load, the longitudinal weight transfer due to braking and thrust, and the lateral weight transfer due to cornering. In this way a new methodological approach has been developed called Sensor Signal Processing Model (SSPM) to obtain the main parameters of the vehicle that update the above mentioned preview model.

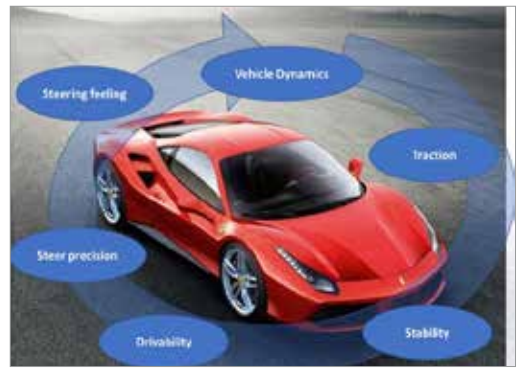


Fig. 1

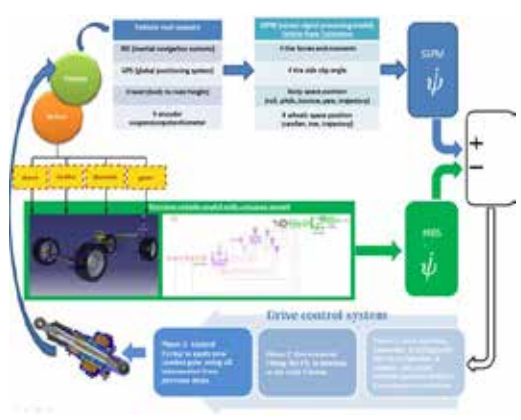


Fig. 2

AERODYNAMICS OF HEAVY TRUCKS

Luigi Salati - Supervisor: Prof. Federico Cheli
Co-Supervisor: Dr. Paolo Schito

The project studies the aerodynamics of the HGV, focusing mainly on two important aspects: the drag reduction obtained using passive devices installed on the trailer and the wind-induced accident involving overturning and handling issue.
The first topic is crucial in order to decrease the fuel consumption of the vehicle with both economic and environmental benefits. In this work, external passive devices installed on the trailer were developed and tested. The idea is to keep the internal load capacity of the trailer fixed. Front-rear trailer devices were developed as the best strategies to reduce drag, with reference to both developing and installation costs. The device reduces the aerodynamic drag around *10 %*.
The second topic is crucial in order to reduce wind induced accidents involving overturning when the vehicle is exposed to strong lateral wind, as when passing on viaducts or bridges.
Since this phenomenon represents a serious concern for the running safety of vehicles, it has been widely investigated in literature.
To increase the running safety, specific fences are occasionally placed both at the edges of bridges and close to towers, shielding vehicles from cross-wind. The design of these devices is however an extremely challenging task since it must account for the dynamic coupling of aerodynamic loads (depending on the bridge layout, i.e. deck, tower and fences) and vehicle-driver response.
This work is the first step toward the validation of numerical models of aerodynamic forces acting on vehicles, used in Multi-Body simulations. It is fundamental also for the design of lateral shields to be installed on the infrastructure, and for studying the coupled driver-vehicle response during the aerodynamic interaction with the tower wake in cross wind conditions.
A CFD numerical approach was developed to overcome the limitations of wind tunnel experiments using moving vehicles and dynamic mesh.
The developed methodology was used in a real case to define the aerodynamic load on an HGV running on the cable-stayed bridge, designed in the "Forth Replacement Crossing" (FRC) project in Edinburgh.
To mitigate wind-induced accidents, in particular overturning, when the HGV is passing over long bridges or viaducts, it is possible to place lateral shield on the sides of the existing infrastructure, or it possible to optimize the aerodynamic response of the vehicle.
In this work, three main ways were used and compared to optimize the aerodynamic response of the HGV:
- changing of the shape of the trailer.
- Vortex Generators (VGs) installed on the leading edge of the trailer.
- Front-rear trailer devices installed along the sides/top of the trailer.

The first test carried out involved the change of the trailer shape making the corner between the top and the side of the trailer as smooth as possible. The performance of the rounded corner, inclined corner and corner cut were tested. All the modifications to the shape of the trailer proposed reduced the trailer load capacity.
At a constant volume reduction, the rounded corner, shows a overturning moment reduction around *25 %* with a limited reduction of load capacity below *1 %*.
VGs positioned on the top separation leading-edge, were implemented to reduce the overturning moment. Comparing the performance of the VGs with the one obtained in the previous strategy, the VGs did not seem a promising solution to mitigate the overturning risk, reducing the overturning moment no more than *2.4 %*.
The strategy of "adding" external passive devices onto the existing trailer was adopted. Their shape was based on the front-rear trailer device previously designed and patented by the author.
This strategy seems to be the easiest one to be adopted by the "truck community;" in particular, if said device does not exceed the maximum vehicle dimension permitted by the regulation.
The proposed device reduces the whole overturning moment by about *7.5 % - 8 %* and whole vehicle drag around *4 %*. The performance of the front-rear trailer devices installed along the sides/top of the trailer were validated with wind tunnel test on a 1:10 HGV model. The developed device has a significant influence on the HGV overturning risk reducing it about *5%-8 %*, as demonstrated in the two scenarios: HGV on flat ground and HGV passing through the wake of a tower largely exposed to crosswind.

Fig. 1

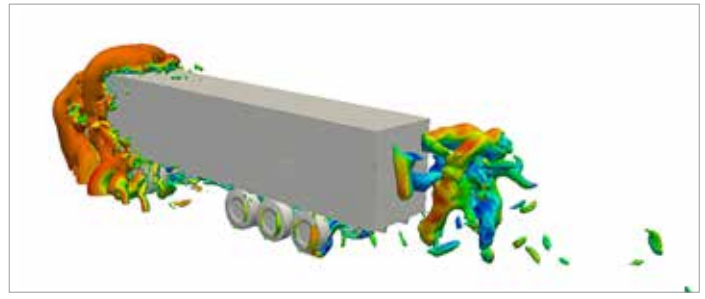


Fig. 2

Fig. 3

THESIS TITLE: REMANUFACTURING PLANNING UNDER UNCERTAINTY

Nazanin Shabanpour - Supervisor: Prof. Marcello Colledani

Introduction

Remanufacturing is recognized as one of the most profitable and environmentally conscious options of the Circular Economy. A remanufacturing process chain includes disassembly, cleaning, inspection, reconditioning and reassembly stages to recover the functionality and value of returned products. However, the profitability of remanufacturing is significantly affected by the variability of EOL (End Of Life) product conditions. Among different steps of the remanufacturing process chain, disassembly is highly affected by the negative impact of the EOL products variability. The effect is the highly uncertain disassembly tasks times. This uncertainty can significantly disturb performance and feasibility of remanufacturing. Therefore, providing the efficient disassembly systems considering these challenges is the requirement of having profitable remanufacturing system. This work develops a novel mathematical optimization model to find the optimal design of disassembly lines with the objective of profit maximization. This model jointly optimizes the disassembly tasks sequencing, the allocation of tasks to the workstations and the capacity of buffers under uncertainty of tasks times in order to achieve the desired service level.

Key characteristics of the disassembly line considered in the optimization model

In this work, we consider an asynchronous and serial disassembly line contains several manual workstations. It is assumed that uncertainties of workstations are due to variations of returned products and the inherent nature of manual operations. The aim is to design a robust disassembly line consisting of a sequence of manual workstations 'W' which are decoupled by 'B' buffers.

Reference mathematical model

Sets

i=1,...,N: Disassembly component, *k*=1,...,K: Sequencing position, *w*=1,...,W: Workstation, *b*=1,...,B: Buffer

Parameters

T(i): Mean of Stochastic task time

CT=Cycle time,

WS: Maximum number of workstations,

N(b): Maximum allowed size of buffer b,

RC(i): The revenue which is gained from re-using target component or subassembly 'i',

DC(i): The cost of recycling or disposing un-reusable non-target component or subassembly 'i',

FC: Fixed cost per operation time unit,

FW: Fixed cost per opening a workstation, *FB*: fixed unit cost of buffer b,

FI: The cost of stocking a component in buffer b

Decision Variables

x(i,k,w): Binary variables. It takes the value '1' if the component 'i' is removed in position 'k' of a sequence and assigned to station w, and'0' otherwise,

α(w): Binary variables. It takes the value '1' if the workstation 'w' is occupied, and '0' otherwise,

n(b): Integer variables. It is the capacity of buffer b.

IT: Inter-departure time between the successive components from the end of the line.

Objective function

The objective function consists in the maximization of the total profit of the system by summing up the total revenues and minimizing the total costs.

$$Maximum \quad R = \sum_{i=1}^{N}[RC_i - T_i \cdot FC]\sum_{k=1}^{K}\sum_{w=1}^{W} x_{i,k,w} - \sum_{i=1}^{N}(1-\sum_{k=1}^{K}\sum_{w=1}^{W} x_{i,k,w}) \cdot DC_i - FC \cdot \sum_{w=1}^{W}\sum_{k=1}^{K} q_{i,w}^{T} \cdot STT_{i,w} - FW \cdot \sum_{w=1}^{W} \alpha_w - \sum_{b=1}^{B}(FB \cdot n_b + FI \cdot \overline{n_b})$$

Constraints

Constraint (1) satisfies the minimum service level:

$$Prob(IT \le CT) \ge 1 - \alpha_i$$

Constraint (2) satisfies maximum buffer capacity:

$$n_b \le N_b \qquad \forall b \in B$$

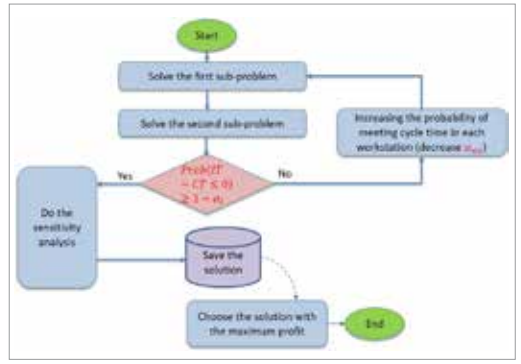


Fig. 1 - Iterative algorithm

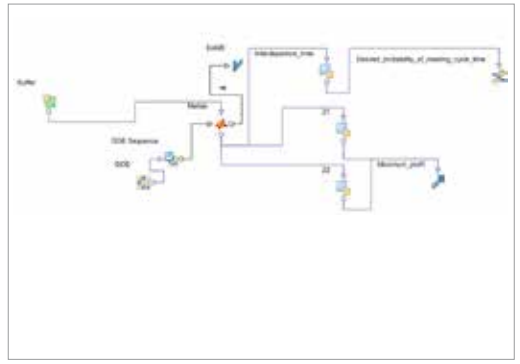


Fig. 2 - ModeFrontier model

Constraints (3) ensures the precedence constraints:

$$\sum_{k=1}^{K}\sum_{w=1}^{W} x_{i,k,w} \le \sum_{k=1}^{K}\sum_{w=1}^{W} x_{i',k,w} \quad \forall i,i' = 1,\dots,N, i' \in S_i$$

Constraint (4) defines the maximum number of workstations:

$$\sum_{w=1}^{W} \alpha_w \le WS$$

Constraint (5) assures the desired cycle time in each workstation:

$$Prob\left(\sum_{i=1}^{N}\sum_{k=1}^{K} x_{i,k,w} * T_i + \sum_{i=1}^{N}\sum_{i'=1,i'\neq i}^{N} IR_{i,i',w} - CT\right) \ge 1 - \alpha_w \quad \forall w = 1,\dots,W$$

Solution Method

In the proposed model, the line inter-departure time and average quantity of buffer are nonlinear. Therefore, the monolithic problem cannot be solved by an MIP (Mixed Integer Programming) model.

The solution method entails a decomposition of the monolithic problem into two sub-problems that can be iteratively solved in order to provide a good estimation of the optimal solution. The problem is decomposed into two sub-problems: 1) disassembly sequence of components and assignment of the disassembly tasks to several workstations, and 2) inter-departure time analysis and buffer allocation problem. The first problem is solved by an MIP model and the second problem is solved by the heuristic algorithm based on the decomposition technique which evaluates long lines performance measures. The two sub-problems are solved iteratively by an iterative algorithm (Figure 1) in order to obtain the optimal or near optimal solution.

Validation of the solution method

Due to the division of the monolithic problem into sub-problems, some feasible solutions are neglected. Therefore, for validation of the obtained solution, Extensive Search Method (ESM) is developed. ESM generates all the feasible solutions and provides the optimal solution on the basis of the maximum profit value. For the implementation of the validation methodology, ModeFrontier software is used which is a powerful software for design optimization (Figure 2).

Conclusions

The main achievements and outcomes of this work can be summed up as follows:

1) An innovative method for optimization of the manual disassembly line design, which integrates several critical domains of the disassembly systems. These domains are categorized into disassembly tasks sequencing, depth of disassembly, workstations configuration and buffer allocation.

2) A new method which jointly optimizes the disassembly sequence path, depth of disassembly and required number of workstations and buffer capacities.

3) An Extensive Search Method (ESM) is developed which validates the accuracy of the solution achieved from the two-step method. The high accuracy of the two-step method is validated by several experiments.

PASSIVE AND ACTIVE VIBRATION CONTROL METHODS FOR THE PROTECTION OF CULTURAL HERITAGE

Ali Siami

Supervisors: Prof. Alfredo Cigada, Prof. Hamid Reza Karimi

In this research, passive and active vibration control methods have been considered to protect objects of cultural heritage against ambient vibrations and earthquakes. The famous statue of Michelangelo Buonarroti Pieta Rondanini has been used as the target of different vibration control strategies. The performance of the proposed algorithms is checked by using the updated model of this structure and its base.

In the first step, the performance of the isolation system of the statue (Pieta Rondanini) has been evaluated and enhanced using passive vibration control methods. For this purpose, a multibody model in ADAMS software (Figure 1) has been built and the model has been updated based on the results of performed measurements on a marble copy of the statue. Furthermore, a mathematical model (multi-degree-of-freedom-model) for the isolator and the statue is developed. The isolator and the statue have been modeled by using a 5DOF model (Figure 2) and different forcing terms have been considered for the model. The response of the 5DOF model has been compared with the experimental results and the model has been updated based on the experimental results. According to the results of the updated MDOF model, we can evaluate the effect of different passive and active vibration control strategies on the isolator and we can improve the performance of the actual system using the results of modeling part. In addition, the effect of geometrical nonlinearities on the mathematical model has been checked. According to these models, the effect of various parameters on the results have been investigated.

To reduce the level of vibration transmitted to the statue, combination of inerter with TMD (TMDI) has been proposed. The effectiveness of the proposed method has been proven by checking the dynamic behavior of the updated MDOF model. In addition, by using two different numerical methods the optimal parameters of the passive device (TMDI) have been found by using two cost functions. The results of two different numerical methods are compared to be sure about the correctness of calculated results.

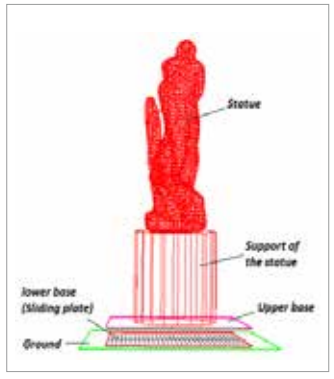


Fig. 1 - Multibody model of the isolating system.

In order to check the performance of the isolator, vibration monitoring results of the statue inside a museum in city center of Milan have been evaluated. Considering the updated MDOF model and the vibration monitoring results, comparison between results have been done. By using the results of this part, we have more information about performance of the isolation system in the operational condition.

Next step of this study is about using active vibration control methods to control vibration of the slender structure placed on the isolator system. The static output-feedback controller design in infinite and finite frequency domains have been applied on the 5DOF model of the isolator. This isolator can be used for protecting valuable objects against earthquakes and ambient vibrations. The output-feedback controller design considering constraints in time domain can provide powerful tool to apply various limitations in physical word such as maximum limit of the actuator's force and allowable levels for some outputs. In addition, using the weighting coefficients for the controlled output has been examined here. In order to evaluate the effectiveness of the proposed method some indexes are used. Furthermore, considering the formulation of the decentralized velocity-feedback controller design, the passive counterpart of an active configuration is presented in infinite frequency range. Using LMIs based formulation for controller design in infinite frequency domain and considering different constraints in time domain, the passive elements can be designed using the results of velocity output-feedback controller.

A scaled isolation system has been designed and manufactured according to the results of full-scale structure and as it has been presented in Figure 3 this scaled isolator has been plotted on a shaking table. This scaled structure has same dynamic behavior with the original isolation system of the statue. The impact of different parameters on the vibrational behavior of the isolation system has been investigated by using this scaled structure. In addition, it is possible to check the efficiency of some proposed methods and strategies by using the manufactured structure.

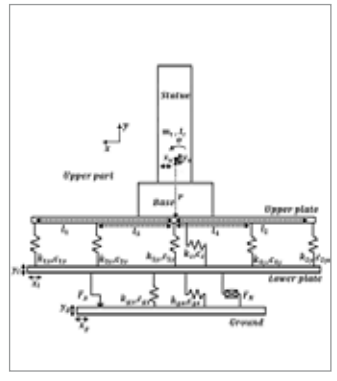


Fig. 2 - MDOF model for the statue and its isolation system.

According to the mentioned activities, the following results can be presented:

1) A multibody model in ADAMS has been developed. The effect of various parameters on the performance of the isolation system has been checked.
2) Using the results of ADAMS model, a scaled model has been designed.
3) A five degree of freedom model (5DOF) has been developed for the isolator and the parameters of this model tuned based on the experiments.
4) The 5DOF model with geometrical nonlinearity has been developed and the response of the nonlinear model compared to the linear one.
5) The monitoring results have been used in order to evaluate the results of the 5DOF model in working conditions.
6) TMDI for vibration reduction in the vertical direction has been proposed and the optimum parameters of TMDIs have been presented.
7) LMI based controller design method in infinite and finite ranges have been proposed to control the vibration of the structure.
8) Using the concept of structured velocity output-feedback controller design, a passive vibration control layout has been developed.
9) The designed scaled structure has been manufactured and it has been tested to evaluate some vibration control scenarios.
10) The effectiveness of TMDs has been demonstrated.
11) A type of inerter has been designed, manufactured and tested.

Fig. 3 - The configuration of accelerometers which have been used for the test.

DESIGN, DEVELOPMENT AND VALIDATION OF FE-BASED COMPOSITES FOR BIODEGRADABLE METALS APPLICATIONS

Malgorzata Sikora-Jasinska

Supervisors: Prof. Maurizio Vedani, Prof. Diego Mantovani

Conventional metallic biomaterials for medical applications are made of corrosion resistant materials and are designed to remain intact in a human body for a long time. They are characterized by appropriate mechanical properties (for searched applications) and excellent corrosion resistance. Although over the last decades permanent materials have been largely used, they have certain disadvantages. Since 2000, biodegradable metallic implants (BM) have been investigated as an alternative for permanent biomaterials. These materials have several advantages in specific applications over permanent implants used nowadays. BMs can adapt to the human body and eventually dissolve when no longer needed. Such materials would help patients suffering from fractures of long bones or limb length discrepancies. Further, the expenses of multiple procedures including implantation, removal, and re-implantation of the permanent implant could be avoided. Another example are metallic stents, used for millions of people to treat blockages in the coronary artery. This small implant can cause an immune response that leads to the growth of scar tissue and the formation of blood clots. If blockages form again, the stent is difficult to be removed, thus additional stents must be implanted, and re-operation is needed. Using BM stents could minimize the risk of invasive procedures. BM stents as well as bone fixation implants have other advantages in pediatric applications showing the ability to adjust to the tissue growth.

To date, in the field of degradable metals, numerous studies on iron (Fe), magnesium (Mg) and zinc (Zn)-based alloys have been reported with efforts on tailoring mechanical and corrosion behavior to address the requirements of degradable load and non-load bearing bone implants, cardiovascular stents, and other implantable medical devices such as biodegradable sutures and clips. From the mechanical point of view, Fe and its related alloys possess high strength and high ductility. On the other side, it is found that there are two main concerns regarding using Fe as a degradable material; first, it cannot be fully degraded over its service period, leaving a large portion of the stent intact even one year after implantation. More importantly, upon degradation, it produces a relatively large volume of potentially hazardous iron oxide products which might not be comfortably metabolized in the body. Mg has received a lot of attention as an attractive BM due to its excellent biocompatibility and low thrombogenicity. However, its rapid degradation in physiological environments leads to early undermining the mechanical integrity of the implant. During the last few years, Zn has been introduced to the biomedical community as a potential biodegradable implant material due to its prominent corrosion rate. However, its mechanical properties still need to be significantly improved for load-bearing implants applications. Fe-based alloys have shown a potential as a degradable material for biomedical applications. Nevertheless, the slow corrosion rate limits their performance as a biodegradable implant. One approach to control and modify their corrosion properties is the reinforcement addition, to create metal matrix composites in which the second phase is aimed at tuning not only the mechanical properties but also the corrosion mode and rate in a physiological environment.

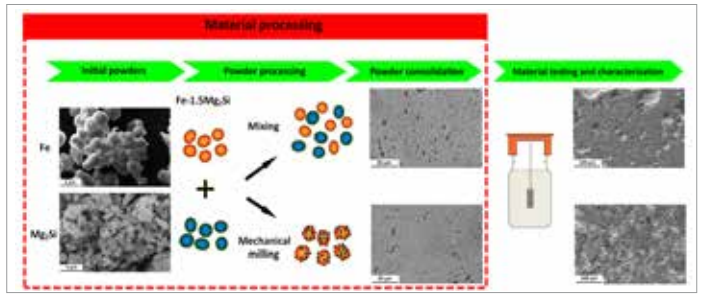


Fig. 1 -Scheme showing manufacturing process and corrosion testing procedure for Fe/Mg2Si composites

This project presents an original and thorough contribution on a very pertinent topic, the design, development, and validation of a new Fe/Mg_2Si composites prepared powder metallurgy. The initial powders were prepared by different combinations of mixing and high energy ball milling processes and finally consolidated by hot rolling as shown in Fig. 1. Mechanical properties, microstructural features, as well as the corrosion performance, were extensively investigated in relation to the reinforcement size and distribution.

The composites made of small size reinforcement particles showed a general increase in tensile strength. For instance, high energy ball milled samples exhibited higher strength (YS = 523 MPa, UTS = 630 MPa) while having the lower ductility (around 4%).

A fundamental understanding of corrosion initiation, protective film formation, and growth on Fe-based materials and leads to a design of smarter and surface responsive biomaterials with modulable degradation rates, at distinct stages of the corrosion process. The presence of the reinforcement particles played a crucial role in the susceptibility of Fe-based composites to localized corrosion attack. The corrosion initiation and its development were systematically monitored. Electrochemical measurements and static immersion tests implied that the introduction of Mg_2Si particles could accelerate the corrosion rate of Fe. It was confirmed that the size and distribution of the reinforcement influenced considerably the uniformity of the corrosion attack. The predominant localized pitting corrosion in Fe/Mg_2Si prepared by mixing was replaced by a more uniform pattern found in samples produced by mechanical milling. Further, it was found that Mg_2Si plays a significant role in the composition and stability of the protective films formed during the static corrosion experiments. Fe/Mg_2Si showed a higher corrosion rates compared to that of pure Fe at all stages of the corrosion experiment (1, 10, 20, 50 and 100 days). However, the release of Fe ions into the solution at later stages of the experiment was limited due to the barrier effect of the insoluble deposit. The final degradation products varied with the substrate chemical composition and microstructure. In case of pure Fe, low solubility ($Fe_3(PO_4)_2$) covered the entire surface, while Fe/Mg_2Si exhibited the presence of carbonates at the latest stages of the test. The study on the long-term corrosion behavior of powder metallurgy pure Fe and Fe/Mg_2Si composites provided a basis about the processes of protective films formation in physiological media, enabling detailed identification of their characteristic features (Fig.2). The details about the degradation behaviour during long-term exposure times to the physiological environment highlighted in this work add a new knowledge on corrosion mechanism of degradable implant materials. In particular, the ability to tune mechanical and corrosion behavior of the composites as a function of reinforcement properties and manufacturing method was experimentally verified, highlighting the microstructure-corrosion property relationship.

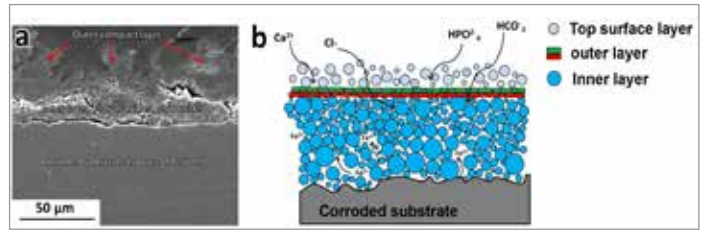


Fig. 2 - a) Cross section of pure Fe after 100 days of immersion test showing the layered structure of protective films formed during degradation b) schematic showing characteristic features of the degradation deposit

CHARACTERIZATION OF METALLIC ALLOYS FOR OIL & GAS APPLICATIONS

Francesca Tavasci - Supervisor: Prof. Barbara Rivolta

The Oil & Gas field is an industrial sector characterized by high-demanding applications, exposed to severe service conditions: the presence of high loads in corrosive environment is often worsen by low working temperature. It means that a material has to be characterized by multiple properties to be applied in this particular field: high tensile properties together with excellent corrosion resistance are desired. Moreover, low temperature toughness is required, for avoiding catastrophic failure due to brittle material behaviour induced by the low in-field temperature. Among all the commercial alloys, Duplex Stainless Steels (DSS) and Nickel super alloys play a major role in many engineering fields and especially in the Oil & Gas industry, being the best compromise between mechanical and corrosion resistance and characterized by low temperature toughness. The great potentialities of these alloys hide a great complexity: well-balanced chemical compositions, heat treatment parameters with narrow ranges, proper high temperature deformation processes are key elements for getting a component with all the desired properties. In this PhD work, both DSS and Nickel super alloys have been studied. DSS represent the major research field. Their properties have been investigated with a classical experimental research approach for reaching the main target of improving their low temperature toughness, given the actual trend of the Oil & Gas market of exploiting all the available natural resources, even the Poles ones. A high-Ni F55 steel of a forged bar has been considered for improving the material toughness. Studying the tensile and toughness properties, a complete material characterization has been performed: not only the effects of the chemical composition, of the heat treatment parameters and of the high temperature deformation process on the microstructure and on the tensile and toughness properties have been analysed, but also the main precipitation phenomena this material is very prone to. All the experimental, theoretical and numerical activities have been performed for addressing the following objectives:

improvement of the F55 grade toughness for extending its low temperature applicability field until -80°C, without worsening its tensile properties;

studying of the fracture mechanisms of the F55 grade by crack path and fracture surface morphology analyses;

characterization of the main high temperature precipitation phenomena the F55 grade is very prone to, not only by traditional aging treatments in the laboratory furnace but also by dilatometry.

In detail, Chapter 2 of the thesis studies the influence of Nickel on the A/F ratio and the mechanical properties in case of ideal quenching. Chapter 3 investigates the influence of the cooling rate on the impact toughness during quenching from the solution temperature. The high temperature precipitation phenomena are discussed in Chapter 4. The crack path, fracture surface and fracture toughness analyses are presented in Chapter 5. The main obtained results are:

1) high-Ni amounts in the chemical composition of the F55 grade are beneficial for the material, which has a good impact toughness even at -80°C, if the solution temperature is properly chosen and the cooling rate is sufficiently high for avoiding precipitation phenomena. Such result is industrially limited by the poor material conductivity, but a higher Nickel amount assures bigger margin on the material toughness requirements.
2) The crack predominantly propagates in the ferritic matrix (70÷80% of the total crack path), despite of the almost perfect equilibrium between the two phases, suggesting that the material toughness is mainly determined by the ferrite behavior.
3) The precipitation of secondary phases during isothermal aging at 980°C starts within 5 minutes. After 10 minutes soaking at 980°C, σ-phase (by dilatometry: activation energy of 280 kJ mol^{-1}) is present in the microstructure of the F55 steel.

Furthermore, by elaborating the impact tests data, a linear dependence of the material impact toughness on both the A/F ratio and the cooling rate has been identified and some parameters for predicting the material impact behaviour prior to testing have been proposed. Finally, considering the relationships between *bar diameter-cooling rate*, *cooling rate-austenite amount* and *austenite amount-solution temperature*, it was possible to directly relate the bar diameter to the required solution temperature for satisfying the actual standard limits of 45J at -46°C as impact toughness, in a given bar position. Nickel super alloys represent the minor research field and have been studied starting from a specific application: metallic gaskets in 625 alloy, produced by forging process, the most common production process for this component, and by centrifugal casting process, the only casting technology admitted by the API standard to produce metallic gaskets. For assuring a proper sealing condition, a maximum hardness of 180 HB is required by the standard. In this research, besides testing the material hardness and its corrosion behaviour and investigating the homogeneity of the gasket, the tensile and compression behaviour of this alloy has been characterized, as well as the main detected secondary phases.

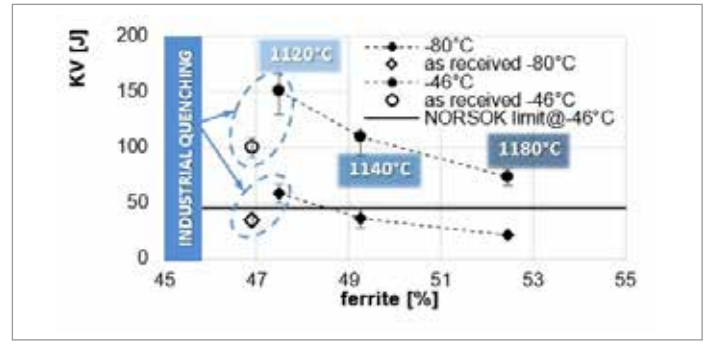


Fig. 1 - Impact toughness at -46°C and -80°C as function of the ferrite amount in the room temperature microstructure of a high-Ni F55 steel.

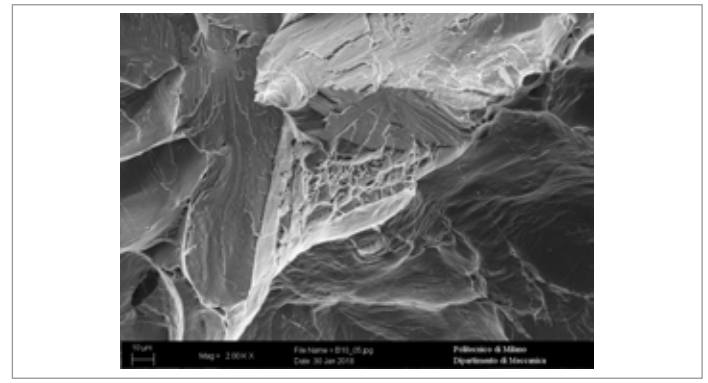


Fig. 2 - Fracture surface of a Charpy specimen at the SEM.

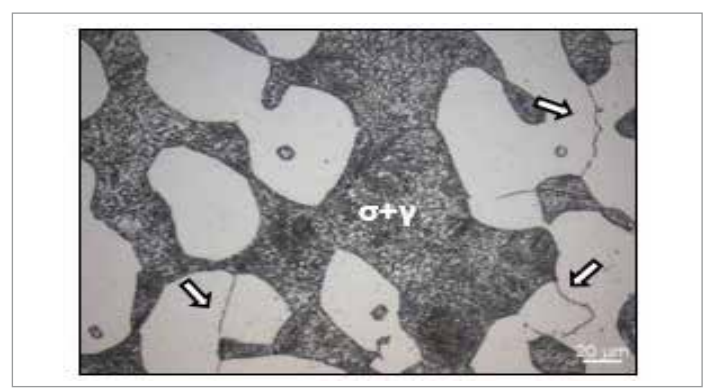


Fig. 3 - Microstructure of the F55 steel after dilatometric test.