



Chair:
Prof. Daniele Rocchi

DOCTORAL PROGRAM IN MECHANICAL ENGINEERING

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 7th in the world according to QS World University Rankings (Mechanical, Aeronautical & Manufacturing Engineering 2019).

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. 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 particular, our candidates have access to a series of research seminars delivered monthly by international top level faculty (Mecc PhD Lectures) and to full courses provided by European and non European academic experts leading to the obtainment of at least 20 ECTS. They also experience in-depth research, lab activities 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. These skills are well appreciated in the industrial field and make their scientific profiles suitable for prestigious positions at national and international level.

In the following pages 21 abstracts belonging to PhDs of the 29th (1), 30th (13) and 31st (6) doctoral cycles (defended in 2018 and 2019) 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%.

Nearly 100% 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. 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.

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, Vehicle Dynamics, 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 Technical 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), ETH Zurich (Cotutelle), University of Illinois at Urbana Champaign (Cotutelle), Laval University (Double PhD), EAFIT (Cotutelle), Qatar University (Double PhD), AGH - Akademia Górniczo-Hutnicza (Cotutelle), NTNU (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).

In 2018 20% of our candidates spent a total of 75 months abroad in European and international

universities and research centres. Incoming Visiting PhDs were overall 11, from 6 different countries (mostly extra UE).

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MECHATRONIC DESIGN AND OPTIMIZATION OF NEW MEMS LOAD SENSORS

Mohammad Abbasi Gavarti - Supervisor: Prof. Francesco Braghin

The growth of the Internet of Things (IoT), electronic consumers, wearable devices, advanced products for health diagnoses, and other applications have pulled up demand for sensors with advanced sensing capabilities that can fit into tight spaces, have high accuracy as well as low power consumption. The reasons behind this continuous interest, especially on micro mechanical applications, is principally based on economical motivations. Mass production technologies typical of integrated circuits industry, and in particular MEMS manufacturing processes can be implemented to develop such devices ensuring low cost and large scales. In other words, the production unit of these devices, called wafer, can contain thousands of identical chips. Among the existing phenomena that are capable of correlating the mechanical field to the electrical one, piezoresistivity is the most suitable for many applications as it can fulfill the requirements behind most of them. In fact, piezoresistive sensors, can provide large and stable outputs, maintaining mechanical strength and

stiffness. These sensors are characterized by high sensitivity and stability, they are small, with low power consumption and can be easily implemented in harsh environments. In recent years, silicon piezoresistive pressure and force sensors have been interested by a constant growth in several applications and environments. In parallel, the need for higher integration and value-added electronics is increasing the need for sensors able to perform advanced measurements with multiple sensing functions. As a result, researchers are focusing on developing piezoresistive force sensors able to perform multi-axial measurements and to sustain larger loads. The following work is the mechatronic design and optimization of novel force or stress sensors which aim to overcome the actual limitations of the state of the art for piezoresistive based load sensors, exploiting innovative approaches by using currently available technologies as well as packaging solutions. The outcome of the work leads to realization of hermetic scalable multi-axial load sensors which can withstand up to very high amount of loads within

harsh environments and can be used within different types of applications. This work has been carried out as an executive PhD through an industrial collaboration between Advanced System Technology & Special Projects department of STMicroelectronics together with Mechanical department of Politecnico di Milano under the supervision of Prof. Francesco Braghin. Within this research and development work, initially, as a general overview, a classification of different types of load sensors with their relative technologies together with existing packaging solutions are discussed. Moreover, considering piezoresistivity effect as the technological approach, several innovative design features which provide effective solutions to realize application-based stress sensors are also explained and their value-added contributions with respect to the state of the art outlined as well. As a micro-scale solution, the development of a general purpose MEMS multi-axial stress sensor, able to measure four different components of a stress field is presented.

The sensor has been designed and optimized in order to ensure best possible performance by using today available surface engineering solutions and technologies. Minimum possible size has been identified and the electronic layout proposed. Besides, sensor's behavior has been validated by FEM analysis in order to assess its characteristics and to provide numerical calibration. Moreover, as an application oriented approach a proper mechanical package with an innovative functionality is proposed to bring out a miniaturized high accuracy load cell which can withstand up to high amount of loads. Instead, as a macro-scale solution, the design and development of a low-cost in-plane stress sensor based on thick-film piezoresistivity technology is described. By combining already discussed innovative features, this sensor is able to measure the axial and in plane components of stress. Moreover, this sensor is hermetic and robust for long-term measurements which makes it a proper solution to be merged inside concrete structures with the purpose of doing structural health

monitoring. The design of in-plane stress sensor as well as its performance have been optimized and validated by FEM analysis. On top of that, a series of prototypes were produced and tested in laboratory by means of compression tests, imposing different boundary conditions and materials to assess the working concept of the sensor. Furthermore, some sensors have been merged inside concrete samples to verify their performance in terms of load measurement and their long-term quality interaction within concrete materials. Finally, an array of these sensors has been installed in tunnel segments and used to assess the behavior of these segments under static and cyclic loading within laboratory conditions. The reported results confirm the targets of the design: the sensors were capable of identifying internal loads of the structure as well as of local imperfections.

ALIGNMENT AND INTEGRATION OF OPTICAL SYSTEMS BASED ON ADVANCED METROLOGY

Matteo Aliverti - Supervisor: Prof. Bortolino Saggin

Looking through the optical elements while mounting them has always been the most typical method for the alignment of optical system in the astronomical field. In the last 150 years, the invention of different instruments like the alignment telescope, the interferometer, and the LASER strongly improved the alignment accuracy allowing for the design of better telescopes and instruments. In the last decades astronomical scientists, on the other side, are pushing optical and mechanical engineers towards instruments with higher and higher performances. The evolution of the spectrographs used to discover and study exoplanets with the radial velocity method is a good benchmark to show this evolution. The first one, ELODIE, was built in 1993 in France and could easily be mounted, aligned and verified on a small optical bench. Thirteen years later, the development of ESPRESSO, an ultra-high resolution spectrograph now installed across the whole Very Large Telescopes facility began. Due to the tight requirements in terms of long-term stability, the typical optomechanical mounts with traditional push-pull systems were not anymore a feasible solution and the use of stiff optical supports screwed to the optical

benches was identified as a possible solution. The aim of this thesis has been the evaluation of this method's viability proposing a mechanical design and an alignment procedure able to guarantee the desired performances in terms of mechanical stability, optical quality, alignment time, and MTTR. Those requirements lead to a new approach based on the CMM characterization of optical elements and semi-kinematic interface adjustments over the 6 degrees of freedom using calibrated shims. The first step consisted in the test of different references with different measurement machines. Once a method with submicron repeatability has been found, different methods for the positioning of the elements have been investigated in both vertical and horizontal direction. The most repeatable methods had a repeatability of about $\pm 2.5\mu\text{m}$ in vertical direction and about $\pm 5\mu\text{m}$ in horizontal direction. The prediction of the CMM accuracy is of paramount importance to understand if the method is feasible for a specific optical system. The CMM uncertainty has been divided in 3 parts: random, bias, and temperature effect and a series of tests have been performed to

discover the different sources of uncertainty. The outcome has been a software able to estimate the alignment uncertainty of a "small lenses optical system" using the information obtained. Said software receives as input the optical characteristic of each element (position, direction, shape, type and Numerical Aperture) and the alignment strategy (number of points acquired, expected alignment time and stylus used) and give as output the 2σ expected position of each element and its effect in term of defocus, decentring and focal plane tilt. A dummy optical system has been developed and aligned to check the whole alignment workflow and to validate the simulation software using an interferometer (see Figure 1). Together with the accuracy, the optical quality of the system is function of the digs

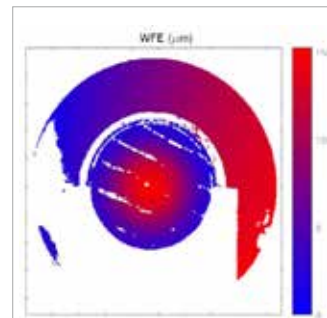


Fig. 1 - Interferometric measurements of M2 and L1 of the dummy system.

generated by the contact between the probing system of the CMM and the optical elements. Those digs could potentially modify the coatings or the substrates decreasing the throughput of the optics and deviate the rays (geometric scattering). For this reason the contact pressure estimation due to the CMM tip has been done in order to evaluate the damage. Two theoretical models have been developed to estimate the contact forces at low and high measurement speed considering the mechanical structure of the probe. A series of tests gave force values spanning between 20mN and 3700mN and allowed to identify the most important variables which include measuring speed, CMM axis involved, gravity vector direction, length of the stylus, and measuring direction with

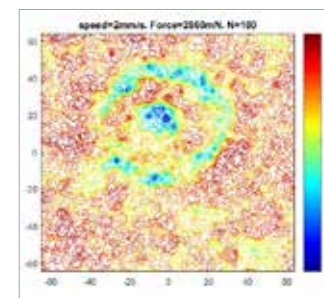


Fig. 2 - Damage on Inconel coating/borosilicate substrate with a central hertzian damage and the maximum sliding ring.

respect to the trigger with the last two playing a major role. The measurements obtained have then been used to estimate the parameters of the models that were then able to describe the actual behaviour of the machine. The last part has been performed to relate the pressure applied to the optical surfaces. Even if different theoretical models for multilayer coatings are available in the literature, literature experimental tests also show a low accuracy of those predictions. For this reason, different samples have been tested to obtain some general rule. The main families investigated are uncoated and coated metallic and glass substrates with metallic and dielectric coatings in the UV, VIS, and IR range. Different results have been observed using a Micro Finishing Topographer: a Hertzian behaviour, a deformation of the surfaces in the zones of maximum sliding, and micro pitting. In the Hertzian case, the damages seen well followed the theoretical predictions based on the known materials. When the materials of the coatings were unknown, an equivalent material has been defined to describe the element's behaviour. The damages appearing in the maximum sliding zone (see Figure 2) were related

to a displacement of the coating due to contact fatigue and they were usually characterized by a low amplitude. The micro pitting was a rare condition and appeared as a small displacement of the coating due to contact fatigue. Those pits usually had a diameter of a few microns and a depth/height of less than 10 nm. The obtained results have been used to estimate the optical effect in terms of throughput loss and geometrical ray deviation after a certain number of measurement/alignment runs. At the end of this thesis work, three complementary softwares have been developed: one of them is used to estimate the accuracy of alignment while performing it with a CMM. The second one is used to estimate the maximum forces and pressures applied to the optical surfaces during the alignment following the strategy defined. The third one estimates the effect on the optical elements in terms of throughput loss and ray deviation. Using these tools, the optimum strategy can be defined and it will appear as a compromise between accuracy and damages.

ON OBJECT RECOGNITION FOR INDUSTRIAL AUGMENTED REALITY

Juan Carlos Arbeláez

Supervisors: Prof Roberto Viganò & Prof. Gilberto Osorio

Like natural systems, man-made systems evolve to become more complex over time. Some reasons are market pressure, an increase of functionality, and adaptability to an already complex environment, among others. Therefore, workers face fast-changing and challenging tasks along with all the product lifecycle that reach the human cognitive limits. Although nowadays some operations are automated, many of them still need to be carried out by humans because of their complexity. In addition to management strategies and design for X, Industrial Augmented Reality (IAR) has proven to potentially benefit activities such as maintenance, assembly, manufacturing, and repair, among others. It is also supposed to upgrade the manufacturing processes by improving it, simplifying decision-making activities, reducing time and user movements, diminishing errors, and decreasing mental and physical effort.

Nevertheless, IAR has not succeeded in breaking out of the laboratories and establishing itself as a strong solution in the industry, mainly because technical and interaction components are far from ideal. Its advance is limited by its enabling technologies. One

of its biggest challenges are the methods for understanding the surroundings considering the different domain variables that affect IAR implementations.

Thus, inspired by some systematical methodologies proposing that, for any problem solving activity, it is required to define the characteristics that constrain the problem and the needs to be satisfied, a general frame of IAR was proposed through the identification of Domain Variables (DV), that are relevant characteristics of the industrial process in the previous Augmented Reality (AR) applications. These DV regard the user, parts, environment, and task that have an impact on the technical implementation and user performance and perception.

Five main processes were found to be influenced by the DV in industrial applications. They correspond to surrounding understanding, user understanding, system, user, and interfaces. The distribution of the different DV that influence the IAR processes found in this research are shown in Fig. 1.

Subsequently, a detailed analysis of the influence of the DV on

technical implementations related to the processes intended to understand the surroundings was performed. The results of this analysis suggest that the DV influence the technical process in two ways. The first one is that they define the boundaries in the characteristics of the technology, and the second one is that they cause some issues in the process of understanding the surroundings.

Further, an automatic method for creating synthetic datasets using solely the 3D model of the parts was proposed. It is hypothesized that the proposed variables are the main source of visual variations of an object in this context. Thus, the proposed method is derived from physically

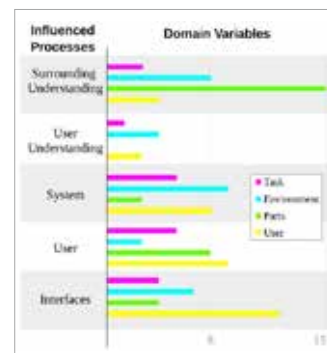


Fig. 1 - Histogram of DV that influence each one of the IAR processes

recreated light-matter interactions of this relevant variables. This method is aimed to create fully labeled datasets for training and testing surrounding understanding algorithms. An example of the produced samples are shown in Figure 2.

Finally, an ablation study was performed using Convolutional Neural Network for Domain Adaptation with the proposed method in an object classification problem. Two cases were evaluated: a particular industrial case, and a general classification problem (using classes of ImageNet, examples shown in Fig. 2).

Results suggest that fine-tuning



Fig. 2 - Example of samples produced with the proposed method used as source domain (left). Target domain samples taken from ImageNet (right).

models with the proposed method reach comparable performance (no statistical difference) than models trained with photos (Fig. 3). These results validate the proposed method as a viable alternative for training surrounding understanding algorithms applied to industrial cases.

Additionally, the results found support the use of the proposed method as valid option to train CNN models in the vision task of image classification. Where its use could reduce the burden of implementation and development of IAR applications. By improvements of the current method, it could be applied to other cases where the accuracy is more significant.

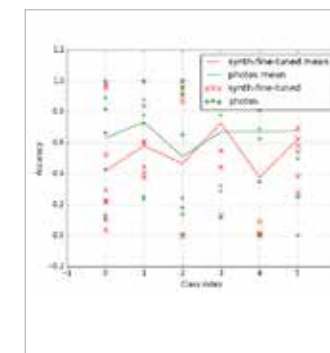


Fig. 3 - Distribution of the accuracies per class of the models fine tuned with synthetic data (red) and models trained with photos (green).

INFLUENCE OF POWDER AND PROCESS PARAMETERS ON SLM FINAL PART PROPERTIES

Stefania Cacace - Supervisor: Quirico Semeraro

Selective Laser Melting (SLM) is a new manufacturing process allowing to build parts directly from CAD models using a layer-by-layer approach. This technology is fundamentally different from traditional machining, where material is removed to obtain the final part. Additive Manufacturing attracted attention in the last decade due to its several ad-vantages in respect to traditional processes, such as free-design and reduced lead times. Due to the increased reliability of the process, its applications are shifting toward aerospace and automotive industries, where quality assessment requirements are strict especially for structural parts. As a consequence, a growing interest on the qualification aspects of SLM parts is of fundamental importance for a wider spread of the technology. In this thesis three topics related to quality assessment of SLM parts are tackled. The first is the relationship between Fluence and final part properties; Fluence is defined as the amount of energy delivered to the powder bed and it depends directly on the process parameters. In particular, the effectiveness of Fluence as indicator for densification is studied using a purposely design of the experiment based on a V-optimal approach.

From literature it is known that the trend between Fluence and part density is the one depicted in Figure 1, however the same Fluence value can be reached using different combination of process parameters. So, the aim of the study was to verify if there exist a region of the parameters where, maintaining the same level of Fluence, part properties do not change. It was demonstrated that in a steady region of the parameters, Fluence is able to predict density and tensile properties with an increased accuracy in respect to individual process parameters. This approach was used to identify new processing conditions with enhanced productivity. The experimental procedure was applied to two materials: Maraging steel and aluminum alloy A357. Secondly, the influence of the atomization process (gas and water atomization, Figure 2) for stainless steel powders was

studied using two particle size distributions and two levels of layer thickness. From an industrial point of view, this research was aimed at investigating the possibility to produce SLM parts using less expensive water atomized powders. As a matter of fact, the industrial practice is to use gas atomized powders as raw material of the process, however the effective advantage of this production process is still argued. An experimental campaign was designed to study the differences in processability of stainless steel water and gas atomized powders using an industrial SLM system. It was found that when changing layer thickness, Fluence is not a reliable index. Despite the differences in terms of shape and chemical composition, the two atomization processes were not found statistically different. The best processing condition was found using small fractions (15-60 μm) and small layer thickness

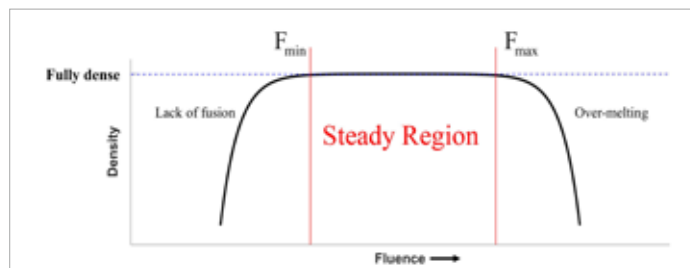


Fig. 1 - Theoretical trend between part density and Fluence.

(50 μm); using these parameters, gas atomization outperformed water atomization. Despite the difference in mean density, tensile properties of water and gas atomized powders showed the same static properties in terms of ultimate tensile strength and elongation. Finally, the relationship between the porosity structure, acquired through X-ray Computed Tomography, and tensile properties was studied. XCT allows to identify the internal structure of

a part without cutting it, so it is possible to identify pores, cracks as well as their position, size and shape. In this research, porosity structures at different processing conditions were qualitatively analyzed and discussed (Figure 3). The influence of process parameters on the porosity structure was studied and an ANOVA analysis is carried out to find optimal processing maps. An empirical relationship between porosity structure and elongation

was obtained which could be used to predict mechanical properties starting from the volume of pores found in a SLM part. It was found that the driver for elongation is the layer with the maximum porosity, rather than the mean density.

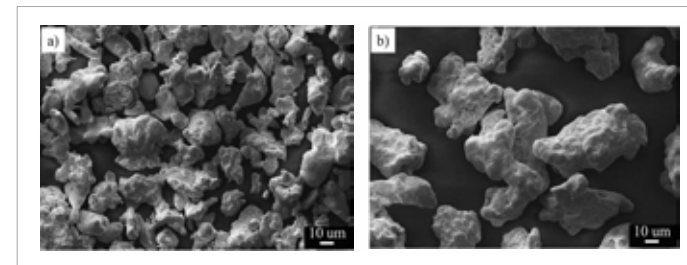


Fig. 2 - Stainless steel powders produced with different atomization processes: a) water atomization, b) gas atomization

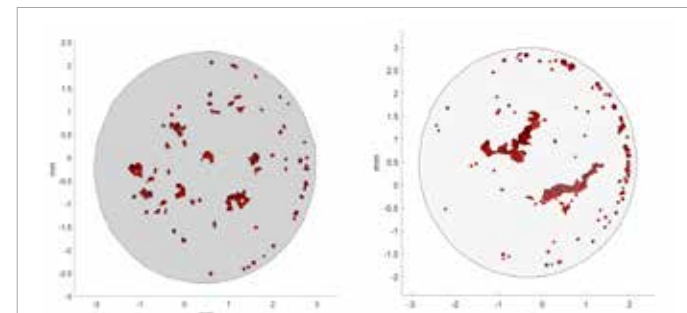


Fig. 3 - Different porosity structures of selected slices in tensile specimens.

CHARACTERIZATION AND COHESIVE MODELLING OF A STRUCTURAL ADHESIVE FOR THE DESIGN OF A SOLAR PARABOLIC TROUGH COLLECTOR

Stefano Cardamone - Supervisor: Marco Giglio

Co-supervisor: Andrea Bernasconi

Adhesive bonding is being increasingly used in various engineering fields, especially in the context of lightweight design. However, predicting the failure of adhesives is still a challenge for engineers, who often prefer traditional mechanical connection methods (e.g. bolting, riveting and welding) for designing the most critical joints in structures. Stress singularities in adhesive joints make traditional stress-based approaches difficult to apply. Instead, failure approaches based on Fracture Mechanics concepts allow to predict the behaviour and the failure of adhesives by Cohesive Damage Models that are implemented in Finite Element codes, provided that parameters are experimentally identified. The subject of this research was an adhesively bonded large-scale structure: a Parabolic Trough Collector (PTC). This structure allows to reflect the sunlight by a parabolic surface and concentrate it into a receiver tube, raising the enthalpy of a working fluid that is used to generate electricity. Solar energy represents, together with other renewables, the desirable way to satisfy energy world demand without drawbacks related to CO₂ emissions. In recent years, Concentrating Solar Power (CSP) systems have

become cost-competitive and PTCs represent the most widespread collectors. A project developed by Politecnico di Milano and Massachusetts Institute of Technology (MIT) aimed to design a new type of PTC, in which most of the mechanical riveted and bolted connections of the structure with adhesive joints bonded with a two-component epoxy. The objective was ensuring high stiffness to the structure made of galvanized steel, also allowing for a significant reduction of weight and components, thus decreasing the energy demand for the collector tracking as well as manufacturing costs. In this work, parameters of Cohesive Damage Models were derived for the chosen epoxy to help the design of the PTC. Cohesive elements are based on softening relationship between

stresses and displacements, called Traction-Separation Laws (TSLs), between crack faces simulating a gradual degradation of material properties. Considering the brittle behaviour of the chosen epoxy, a triangular TSL was chosen, with three unknown independent parameters per loading mode. The critical strain energy release rates G_{IC} and G_{IIC} represent the most important cohesive parameters. In this work, they were evaluated performing the Double Cantilever Beam and the End Notched Flexure tests respectively (Fig.1). Conversely, the stiffness parameters e_i and the ultimate stresses σ_i were obtained by a numerical optimization using the commercial software Abaqus™ and Isight™ (Fig.2). All the cohesive parameters were evaluated at different temperatures, ranging from 25°C to 70°C. An

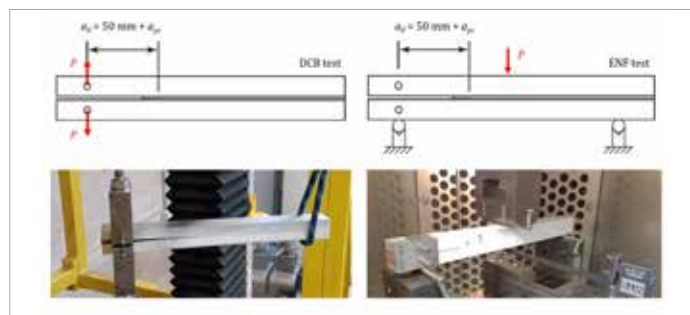


Fig. 1 -. Double Cantilever Beam (DCB) and End Notched Flexure (ENF) tests.

environmental chamber was used for the experimental tests. Another objective of the project was to build a full-scale prototype of the new PTC. A first pre-prototype analysis dealt with the evaluation of the performances of three adhesively bonded joints of the structure, compared to their corresponding riveted and

bolted versions. A second pre-prototype analysis involved Single-Lap Joint tests to evaluate several bonding conditions on galvanized adherends. The effectiveness of bonding this large structure was proved by the assembly and the experimental tests on the prototype. The biggest issue concerning

adhesives and large-scale structures is related to the time to wait before handling adhesive joints. A new hybrid joint, made of epoxy and Pressure-Sensitive Adhesive tape, was designed aiming to reduce the handling time. Tests proved that this hybrid joint allows for obtaining an almost instantaneous handling strength without compromising the performance of the joint. The TSLs of the epoxy were obtained at different temperatures allowing for simulating the mechanical behaviour and failure of the adhesive (Fig.3). These laws were successfully applied to Finite Element models of small- and full-scale joints. The tests on the prototype and the application of the Cohesive Models to the Finite Element model of the whole structure supported the choice of opting for adhesive bonding for the main joints of the PTC. Results proved that temperatures up to 70°C do not significantly affect efficiency and safety of the structure.

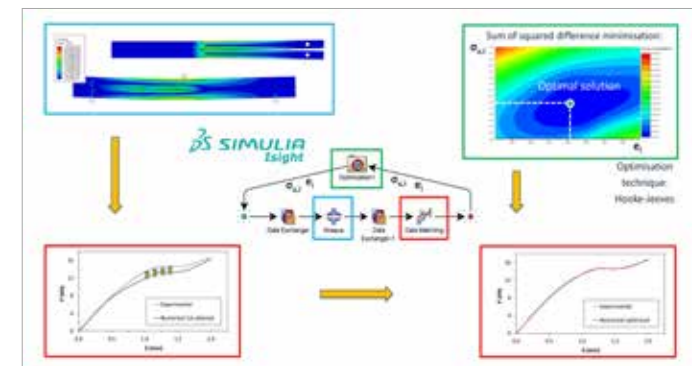


Fig. 2 -Workflow used for the cohesive parameters evaluation.

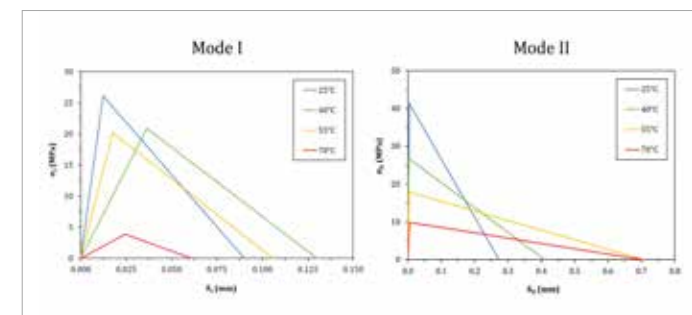


Fig. 3 - Mode I and Mode II Traction-Separation Laws at 25-40-55-70°C.

THERMO-MECHANICAL FINITE ELEMENT MODELING OF AISI316L STAINLESS STEEL SELECTIVE LASER MELTING

Claire Bruna-Rosso

Supervisors: Barbara Previtali, Maurizio Vedani

Selective Laser Melting (SLM) is one of the additive manufacturing process. It consists in printing a 3D geometry layer by layer, by melting metallic powder with a laser beam. It is a promising process, in particular for biomedical applications. Indeed, it offers large possibilities of personalization, enable the building of geometries otherwise not manufacturable, small series at no prohibitive costs. However, the rigorous norms and regulations that apply to the biomedical devices require an elevated level of knowledge and management of the manufacturing process for it to be fully qualified.

The novelty of the process coupled with technological difficulties related to its monitoring currently limit the experimental characterization of the SLM and restrains its wider industrial use. To address these issues, a predictive model able to reproduce the appearance of some of the defects that were identified as highly influential on the part functionality was developed. These defects are lack of fusion porosity, residual stress and geometrical distortions (i.e. the discrepancy between nominal and as-built geometries). In accordance with the phenomena leading to their formation, a

millimeter-scale approach was chosen. As commercial software were found not to be suitable, a thermo-mechanical finite element model was in-house developed, experimentally calibrated and validated. The global approach that was followed is illustrated figure 1.

The model is made of two sub-problems:

- The thermal one, that intends to compute the temperature field.
- The mechanical one that compute the stress and deformation due to the temperature variations in space and time

The thermal problem includes a phase change algorithm that allows to compute at each node of the mesh the quantity of melted or solidified material, which makes possible the tracking of

potential unwanted remaining powder. The mechanical problem uses a thermo-elasto-viscoplastic constitutive law, which allows the representation of temperature and plasticity effects on the material behavior and the part global equilibrium. The model was implemented using an open-source finite element library "deal.ii", implemented in C++. It allowed to use state of the art numerical techniques, thus offering good performances in terms of computing times. For instance, adaptive mesh refinement was included, which ensures an optimal number of elements by refining the mesh where high precision is needed and coarsening it elsewhere. The model was validated against experiment by comparing the molten pool geometries recorded with a high-speed camera with the

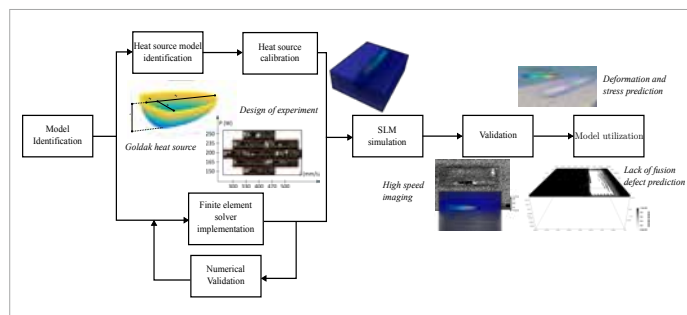


Fig. 1 - Methodological approach

ones produced by the FEM, and good agreement was found. Figure 2 shows the time evolution of the temperature, stress and plastic strain during the cooling time after processing of three tracks of 5mm length with SLM, with process parameters $P=200W$ and $v=500mm/s$. It shows how the stress mainly appears during the first instants of the cooling time. This is due to the fact that it is the period in which the highest cooling rates are experienced by the material, giving birth to significant thermal deformations. Moreover, the peaks values close to the track extremities. This is a consequence of the extinctions/ignitions of the laser in these areas that create high thermal gradients and cooling rates. Similar observations could be made for the plastic strain field. Lack of fusion defect, residual

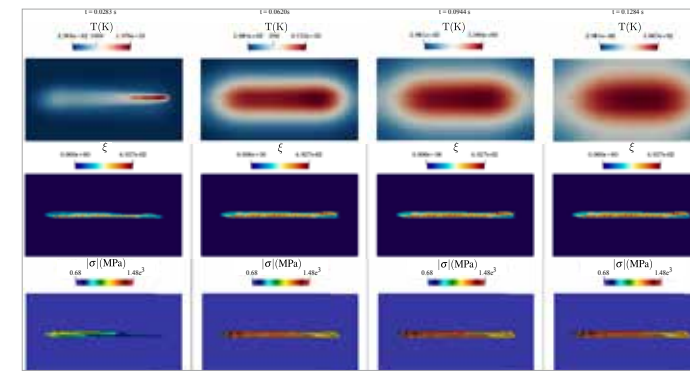


Fig. 2 -Temperature, Cauchy stress and plastic strain evolutions during the cooling phase

stress and plastic strain mechanisms of appearance were unveiled and analyzed. The transient behaviors of temperature, stress and strain fields suggest to use in-process adjustable parameters to comply with the variable situations to which the material is submitted. For instance, a gradual ignition/ extinction of the laser at each track beginning/end would diminish the detrimental effects of excessive heating/cooling rates. This is currently not implemented in any industrial hardware, but the results of the present study suggest to consider this improvement in the future generations of SLM machines. Comparison of the final geometry of the tracks with the nominal ones highlighted the influence of the molten pool dimensions

on geometrical errors. Figure 3 illustrates the mechanisms producing the oversizing experimentally observed in SLM produced parts. This effect is particularly detrimental for small geometries, since the errors is within the order of magnitude of the part nominal dimensions. The model, making possible the quantitative evaluation the melt pool dimensions can be used to perform a priori corrections. Simulations made us able to answer the research question by explaining the phenomena creating major defects and proposing innovative strategies to reduce them.

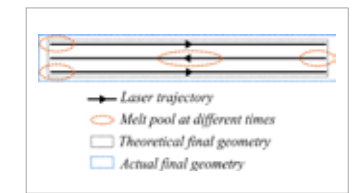


Fig. 3 - Geometrical error mechanism

DESIGN AND CHARACTERIZATION OF INNOVATIVE AL-7SI-MG CASTING ALLOYS WITH ER AND ZR ADDITIONS

Marco Colombo - Supervisor: Prof. Elisabetta Gariboldi

The more stringent requirements for fuel consumption optimization and efficiency increase for environmental reasons are constantly pushing industries and scientific institutions to develop stronger and more microstructurally stable Al alloys, to substitute steels and cast irons in vehicles.

A general-purpose Al alloy used in the transportation industry for structural applications is A356 (Al-7Si-0.4Mg). Literature review showed that microstructural characteristics and mechanical properties at room and high temperature of A356 are found to be strongly influenced by suitable additions of alloying elements. In particular, suitable additions of rare earth Er improved the room temperature mechanical properties of A356 alloy, due to the formation of $L1_2$ Al_3Er strengthening dispersoids.

Literature studies demonstrated that combined additions of Er and Zr to pure Al caused strong improvements in its mechanical properties and thermal resistance, due to the precipitation of $Al_3(Er, Zr)$ $L1_2$ strengthening and coarsening resistance dispersoids. Despite the promising effects of Er and Zr, the state of the art on this topic is limited and many questions have not been solved yet.

Thus, the present PhD research is intended to have both a scientific and an industrial relevance. From

a scientific point of view, this work is aimed at expanding the state of the art regarding the influences of Er and Zr on commercial Al-Si-Mg alloys. In particular, the focus is on characterizing, understanding and modelling the effects of Er and Zr additions on eutectic Si modification, on the age-hardening response and microstructural stability, on the mechanical behaviour (at room and high temperature) and, finally, on the corrosion resistance of Er- and Zr-containing alloys, based on A356. More specifically, in the first part of the work, the designed alloys were characterized from a microstructural point of view by means of optical microscope, SEM and STEM analyses and from a mechanical point of view at different temperature and after different exposure times at high temperatures.

From a microstructural point of view, additions of Er caused a modification of the eutectic Si morphology, which in the as-cast state passed from plate-like to fibrous. Further, the addition of Er hindered the formation of Fe-containing intermetallic compounds usually found in commercial Al-Si-Mg alloys. On the other hand, different classes of intermetallic compounds containing Er formed, according to the chemical composition of the alloy.

Further additions of Zr did not cause relevant modifications in the

eutectic Si morphology with respect to alloys with only Er. As intermetallic compounds are concerned, those already present in Er-containing alloys were slightly enriched in Zr. Additions of 0.59 wt.% Zr caused the formation of pro-peritectic (Al, Si)₃(Zr, Ti) intermetallic compounds which acted as inoculants for Al dendrites, changing their morphology from elongated to globular.

From a mechanical point of view, suitable Er and Zr additions increased the strength and ductility of A356 and its resistance to prolonged high temperature exposure. In particular, among the alloys containing only Er, additions of 0.3 wt.% of this element (named E3) resulted in the best combinations of ductility and strength, due to a modified eutectic morphology, a low amount of embrittling intermetallic compounds and the presence of Al_3Er coarsening-resistant strengthening dispersoids. Among the alloys containing Er and Zr, the one with 0.3 wt.% Er and 0.59 wt.% Zr additions (named EZ35) showed the best ductility and the highest mechanical properties, due to a modified eutectic morphology, relatively low amount of embrittling intermetallic compounds, globular morphology and $Al_3(Er, Zr)$ strengthening dispersoids. Considering the results obtained from tensile tests and preliminary

microstructural observations, A356, E3 and EZ35 were selected for the studies performed in the rest of the work.

The three alloys were studied by means of SEM micrographs on deep etched specimens subjected to different Solution Heat Treatment (SHT) times, in order to characterize the influence of high temperature thermal treatment on the evolution of eutectic Si morphology and on intermetallic compounds. The mechanisms underlying eutectic Si morphology evolution in the three alloys were identified and successfully modelled using thermodynamic and kinetic models. STEM micrographs were taken and DSC tests performed on samples in different thermal treatment conditions, in order to assess the influence of Er and Zr on the age hardening response of A356. In particular, it emerged that Al_3Er and $Al_3(Er, Zr)$ strengthening dispersoids precipitated during SHT, suggesting that conventional SHT could be optimized for modified alloys. Al_3Er and $Al_3(Er, Zr)$ also precipitated during subsequent aging. Finally, the presence of Er and Zr reduced the activation energy for precipitation of Mg- and Si-containing β'' and β' dispersoids.

To conclude the first part of the thesis, MatCalc simulation software was used and thermodynamic and kinetics models applied to a ternary Al-7Si-0.4Mg alloy, to study the influence of thermal treatment on the evolution of its microstructure and mechanical properties. Simulations started with the identification of the phases formed during solidification. Subsequently, the model alloy was subjected to 5h SHT at different temperatures,

in order to study the dissolution kinetics of intermetallic compounds and the ability of the software to describe the influence of temperature on the process. The model alloy was then subjected to quenching at different quenching rates and subsequently aged at 200 °C for 3h. Scope of this part of the analysis was to simulate the quench sensitivity of Al-7Si-0.4Mg alloy and the influence of quench rate on its mechanical property after aging. Simulated results were validated using experimental results from a commercial A356 alloy. Thermodynamic and kinetics models implemented in MatCalc can be used to effectively predict the influence of complex thermal treatments on the evolution of microstructure and mechanical properties of cast Al-Si-Mg alloys. The second part of the thesis was devoted to a characterization of the electrochemical properties of A356, E3 and EZ35 in 3.5 wt.% NaCl aqueous solution. Short- and long-term corrosion resistance were studied by means of potentiodynamic polarization tests, electrochemical impedance spectroscopy and microstructural characterization after different immersion times (1h, 1 day, 4 days, 1 week, 2 weeks and 4 weeks). Further, scanning Kelvin probe force microscopy was used to measure the electrochemical potential difference of intermetallic compounds with respect to Al, quantifying microgalvanic coupling. E3 was the alloy showing the best corrosion resistance, thanks to a relatively low amount of intermetallic compounds with a small electrochemical potential difference with respect to the matrix and to a

modified eutectic Si, which reduced microgalvanic coupling. On the other hand, the high electrochemical potential difference of intermetallic compounds in alloy A356 with respect to Al and the elongated morphology of eutectic Si induced a more intense microgalvanic coupling, reducing its corrosion resistance. The addition of Zr to the chemical composition of E3 reduced the corrosion resistance of EZ35. The higher amount of intermetallic compounds with slightly higher electrochemical potential difference with respect to Al and the globular morphology of Al dendrites were considered as responsible for the reduced corrosion resistance of the alloy. After a proper understanding of the influences of Er and Zr on the microstructural, mechanical and electrochemical characteristics of A356, alloys with suitable chemical composition could be proposed on an industrial scale, in order to improve the performances of commercially used Al-Si-Mg alloys and expand their applicability.

FORCE SENSORS AS SMART VEHICLE SUBSYSTEMS TO IMPROVE SAFETY IN INTELLIGENT TRANSPORT SYSTEMS (ITS)

Francesco Comolli

Supervisors: Prof. Gianpiero Mastinu, Prof. Massimiliano Gobbi

Safety is one of the most important requirements in the transportation world. The reduction of the number of road accidents is an always up-to-date argument. In the last decades, the number of fatalities was almost halved together with the related social costs, but still today the accidents number is impressive (1 million only in Europe in 2015). Increasing the road safety is an ethical challenge that could save human lives and reduce social expenditures.

In this thesis, two kinds of force sensors for detecting loads acting on vehicles have been developed and tested. The first family of sensors refers to intelligent wheels, able to measure three forces and three moments acting at the hub. The wheels are motorcycle type, particularly suited for future urban light vehicles. The second kind of sensor is a steering wheel, particularly suited for Advanced Driver Assistance Systems studies.

Starting from a Politecnico di Milano patent, the sensors have been developed up to actual production and professional employment. The development of the sensors focused primarily (but not only) on an optimization algorithm that was developed to define the best geometry for

optimal measuring performance. All of the sensor components have been designed with a 3D CAD modeller and verified by means of a Finite Element Analysis. The sensors have been instrumented with twelve strain gauges each and experimentally calibrated to obtain the best measuring performance. Finally, the force sensors have been experimentally tested and used on real vehicles, either motorcycles or cars.

Two different smart wheels for motorcycle have been developed, that allow the estimation of the contact forces between the motorcycle and the road (Figure 1). After the construction and the experimental calibration, the smart wheels have been used on a race motorcycle during a track test. The acquired data were used to derive combined load spectra with an innovative method. The

track is split in several well defined manoeuvre patterns, like the straight acceleration or braking, the acceleration or braking in exiting or entering a curve, the steady state turning, the curb hitting and the gear-shifting. New combined load spectra could be evaluated for the motorcycle, useful in the design phase of the new components.

The second force sensor developed is an innovative Instrumented Steering Wheel that measures the forces exerted by each hand of the driver (Figure 2). A carbon fibre reinforced composite structure is fitted with two original six-axis load cells (Figure 3). The carbon fibre reinforced structure has been modelled with a Finite Element method to verify the stress state and the eigen-frequencies. The load cells have been instrumented

with twelve strain gauges each and experimentally calibrated. Finally, the Instrumented Steering Wheel has been tested on a track. The vehicle passed by a kick-plate that induced over-steer and eventually spin if the driver did not react properly. The data from nine different drivers were acquired. In order to obtain the highest possible sensitivity, the inertial force contributions acting on the steering wheel structure have been compensated. Analysing the acquired data, some common driving behaviours among the drivers have been highlighted, either for a classic turning manoeuvre, or for an emergency manoeuvre. Moreover, forces variations have been noticed before the actual rotation of the steering wheel in the emergency manoeuvre, before the yaw acceleration. This occurrence could

be useful in tuning properly the ADAS to shorten the intervention time and increase safety. A new approach is presented to find new KPIs for the steering evaluation, analysing the different forces applied by the driver with the introduction of the ISW. Finding a complete correlation between the driver feeling and current objective indexes is typically difficult to achieve. Existing analysis techniques generate KPIs which are based on the vehicle and the steering dynamics magnitudes: lateral acceleration, steering torque, steering angle, etc. However, driver action is only partially captured by the resulting steering torque. The new KPI is defined as steering efficiency, defined as the ratio between the tangential steering forces and the total

forces. Moreover, the knowledge of the loads exerted by the driver could lead to a deeper knowledge of the steering behaviour: the loads applied by the driver could change with the vehicle response. The driver should be considered in the steering loop. Both of the two force sensors allow to improve the knowledge of vehicle interaction with the road and with the driver in order to increase safety in Intelligent Transport System framework.



Fig. 1 - Left: Rear Smart Motorcycle Wheel, Right: Front Smart Motorcycle Wheel



Fig. 2 - Instrumented Steering Wheel



Fig. 3 - Instrumented Steering Wheel Load Cell

MODELLING OF TRAIN-TRACK INTERACTION AT HIGH-FREQUENCIES AND ITS APPLICATION TO INVESTIGATE TRACK DEGRADATION PHENOMENA

Wenshan Fang – Supervisor: Stefano Bruni

High speed railway operation developed rapidly in many countries in the last decades. The demand of higher vehicle speed has led to increasing dynamic problems of interaction between vehicle and track interface, simulation tools for vehicle-track interaction therefore has been extensively investigated in the last 50 years and various vehicle-track interaction models have been developed and proved to deal satisfactorily with many dynamic problems arising at the wheel/rail interface. However, open problems still exist related to wheel-rail interaction in the high-frequency range and its relationship with wheelset and track flexibilities. Furthermore, the relationship between train-track interaction and track damage still needs to be investigated in full. In the state-of-art research on vehicle-track interaction in high frequency range, efforts has been made both on modelling of flexible wheelset/track and on more realistic wheel-rail contact. On the one hand, while the vehicle has been modelled as multi-body systems with the track as Euler-Bernoulli or Timoshenko beams in last decades, recent trends of vehicles modelling in high frequency considering flexible wheelset and tracks modelling in general finite element method.

On the other hand, to get a more realistic contact condition, efforts has been made by introducing a more complex contact model into the train-track interaction system. However, detailed 3D finite element wheelset/track model together with complex contact model for vehicle-track on-line dynamic analysis is still challenging due to the huge model size and large computational cost. This work therefore focuses on the development of a more accurate and efficient high-frequency numerical model of vehicle-track interaction to extend the valid frequency range of current vehicle-track interaction models and hence to support the investigation of track damage phenomena in high frequency range. The final results of this research will hopefully help to expand the valid frequency ranges of existed vehicle-track interaction models. In current work, investigation of wavelength-fixing mechanism of rail corrugation is chosen to be an application of the improved model, but the whole model proposed in this thesis can also be expected to deal with other wheel/rail interface problems in high frequency range, e.g. high level of noise and rolling contact fatigue. The PhD work proposed a high-frequency 3D numerical model of train-track interaction

to extend the valid frequency range of current vehicle-track interaction models and hence to support the investigation of track damage phenomena in high frequency range. There are two main achievements of this thesis: the first is developing of a new configuration of wheelset-track interaction modelling valid in a frequency range up to some kHz in time domain using 'Eulerian' modelling approach with non-Hertzian contact solution and investigating the influence of the structural deformations of a detailed train-track model on contact forces and other running behaviours. The second is making an application of the improved vehicle-track interaction model by identifying the relation between rail corrugation phenomenon and some parameters of the high-frequency train-track system. When modelling the 3D train-track interaction model, the usage of the 'Eulerian' approach and non-Hertzian contact assures modelling accuracy and efficiency simultaneously. The wheelset and the rail are modelled using 3D solid element, making it possible to describe structure flexibility for some kHz. For the wheelset model, an 'Eulerian' description makes the contact point a fixed spatial point and successfully includes the rotational effect using the rotating

'Eulerian' coordinate. For the track model, an 'Eulerian' description ensures the contact point fixed on the middle of the rail, thus makes it possible to describe the 3D finite element rail in a relatively short length. The wheel-rail contact is a newly proposed non-Hertzian EKP contact instead of traditional Hertzian contact. Curvature variation of the real wheel and rail profiles is taken into consideration, leading to non-elliptical contact patch and pressure distribution. The effect of structure flexibility on wheel-rail interaction is discussed by comparing running behaviours i.e. contact forces and structure vibration under certain wheel and rail defects using different model configuration. Wheelset flexibility shows remarkable influence on wheel-rail contact force for certain wheelset modes, especially on the lateral direction. Moreover, rotary modes caused by wheelset rotating may lead to higher dynamic ratio compared with non-rotating flexible wheelset model. Wheelset flexibility also influences the dynamic forces caused by a wheelflat defection, which can produce higher maximum contact forces and additional force peaks with different vehicle velocity. With different track options, the 3D 'Eulerian' track model shows a non-negligible effect on wheel-rail contact forces in high frequency range, especially on the lateral direction. Compared with continuous supported rail, rail with discrete support shows significant effect on contact forces in low- and mid-high frequency range. Vibration on different positions of the rail section also

shows remarkable differences between each other for the 3D 'Eulerian' track. Considering the computational cost, the Timoshenko beam track model can be used for interaction problems below 1 kHz, such as studying the effect of wheel flats and wheel out-of-roundness, while the 3D solid FE model with continuously supported rail may be applied in wheel-rail interaction problems concentrating on the high frequency range, such as high frequency rail-wheel noise generation. Overall, the results show that simulation results are highly sensitive to the wheelset and track model adopted.

Thanks to the detailed description of wheel/rail contact, the interaction model can be used to investigate the formation of short pitch corrugation on the rail head. In the case study of rail corrugation, the improved train-track model and the non-Hertzian contact model is applied to the short term train-track interaction part, while a wear model and a profile updating procedure is applied to achieve profile evolution as the long term damage mechanism part. Corrugation growth is analyzed from both the spatial history of wear depth accumulation and the global growth rate of railhead corrugation. Wheelset flexibility shows a remarkable influence on corrugation growth rate for wavelengths longer than 0.2m. Moreover, rotary modes caused by wheelset rotating may lead to an increase of corrugation at certain wavelength related to the mode frequency compared with non-rotating wheelset.

Track options can also influence corrugation growth of the railhead profile. Discrete rail support plays an important role on corrugation growth at several wavelengths, while the difference of corrugation growth rates between the Timoshenko beam discrete supported track and the 3D discrete supported track is less obvious. Finally, the corrugation growth rate using rotating flexible wheelset and 3D discrete supported track interaction model with different railpad stiffness is checked. It can be concluded that stiffer railpad leads to corrugation growth on longer wavelength. Moreover, the wavelengths with positive corrugation growth corresponding to stiff railpad condition are longer than the typical and soft railpad conditions, especially for the high rail side. The final results of this research help to expand the valid frequency ranges of existed train-track interaction models and to gain a better understanding of train-track dynamics and damage phenomena in high-frequency range.

NEW SMA BASED ARCHITECTURE FOR WIND TURBINE BLADE

Pouya Haghdoost

Supervisors: Prof.ssa Antonietta Lo Conte, Prof. Alberto Zasso

It is well known in today's engineering community that the wind turbines are going to play a major role in power generation through the next decade. Many steps toward this goal have been already taken and many other aspects are yet under further investigations. The total capacity of electricity generated by wind energy in the United States grew from 6.6 GW in 2004 to 61.9 GW in 2014. According to one scenario presented by U.S Department of Energy 20% of the U.S. electricity needs in 2030 are generated through wind energy. Following the advances of wind turbines for energy generation they are getting bigger and bigger in size, as bigger ones are more efficient. MHI Vestas V164 is a 9.5 MW turbine with 80 meters in length blades, which is now online, is the largest wind turbine ever built. This is a large increase from only 30 years ago, when 100kW turbines were prominent designs. While the more large-scale designs are being introduced, new challenges are also being reported. Gravity and inertia loads have started to dominate more than aerodynamic loads, blades are being more flexible and thus more sensitive to dynamic excitations. According to the mentioned challenges in the new blade designs, vibration

control of the blades is grabbing more attention. An efficient vibration control can increase the fatigue life of the blades and prevent long downtimes due to blade failures, all leading to economical and environmental and turn overs. The scope of this PhD project was to investigate the possibility of overcoming the excessive vibrations of the blade by proposing a SMA embedded architecture (Hybridized architecture) of wind turbine blade, which enables us to control the vibration by taking a passive strategy. The project was started by recognizing a suitable high damping material. Cu 85.35 Al 11.65 Mn 3 shape memory alloy, was cast and hotrolled successfully to thickness of 0.4-0.3 mm, which is the required thickness of the sheets to be embedded inside the SMA/GFRP hybrid composites. This is considered as an important achievement of this work, since usually Cu based alloys are brittle and fail in the rolling procedures. Instead the investigated material exhibits good ductility and through the optimized temperature and reduction percentage at each rolling pass it is possible to perform hotrolling up to desired values. The transformation temperatures, micro-structure

and damping of the material under question has also been investigated through dedicated experimental techniques. It is observed that the as hot rolled specimen have austenitic micro-structure and the martensitic structure can be obtained by performing heat treatment. Material's damping was investigated through cyclic tensile tests and high values comparing with other SMA compositions and also a high nonlinearity was observed. Effect of different heat treatments on damping was also investigated. It is concluded that a longer treatment results in higher damping of the material. The mechanisms involved in this was attributed to the higher interfaces inside the grains as confirmed by SEM micrographs. The martensite to austenite transition temperatures were also examined by performing DSC and it very high transition temperatures were observed which would guarantee the martensitic microstructure at the operating regime of a wind turbine blade. In order to provide the possibility of modelling non-linear damping of the investigated material in numerical simulations, a model has been developed based on hysteretic behaviour of the material under question. The

model is developed based on Masing's rules of hysteresis with some modifications to improve its accuracy. It was implemented in the UMAT interface of the Abaqus and was calibrated and validated with experimental cyclic tests which have been performed for the investigated material. The model provides a good accuracy for modelling the cyclic behaviour of the material and is much more accurate than the original Masing. Possibility to model non-linear damping in dynamic simulations in the time domain by implementing the model is confirmed. To assess the efficiency of using SMA/GFRP composites for damping issues, experimental tests were needed. To do so a hybrid SMA/GFRP composite plate was fabricated. This part of the project was started by fabricating to patterned SMA patch. The square patches were fabricated using a two directional hotrolling technique, which was followed by a laser cut for introducing the microholes on the patches which would guarantee the perfect bonding of the patch in a laminated composite with resin matrix and will avoid the delamination problem. The fabricated patches have been embedded in a GFRP laminated layup and were cured in dedicated press machine (Figure 1). A

simple plate only made of GFRP was also fabricated to be used as the reference for measuring the damping improvements. The damping of the hybridized plate has been measured in the free decay situation and the results were compared with the vibration of a simple GFRP plate with same geometries. It is proved that the hybridization is an effective approach to improve the damping of laminates. In one case a 53% improvement was observed. Based on the experiences in the previous parts, the embedding of patterned SMA sheets into a wind turbine blade structure in order to improve total system damping of the system was investigated. According the elastic energy concentration in different modal shapes of the blades, new hybridized architectures of the blades are proposed. To

simulate the amplitude-dependent damping of SMA material, the hysteresis behaviour of SMA in the martensitic state was replicated by implementing the developed model. Implicit dynamic simulation was performed on the proposed architectures. Free decay responses of proposed architectures were analysed, the damping ratios were compared and the optimized configuration is recognized. It is observed that the blade damping can be enhanced by embedding SMA sheets in the original layup, without significant changing the dynamic behaviour of the blades. In one of the proposed cases, the damping of the blade was improved by 30 percent.

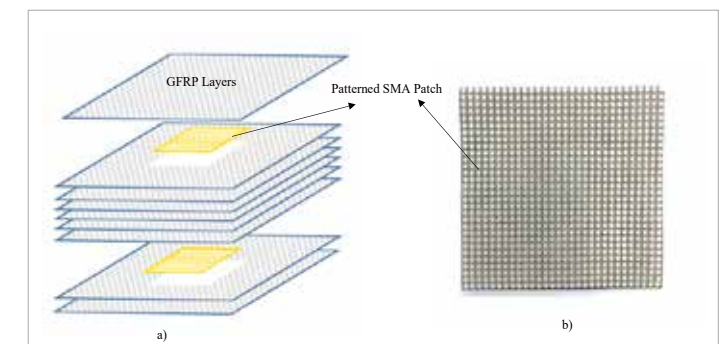


Fig. 1 - a) Architecture of hybrid SMA/GFRP plate. b) patterned SMA patch.

AN INTEGRATED APPROACH TOWARDS INCREASED ENERGY EFFICIENCY OF VEHICLE SUBSYSTEMS

Nikola Holjevac

Supervisors: Prof. Federico Cheli, Prof. Massimiliano Gobbi

Energy demand growth, environmental issues and future fuel availability are strongly influencing the global scenario and leading to deep changes in shaping future society. Transportation and in particular road mobility of passengers and goods play a major role in energy share frame, representing therefore a crucial field for important achievements towards energy savings. International committees and public agencies enacted several standards and regulations forcing automotive manufacturers to provide more energy efficient vehicles in fulfilment of pollutant and emission restrictions. The outbreak of the diesel scandal has put the automotive manufacturers even more on pressure requesting to promptly bring the energetic issue as a central topic in the vehicle's development phase and if necessary to even rethink the vehicle's architecture towards environmental friendly energy sources and therefore new technologies. The early concept design of a vehicle is becoming increasingly crucial to determine the success of a car. Broadening market competition, more stringent regulations and fast technological changes require a prompt

response from carmakers. Computer-Aided-Engineering (CAE) has emerged in recent years as the promising way to provide more efficient and cost-effective design procedures by also cutting development time and costs. Simulation models are increasingly adopted in the entire vehicle development and analysis flow, specific methods and tools are used according to the required accuracy, level of detail and computational cost. The possibility to rapidly assess the vehicle behavior through simulation has promoted the use of optimisation techniques

in vehicle design. The increasing system's complexity, especially with the introduction of new technologies, can be successfully tackled with optimisation methods to rapidly drive the design process to the best solutions. The modelling and simulation of the vehicle follows a bottom-up approach moving from the individual subsystems to the entire vehicle system. Specific mathematical and numerical approaches and tools are adopted and developed according to the individual subsystems and the required level of detail. The internal combustion engine model

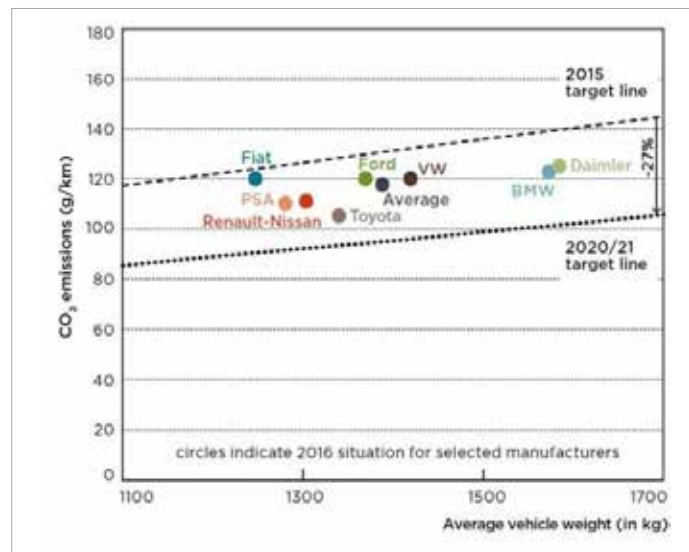


Fig. 1 - 2016 CO2 performance of key European passenger car manufacturers

combines the fluid dynamics results obtained from a 1D CFD model and an analytical formulation regarding the mechanics. The electrical system includes motor, inverter and battery. A 2D electromagnetic FEM model allows to analyse the complex behaviour of the motor while data from manufacturers datasheets, respectively Infineon and Panasonic, are used for the inverter and the battery model. The transmission model benefits from established formulations provided by FZG and SKF offering a detailed insight on the energy losses. The vehicle system is then

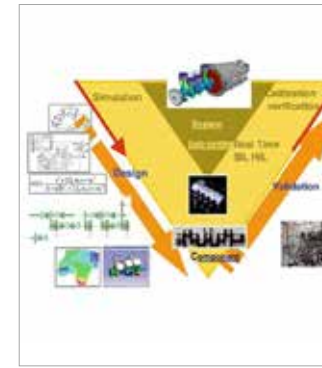


Fig. 2 -Adoption of simulation-based approach in the product development

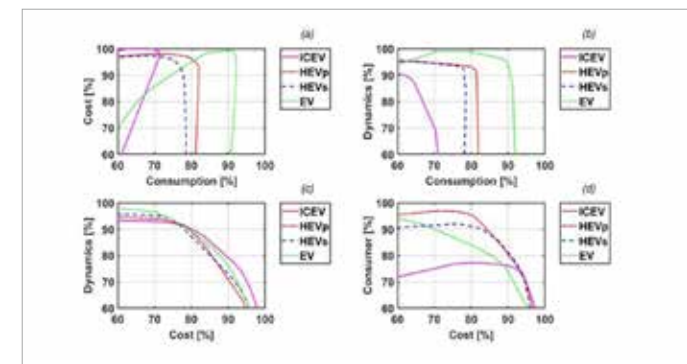


Fig. 3 - Objectives frontiers: cost-consumption (a), dynamics-consumption (b), dynamics-cost (c) and consumer-cost (d)

described through a lumped parameter model coupling the various subsystems with the appropriate controllers and allowing to solve a multi-physics problem involving thermal, electrical and mechanical aspects.

The results allow a comparison between the different powertrain architectures for all wheel drive (AWD) vehicles. Battery electric vehicles (EV) represent the most promising solution towards consumption reduction and therefore towards cleaner and emission-free mobility while the possibility to further improve vehicle dynamics shows interesting prospects for the sport vehicle segment. A major issue concerns the very limited range, this problem might be overcome with hybrid electric vehicle (HEV) configurations which furthermore, meet both requirements from emission regulations and from the consumer side providing suitable solutions for middle and upper vehicle segments. In this work parallel (HEVp) and series (HEVs) are considered. The internal combustion engine

vehicles (ICEV) on the other hand, still represent the most effective solution for low cost vehicles but the future deployment is strongly limited by the oncoming emission regulations. The vehicle optimisation procedure requires to solve a complex problem involving the individual subsystems and the components, their mutual influence and their impact on the whole system. The study exploits several powertrain configurations and for each a set of main design variables of the subsystems is defined and analysed. Nevertheless, the conflicting nature among the several objectives plays a relevant role in the selection of the optimal design solution. The model-based approach is fully exploited at both component and system level by showing the capability to guarantee accuracy and reliability through the adoption of specific models. The results obtained allow for an analysis of vehicle's consumption and dynamic performances with respect to powertrain technology, topology and components design. The optimisation procedure's definition is strongly coupled with the development of suitable models and the appropriate selection of the design variables and objectives. The results analysis faces a multi-objective optimisation for which effective methods and tools are adopted to visualise and compare the results.

UNCERTAINTY ANALYSIS AND IMPROVEMENT OF VISION BASED MEASUREMENT TECHNIQUES IN VIBRATION TESTING

Alberto Lavatelli - Supervisor: Emanuele Zappa

Introduction - The application of vision systems has become a topic of broad interest all through the scientific community. The practice of vibration testing makes no exception. The advantages of measuring a body with minimal perturbation due to the contact-less operation pushed the development of cameras in vibration testing, with new applications being deployed every year. However, scientific literature misses a comprehensive uncertainty analysis about the application of vision based methods to vibration testing. This is felt as a limiting factor since vibration testing is usually employed during product validation and qualification, where uncertainty must be kept under control. Consequently, this research tries to close this gap in the present knowledge by proposing an extensive analysis of uncertainty and tries to propose methods to reduce uncertainty and improve accuracy of vision based vibration monitoring techniques in operative conditions. The vision based measurement techniques investigated in this dissertation are Stereo Vision Blob Analysis and Digital Image Correlation (DIC).

How - What makes vibration imaging different from any other imaging task is that the

measured object is continuously moving during the exposure time needed for image formation. This peculiarity convolves the motion of the measurand with the acquisition window, generating the motion blur phenomenon. Whether visible or not, motion blur is always present inside the images. So, the analysis of uncertainty presented in this dissertation is based on the physical modeling of motion blur and on describing how it interacts with the measurement process. The analysis presented in this dissertation is built upon the solid pillars of the ISO-GUM uncertainty analysis framework. Initially, the thesis analyzes the problem of displacement measurement uncertainty in camera based vibration testing. Secondly, the research addresses the problem of propagating this kind of uncertainty to the broad range of modal testing, with focus on the estimation of modal parameters. In light of the previous analysis, the thesis focuses on the topic of reducing uncertainty by means of optimizing experiments and removing motion blur. Experiment optimization is carried out by using modern image simulation technologies, while motion blur is removed thanks to a novel deconvolution algorithm.

Results - This research

work delivers new models to describe the behavior of uncertainty in vibration displacement measurements. The analysis returned uncertainty quantification models for the generic application of a vision based method to mono-harmonic vibration testing. The main finding is that the observation of displacement by means of vision methods underestimates the amplitude of vibration. These models can be used to design a vision rig upon requirements of accuracy. Moreover, mathematical derivation and synthetic experiments demonstrate that motion blur acts as a noise amplifier in DIC measurements. The analysis of the single harmonic component does not address the case of the broad band vibration testing, such as the estimation of the mechanical Frequency Response Function (FRF). The challenge of estimating how displacement uncertainty propagates to the FRF measurement has been tackled by means of Monte Carlo methodologies. Results show that also the FRF measurement is biased. It is important to note that the analysis of uncertainty is carried out both by a Type A and Type B approach according to ISO-GUM guidelines. In fact, the analytic models provide a

Type B estimation. However, all these theoretical and heuristic derivations are further validated experimentally in a Type A fashion. For what concerns the improvement of accuracy of vision based vibration monitoring, this dissertation demonstrates the feasibility of uncertainty rejection by means of DIC pattern optimization. Due to the complexity of the problem, optimization has been performed by means of experiment simulation. For this task, a dedicated stereo vision simulator has been implemented and validated experimentally. In parallel, also the topic of motion blur removal has been investigated. In this context, a novel motion blur estimation and deconvolution algorithm has been developed. The algorithm removes a variable motion blur inside the images (since motion blur is hardly homogeneous in vibrating bodies) and it provides uncertainty reduction up to 80%.

Application - The main application of this research is to address the need to design stereo vision measurement systems that handle vibration in a safe and accurate manner. As a result, the thesis describes case studies that demonstrate the usefulness of the developed tools in practical applications.

It has been documented that it is possible to give reasonable uncertainty budgets starting from the data sheet of the vision rig. Furthermore, it is demonstrated that it is possible to optimize the conceptual design of a drone carried 3D DIC system based on the developed uncertainty analysis tools.

THERMALLY CONTROLLED MICROBALANCE FOR CONTAMINATION MONITORING

Marianna Magni - Supervisor: Bortolino Saggin

QCMs can operate in micro or zero gravity environments as their oscillation generates the acceleration without relying on the gravitational one. This characteristic, coupled to their low mass and volume, makes them particularly suited for space applications. In addition, they achieve sensitivities much higher than those of other mass sensors commonly used in laboratory, reaching mass detection thresholds of few ng cm^{-2} . So, QCMs are often used in thermo-gravimetric analysis, a widely established technique to investigate deposition/sublimation and absorption/desorption processes of volatile compounds in different research areas, such as outgassing contamination in space, dehydration and organic decomposition in minerals, moisture content in foods and the development of temperature profiles for firing ceramics. The QCM device object of this work consists of a quartz crystal oscillating in shear mode with deposited on its surfaces a thermometer and a micro-heater that can be used in the TGA. The innovation behind the proposed concept is the exploitation of the deposited film resistors both as heater and temperature sensor. The configuration allows measuring the shear resonance of

the crystal but also measuring and controlling its temperature. This is extremely important because, the oscillating frequency of the crystal depends on its temperature. In literature, the effect of the temperature on these devices has been extensively analyzed but only in case of uniform distribution. The microbalance under study conversely, when heated through the film deposited heater operates under a strong non-uniform thermal field. This is a consequence of its innovative design, which allows delivering the heating power to the area adjacent to the electrode. This condition had to be studied because unexpected frequency shifts were observed during the high

power phases implemented to induce fast temperature changes. The experimental activities were carried-out on a microbalance with thickness shear frequency at ambient temperature of 10 MHz. The temperature effects have been assessed at first under a uniform temperature distribution. Subsequently a temperature gradient has been generated and the observed relevant resonance shift characterized. The gradient problem, beside our condition of direct heating with film resistors, is significant in applications where the sensors operates in dynamically variable environment over wide temperature ranges or with varying external heat fluxes e.g. because of sun illumination.

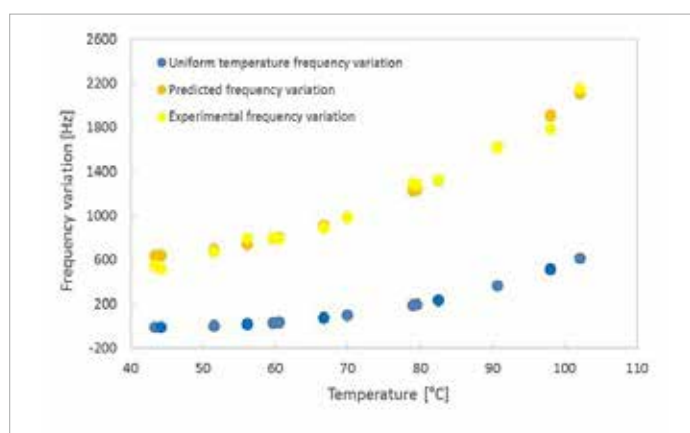


Fig. 1 -.Corrective factor of the thermal gradient applied starting from the frequency variation of the uniform temperature. The results is compared with the values obtained experimentally.

The compensation of the well-known (uniform) temperature effects in microbalances is still a critical issue. The problem is complex because many parameters affect the frequency-to-temperature sensitivity, mainly crystal angle cut and thickness but even small variations in the crystal electrodes thickness cause thermal sensitivity variations. In many situations, therefore, the sensors readings are affected by the QCM's temperature induced frequency shifts and this causes measurement errors. In order to compensate the temperature effect, the most common solution uses a dual QCM oscillator in which the first quartz crystal is used as reference device, while the other one is the actual sensor. Temperature changes should affect the two in the same way therefore the beating frequency should be immune from temperature effects. Being difficult to fabricate two coated QCMs with the same temperature sensitivity and maintaining them at the same temperature, any difference between the crystals will impair the compensation making also this configuration sensitive to temperature. This research aims at optimizing the performances of the microbalance under development and it will be carried-out following the classical approach. Crystal temperature sensitivity assessment has been performed within different environments, a temperature-controlled enclosure in air and in vacuum. Qualitative agreement with the literature models has been evidenced, while matching was not expected because of the

dependency of the behavior on the specific crystal manufacturing characteristics. The issue of the sensitivity to temperature gradients was carried-out in parallel with the design of an experimental campaign allowing to characterize the quartz crystal behavior under different temperature distributions and finally the implementation of the models of the quartz crystal resonance frequency for the compensation of all the identified input disturbances. The analysis has then focused on the crystal frequency behavior under temperature gradients. The results of the thermal gradient effect on the frequency variation have been compared with the uniform temperature-frequency variation relationship. It has been evidenced that, with the adopted configuration, the effect of thermal gradients can be far more relevant than that of the average temperature. The temperature field on the crystal surface was measured with a thermal mapper. The measurement on the original quartz crystals was not feasible because of the gold plating of the electrodes so, the gold coating was removed and the emissivity of the underlying metal measured. The thermal image processing allowed determining the temperature distribution and the thermal gradients at the electrode border. The information nevertheless was affected by the low spatial resolution of the thermal image and was applicable only after the gold coating removal that means almost destroying the QCM. To determine the temperature field on the surface of a standard

QCM, a thermal model has been therefore developed. The model of the gold removed crystal was first validated by comparing the predicted temperatures with those measured through the thermal mapper. The model parameters were tuned until the predicted temperatures were quite close to the measured ones i.e. with maximum errors on the electrode temperature below 1 °C. Thus, the validated mathematical model was used to evaluate the thermal gradients on the crystals. Finally, in order to correlate the temperature gradient with the frequency variation, different thermal loads and the boundary conditions, used during the experimental activity, were simulated assessing the corresponding temperature gradients. A sensitivity factor of the frequency with the temperature gradient has been computed, enabling to perform a first order correction of the effect. The correction procedure has been implemented in a few cases and the residual error assessed. Despite this was just the first attempt of correcting the gradient effects, the result was promising, being the residual error in the range of 1 to 8 % of the original effect. The correction procedure has then been implemented also on a standard crystal achieving residual errors below 7% for temperatures above 50°C.

AN APPROACH ADDRESSING PRODUCT SYSTEM CO-EVOLUTION FOR THE CONFIGURATION OF AN ASSEMBLY CELL IN THE AUTOMOTIVE INDUSTRY

Massimo Manzini - Supervisor: Prof. Marcello Urgo

The continuous increase of the variety of products, the change of volumes and the uncertainty of market pushes the manufacturing sector in a complex situation the companies that want to compete in this market have to face. These trends also affect the automotive sector, in particular the one devoted to the spare parts. The spare part market is characterized by the request of a high number of products entailing complex production processes, the use of different technologies and different materials. From a production point of view, this high variety entails the need to cope with different products, different production processes and small batches in a continuously changing environment. This has to be supported in the manufacturing system with the introduction of adaptation enablers, both logical and physical, that allow the system to smoothly and rapidly change and adapt to the market evolution dynamics.

In this context, the design of manufacturing systems is a strategically way and with a long-term vision, with the need to predict market behaviour and its uncertain dynamics. When the market evolution is uncertain

or the information about it are incomplete, the design of the system has to be carried out taking into consideration a measure of the associated risk, both in terms of costs and performance.

Considering the automotive market, *OEMs* typically rely on *tier-1* suppliers of car-body components for the after-market, and focus their internal production capacity on the series production and ramp-up phases. In order to remain competitive in this segment, *tier-1* suppliers have to match market evolution in a *co-evolution* way of thinking by acting proactively and providing the capability to integrate new technologies into the assembly system. In addition to this, since *OEMs* decide upon the products, their processes and associated technologies, the suppliers do not have degrees of freedom, except the ones related to the design and management of their production systems.

Grounding on the requirements provided by *Voestalpine Polynorm*, a *tier-1* car-body supplier based in Bunschoten, Netherlands, the adoption of reconfigurable assembly cells could be beneficial for facing this uncertain market. This assembly cell is based on a standardized layout that considers

a turntable as the input gate and a conveyor as the output. Inside the cell, a set of modular devices (see Figure 1) are arranged around a 7-axis robot, they can host a set of pieces of equipment able to provide alternative assembly technology with alternative implementing solutions. The 7-axis robot moves parts and components through the cell and, in some cases, it can take part to the execution of assembly operations.

The assembly cell can be easily reconfigured with a substitution of a modular device with another one and, thus, with a quick action it is possible to change the set of assembly processes the cell can handle without changing its architecture. Although conceptually simple, the use of such an assembly cell

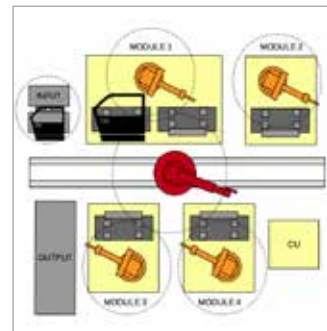


Fig. 1 - example of reconfigurable assembly cell.

paradigm entails a higher degree of complexity in its design and management considering all the characteristics of both the technology and the environment in which it operates. For these reasons, the motivation of this PhD thesis lies on *developing an approach able to support the decision-maker during the design and the management of a reconfigurable assembly cell in the automotive sector and operating in an uncertain context.*

For the solution of the presented problem, we propose a sequential approach that firstly generates the set of candidate cell layouts over a given time horizon (typically years), evaluates their performances and then chooses the optimal configuration sequence by optimizing a risk function. In doing this, the approach is organized in three different steps, following the framework depicted in Figure 2.

1) *The Assembly cell configurator* considers the requirements associated to a market scenario in terms of assembly processes, technologies and related equipment, and generates a set of candidate

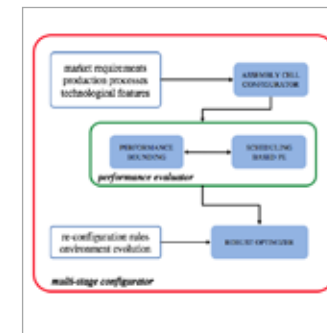


Fig. 2 - solution framework.

layout solutions. To this aim, it selects the pieces of equipment to be part of the configuration and their positioning around the 7-axis robot and its track, also considering alternative execution modes for each technological piece of equipment.

- 2) *The Performance evaluator* estimates the performance of a candidate layout solution through two approaches:
 - a). *the Performance bounding* step uses an analytical approach for a fast estimation of the boundary performances of each candidate solution for slimming down the candidate list;
 - b). *the Scheduling-based performance evaluator* estimates the exact performances of the candidate layouts using a scheduling-based approach exploiting both formal properties of scheduling policies and a heuristic procedure.
- 3) *The Robust optimizer* exploits the performance estimated in the previous steps to identify the sequence of configurations to optimize the Conditional value at Risk of the total management cost of the cell over the entire time horizon.

The configuration approach has been applied on an industrial use-case considering a pool of products to be processed over a time horizon of months. After the generation of the candidate solutions, the first level performance evaluation discarded

almost the of the solution identified, while the second level focuses on the residual ones. The solution identified with the *Robust optimizer* has been compared with the ones related to alternative approaches. This configuration approach is beneficial because it protects the company from the occurrence of any of the considered scenarios better than alternative approaches.

The main scientific results achieved within this research are the following.

- The introduction of a formal representation of reconfigurable assembly cell paradigm together with the definition of execution mode concept.
- The development of a *proactive-reactive* approach used to address the performance evaluation of a cell configuration. In the development of this approach, four theoretical results about *flow-shop* production system have been presented.
- The use of risk minimization approaches in an industrial context.

AN INVESTIGATION IN MECHANICAL CONSTITUTIVE THEORIES FOR NON-METAL BRITTLE MATERIAL

Aria Mardalizad - Supervisor: Prof. Marco Giglio

Co-supervisor: Prof. Andrea Manes

The numerical simulation of penetration into rock is an important tool to gain insights into rock drilling mechanisms, since it can be exploited as an alternative to the expensive field testing in the pertinent fields of engineering. Developing a reliable numerical modelling technique able to deal with the dynamic bit-rock interaction process, is considered as an important challenge for fracture assessment of the geological materials. This PhD thesis presents experimental and numerical investigations in the rock mechanics domain with the focus on the oil and gas requirements. An innovative simulation method of the tool-rock penetration process was implemented. The numerical method was based on the coupled FEM-SPH approach where the severely distorted finite elements were converted to SPH particles representing crushed rock. As the constitutive description of the rock material, the capability of an advanced material mode, called KCC material model, was critically discussed. Several experimental tests were performed in this thesis, namely: the uniaxial compression test, the Brazilian (quasi-static) test, the Flexural test, the triaxial compression test, the punch

penetration test and the dynamic Brazilian disk test, in order to investigate the mechanical response of rock materials experimentally. The unconfined compression test, used to be performed on the base of standard protocols, i.e. ASTM. This conventional test presents a drawback, mainly due to the radial shearing forces that are generated at the contact interface after applying the compressive load. These undesired radial forces are appeared due to the different elastic properties of the steel of the testing machine platen and the rock specimen. Another arrangement has been found in literature (Mogi specimen) to design the specimen in order to reduce these drawbacks. The experimental and numerical analyses presented in this project demonstrated that the Mogi's suggested method, which is not tough and effortful to be prepared, lead to measure the UCS parameter more precisely. The experimental tests revealed that the variability of the results obtained by Mogi's configuration are much lower than the ones of conventional configuration. The assessments performed on this PhD research project based on numerical simulations justified this issue when the existence of stress

concentration was considered at the rock-steel (of compressive platen) interface of conventional configuration. A procedure proposed in this thesis for calibrating the KCC material model specifically for Pietra-Serena sandstone, however it can also be used for other quasi-brittle materials. This calibration procedure was mainly based on a couple numerical-experimental approach aimed to overcome the main drawback of the KCC material model. The input parameters were investigated and classified into five distinct categories; tensile strength, failure (fixed) strength surfaces, tabular damage function, equation-of-state, damage parameters and strain rate enhancement. The quasi-static Brazilian disk test was used to measure the ultimate principal tensile strength. The triaxial compression test, with three levels of confining pressure, was carried out to determine the other groups. The yield, the ultimate and the residual strengths measured via the experimental tests were used to determine the ai-parameters, which are the KCC input parameters to describe the fixed-strength surfaces. Since the KCC model decouples the deviatoric and volumetric responses, the

experimental data of the isotropic stage (of triaxial compression test) can potentially be used to define the equation of state for a given material. However, due to the absence of an appropriate laboratory device to measure the radial displacement, the equation of state dedicated to the material under investigation in this study was determined analytically, based on the experimental data of the axial displacement. A modification to the tabular damage function was suggested based on the experimental data of the triaxial compression test in the deviatoric stage. Exploiting the availability of the numerical models, a sensitivity analyses was performed to determine the bi-parameters, which are the damage parameters of the KCC material model. Finally, the proposed formulation by Malvar and Crawford is used to determine the effect of strain rate. The diagram of DIF-strain rate, which serves the role of updating the failure surfaces, was calibrated based on the experimental results of dynamic Brazilian test. Therefore, a material model specifically calibrated with the required full set of input data was developed for Pietra-Serena sandstone. The fully calibrated material model was implemented to replicate the experimental tests (verification). The numerical results for both the triaxial compression and the Brazilian tests significantly agreed with the experimental test results. The fully calibrated material model was then further validated by replicating a Flexural test, which includes both the compressive

and tensile stresses, and dynamic Brazilian disk test. The critical comparison between the numerical and the experimental test results demonstrated the capability of the calibrated material model. Therefore, the procedure proposed in this PhD thesis presents a potential new framework for the numerical assessment of quasi-brittle materials. This numerical approach was then applied in the simulation of the punch penetration test on Pietra-Serena sandstone. Moreover, experimental PPT tests were performed in order to validate the numerical results. Three different numerical techniques for dealing with fully damaged finite elements were applied in order to replicate the PPT test: (a) constant stress (reduced integration) FEM with erosion of heavily distorted elements, (b) fully integrated FEM with erosion of heavily distorted elements, and (c) reduced integration with coupled FEM-SPH. The numerical results with method (a) exhibited an excessively too soft response. The full integration with erosion method (method b) performed significantly better; however, more severe fluctuations were attested in the force-penetration curve caused by the element erosion events. The reduced integration with a conversion to SPH particles (method c) resulted in a slightly too stiff response compared to the experiments due the continued ability of the SPH particles to bear compressive stresses. However, the major fracture types, excluding lateral spalling, observed in the experiments were also attested

in the numerical simulations. Therefore, it can be concluded that the FEM-SPH method, in conjunction with KCC material model, can be considered the most realistic method among the tested methods. Finally, the proposed numerical method was employed in an attempt to investigate the practical issues in designing offshore deep hole drilling of real projects in the field of oil and gas industries. A drilling problem at extreme conditions was studied by penetrating a double conical tool into a reservoir rock below the seabed. A substantial decrease in the damaged zones beneath the tools as well as a prevention of the lateral chipping between the tools were predicted under the confined stresses expectable at 3 km of depth. Moreover, the simulations demonstrated the importance of the correct spacing of the tools. It was also found that if the vertical pressure at the borehole bottom can be relieved, the drilling at great depths becomes substantially more efficient. Finally, the percussive rock drilling at a certain depth below the seabed is investigated numerically with focus on the effects of impact velocity, depth of drilling and effect of in-situ pressures. Based on the simulation results, it can be concluded that the present numerical method has some predictive capabilities, hence, it can serve as a tool in the research and development pertinent to petroleum engineering.

CONTINUOUS HEALTH MONITORING OF RAILWAY AXLES USING VIBRATION MEASUREMENTS

Mohamed Hassan - Supervisor: Prof. Stefano Bruni

Railway wheelsets are one of the important elements affect the reliability of railway vehicles in the perspective of safety. The axles are one of the most critical components in railway vehicles since their failure can lead to derailment and, potentially, to catastrophic accidents. Because the axles are operating under harsh conditions of rotating bending at high number of cycles, a large proportion of all accidents in the rail industry, related to rolling stock failures, is due to crack propagation in the axles. Cracks in railway axles generally propagate in a plane perpendicular to the axles axis, taking the name of transverse cracks. Railway axles are inspected periodically at regular intervals, e.g. for freight wagons, every 600,000 km or 6-year distance, to detect any defects and prevent axles rupture.

Although the high standards of present engineering practice in non-destructive inspection of axles, fatigue induced in-service failures of railway axles still occasionally occur, representing a serious threat to the safe operation of railway systems. Therefore, it's needed to introduce an innovative and effective approach for railway axle continuous structural health monitoring (SHM) to play a pivotal

role in further reducing occasional in-service failures of railway axles, which is not meant to replace the existing non-destructive test (NDT) inspections, but rather to serve as an additional safety measuring tool.

In this thesis, a new method of continuous SHM for railway axles, based on measuring the axle in service bending vibration to detect the presence of a crack is proposed. Due to the so-called crack breathing mechanism, the presence of a crack perturbs the axi-symmetric bending stiffness of the axle affecting the bending vibration at frequencies that are multiple integers of the frequency of revolution, referred to as $NxRev$. The proposed SHM strategy therefore entails the measure of the first 3 harmonic components of axle vibration.

This strategy has been successfully applied in the past to the detection of cracks in turbine shafts.

However, in the case of railway axles the detection of $NxRev$ components is more problematic due to:

1. The high level of disturbance generated by track irregularity and wheel out-of roundness (OOR).
2. Railway axles are rotating at speeds below their first critical speed, whereas shafts in turbomachinery and other industrial machinery are often

working above at least the first critical speed.

3. Limited space is available in wheelset to install the measuring sensors because the axle body is providing support for auxiliary systems.

4. The angular speed of railway axles is changing in complicated way therefore, it produces non-stationary vibration signals. Considering these challenges, a combination of modelling, simulation and testing activities have been carried out to assess the possibility of using the SHM approach proposed in this thesis. Three models have been built based on non-linear Finite Element (FE) models of the cracked railway axle and simulated at different conditions of crack sizes, crack locations and track disturbances. After examination of the State of the Art, the first model, non-linear solid Finite Element model of cracked railway solid/hollow axle, is developed using 3D elements (C3D8R) included in the commercial software ABAQUS/CAE representing the crack by means of non-linear contact elements with or without friction. This model is expensive from calculation time point of view because it represents the exact size and shape of railway axle (even with some simplifications for 3D analysis). To overcome the drawback of

highly computationally intensive of the solid FE model, the second model of a cracked axle is defined using Timoshenko beam Finite Element with 6 DOFs per node and a simplified crack breathing mechanism model is applied to a specific element, depending on the crack location, to represent the change of the cross-section area and moments. The Timoshenko beam FE model was coded by MATLAB and verified using results obtained from the solid FE model and validated against results measured from full-scale rotating bending tests performed on the Dynamic Test Bench for Railway Axles available at the labs of Politecnico di Milano.

After validation, different sizes and locations of the crack were simulated for different boundary conditions of railway axle. Because the proposed SHM technique needs to take into account properly the effect of disturbances associated with track irregularity, wheel OOR and flexibility of the track, more realistic boundary conditions than the ones used in the solid FE and the beam FE models need to be considered for the wheelset. A multi-body (MB) model of a railway vehicle also considering track flexibility is merged with the Timoshenko beam FE model of one cracked axle to form a detailed model of a railway vehicle with one cracked axle (third model). To this aim, the beam FE model is used because it is highly efficient from the computational point of view compared with the solid FE model. In this model, called MB-FE model, the crack breathing mechanism is applied to a specific beam

element, depending on the crack location. Also, in this model, track flexibility in vertical and lateral directions has been considered by using the so called "moving track models". The moving track models are assumed to follow the longitudinal forward movement of the vehicle. After verification, the MB-FE model is used to study the influence of crack propagation, at two positions, on the vibration signals measured at the axle-box in vertical and horizontal (perpendicular to the axle axis in travelling direction), directions. A tentative crack detection criterion, depending on the mean value and standard deviation of a healthy (without considering crack) acceleration signal is proposed. Different signal processing techniques are tested to propose an effective technique able to extract the useful information from noisy and non-stationary vibration signals which are representative of signals obtained from railway field. The proposed technique is a combination of diverse techniques from the State of the Art. Because the proposed signal processing technique requires a tacho signal but in some railway vehicles, it's not possible to add a tachometer hardware, a tacho-less technique suitable for railway continuous SHM applications is proposed and validated.

From the results of the numerical and experimental activities, the following conclusions are formulated:

- 1) The presence of a crack in railway axle affects not only the vertical vibration, but also

the horizontal one and the first three harmonics, $1xRev$, $2xRev$ and $3xRev$, can be used to detect the axle crack.

- 2) Axle-boxes measurements can be used to detect the presence of a crack at any position along the axle.
- 3) The measure of the horizontal vibration provides a promising indicator of axle fault development because this component is nearly insensitive to the effect of various sources of disturbance, particularly wheel OOR, compared to vertical vibration.
- 4) The signal processing technique, including tacho-less technique, proposed in this thesis is able to rule out the signal components that are unrelated to the angular speed of the axle and provides an order spectrum which enables the clear tracking of $NxRev$ components of vibration even in presence of large noise caused by wheel-rail interaction.
- 5) The simple criterion for crack detection, introduced in this work, shows the possibility of detecting cracks with size in the order of 15-20% of the total section area, depending on the crack location. This means that crack detection according to the method proposed here can be performed when the crack size is still much smaller than its critical size, so that the cracked axle can be safely put out of service avoiding dangerous in-line failures.

PROBABILISTIC FATIGUE LIFE ASSESSMENT OF ADDITIVE MANUFACTURING COMPONENTS THROUGH COMPUTATIONAL MODELS

Simone Romano - Supervisor Prof. Stefano Beretta

The progressive improvement of additive manufacturing (AM) techniques enables the production of geometrically complex and lightweight parts, which explains the incredibly fast growth of AM for aerospace applications. Despite the disruptive benefits of AM, the full potential of the technology is today far to be reached. The necessity to comply to very strict reliability requirements is hindering most of the safety-critical and structural applications because of the large scatter and low reproducibility always associated to AM, especially in terms of fatigue strength. In these regards, the initial part of this research activity is devoted to evaluating the fatigue behaviour of metal alloys produced by AM, focusing in particular on the sensitivity to defects and inhomogeneities of alloys widely used in the aerospace sector, i.e., AlSi10Mg and Ti-6Al-4V. The analysis shows that fatigue properties and key variables do not differ with respect to those of traditional manufacturing processes. Furthermore, it is evidenced that manufacturing defects are the main variable responsible for the experimental scatter and that defect-tolerant design concepts can be adopted for the assessment of AM components. On the top of that, other typical process-related issues

can influence the performance of the parts, as depicted in Fig. 1. One of the most suitable techniques for detecting defects in the complex geometries achievable by AM is micro-computed tomography (μ -CT). A simple and robust method to analyse the CT data is thus investigated. On this base, the critical defect size for a volume of material can be determined applying statistics of extremes and is the input for damage-tolerant (DT) assessment (see Fig. 2). These concepts are then applied and verified on the AlSi10Mg alloy. The material has been manufactured by Selective Laser Melting (SLM) according to three processes, and extensively characterised in terms of static, fatigue and fatigue crack growth (FCG) properties. Microstructural investigations, CT and fractographic analyses have been conducted as well. The data clearly show that manufacturing defects are the main variable responsible for the scattered fatigue resistance of the specimens (see Fig. 3). The investigation demonstrates that a combination of defect-tolerant design with well-established and newly proposed fracture mechanics methods is the key to expressing the relationship between fatigue strength and material quality and

to support the application of AM to safety-critical components and their qualification. In fact, Fig. 4 demonstrates that both the trend and scatter of the fatigue data in a large range of loading conditions can be robustly assessed by elastic-plastic FCG simulations based on the analysis of CT measurements. This allows to draw design maps based on material quality. All the results obtained lead to the final topic of the research activity, which addresses the fatigue strength of complex AM parts. The AM community and the main aerospace industries are starting to agree that DT approaches are necessary and that probabilistic methods are best-suited to obtain reliable but not over-constrained assessments. In this regard, the research performed has set the base for the concept and development of Pro-FACE, a fully-probabilistic software that aims to robustly assess the fatigue strength and critical locations of complex components in the presence of defects (see a scheme in Fig. 5).

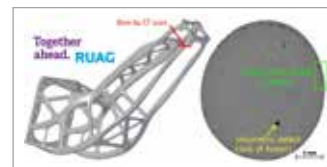


Fig. 1 - Manufacturing defects detected in one of the aerospace components investigated.

Pro-FACE takes as input the finite element analysis of the part, the defect distribution detected by CT and the fatigue strength of the material in terms of Wöhler curve and Kitagawa diagram. On this base, statistical calculations are performed to evaluate the fatigue resistance in correspondence of every integration point of the model. The tool gives as output the local and global failure probability and the critical defect size in every location. A first validation has been performed by means of state-of-the-art simulations on simple geometries. A deeper investigation considering notched specimens manufactured by SLM has demonstrated the capability of Pro-FACE to define the critical regions for a batch of parts and the critical defects among those detected by CT on the particular samples. A simple and analytical fatigue assessment method was defined and proved to provide slightly conservative results with low effort. Pro-FACE has been implemented as a standalone post-processor and as an Abaqus plug-in. The software has finally been used to assess the fatigue resistance of two parts designed by topological optimisation: a bracket designed by RUAG Space to hold an antenna on the Sentinel One satellite, made of AlSi10Mg (see a map of the critical defect size in Fig. 6); an aeronautic cabin bracket designed by Airbus for Airbus A320 and 350, made of Ti-6Al-4V. The analytic formulation makes this tool ideal to evaluate very low failure probabilities with limited time and effort, which can be valuable information to significantly improve part design

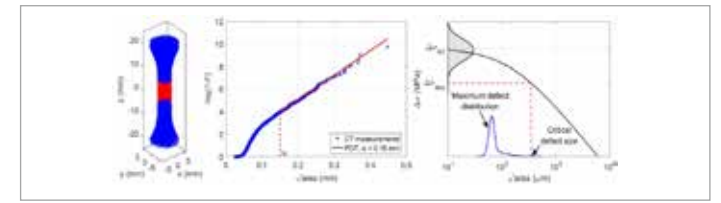


Fig. 2 - Statistical analysis of CT measurements aimed at determining the maximum defect size in the volume investigated. The criticality assessment is then performed in the Kitagawa diagram.

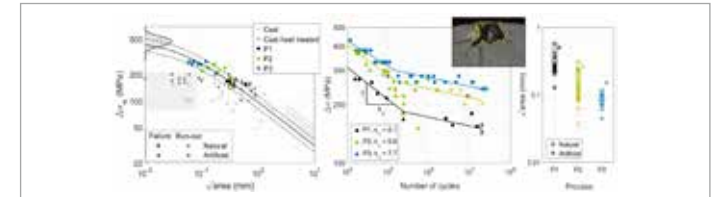


Fig. 3 - Results of the HCF tests on the three processes: Kitagawa diagram, Wöhler curves and size of the killer defects. Size estimates based on CT measurements reported with the box plot (average + 90% scatter band).

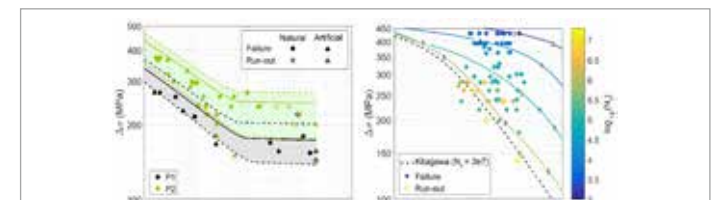


Fig. 4 - Estimates of fatigue life in elastic-plastic condition obtained by fatigue crack growth simulations. The experimental scatter and difference between batches are correctly assessed based on the size of the killer defect estimated by statistical analysis of CT data.

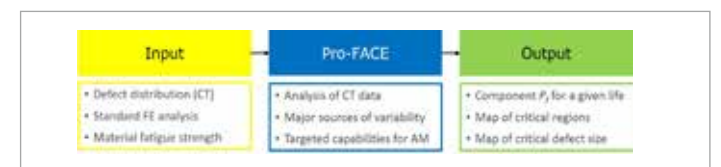


Fig. 5 - Concept of the model for defect tolerant PRObabilistic Fatigue Assessment of ComponEnts (Pro-FACE).

and qualification and to define defect acceptability criteria. The research activity has been funded by ESA through the Networking Partnering Initiative (NPI) 482-2016, with the support of RUAG Space.

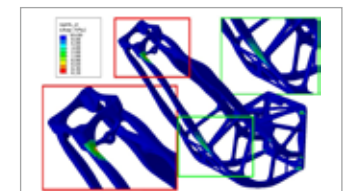


Fig. 6 - D map of the critical defect size for RUAG bracket.

MICRO ABRASIVE WATER JET SYSTEM FOR ULTRAFINE CUTTING

Francesco Viganò - Supervisor: Prof. Massimiliano Annoni

Abrasive Water Jet (AWJ) technology is a flexible cutting solution, based on the material removal performed by a high velocity jet, made of water and abrasive particles. The modern trend of miniaturization and precision manufacturing pushes researchers and companies towards the creation of micro Abrasive Water Jet (μ AWJ) solutions for cutting fine features on almost any material. The process result is a near-net-shape component or also a complete operation, if the AWJ-cut surface characteristics are accepted.

The study designs and develops a novel μ AWJ cutting system that exploits a mixed jet, finer than what is known nowadays in literature or on the market. A complete cutting head equipped with a \varnothing 0.13 mm focusing tube is carried out to this purpose. Specifically designed \varnothing 0.05 mm diamond primary orifices and stainless steel mixing chambers are developed. The cutting head components are coupled by matching tight assembly tolerances. For this purpose, the focusing tube is retained to the cutting head by shrink fitting, for the best centring and alignment condition. The cutting head is shown in Figure 1 on the left. The most used abrasives for AWJ and μ AWJ are inspected,

highlighting the particle shape influence on the actual drag coefficient C_D . This is always higher than the one assumed in most studies (corresponding to 0.47, the sphere typical one), thus allowing a new design of the focusing tube, shorter than usual. A novel and finer abrasive size is used, Barton W0, although currently not applied to μ AWJ. The main feeding issue deriving from such small abrasive powders (average particle diameter equal to 26 μ m) is due to its low flowability and high hygroscopicity, which cause irregular flow and dramatic clogging in different regions of the feeding device. An excellent result is achieved by using the dedicated Gel Based Slurry feeding system developed for this specific application (patent pending). This device allows feeding very low abrasive mass flow rates ($m_a = 2 - 10$ g/min) by pumping it after

mixing with a water-based gel. The pumping system gives complete control on the abrasive mass flowing until the release, which is close to the jet axis in the mixing chamber, thanks to a dedicated injector, shown in Figure 1 on the right.

The entrained air flow, coaxial to the abrasive one in the injector, is reduced at its minimum to increase the average specific mass of the jet and thus its cutting effectiveness. Nevertheless, the complete monitoring and control of this air flow is exploited for setting the mixing chamber pressure $p_{mc} = 0.78 - 0.80$ bar (absolute pressure). The p_{mc} monitoring gives a real-time feedback on the health status of the entire cutting head, while the air flow control guarantees the jet steadiness and the consequent high cutting quality even if the water pressure or the abrasive



Fig. 1 - The μ AWJ cutting head (left) and the injector (right).

mass flow rate changes. The novel system demonstrates its potential by cutting AISI 301 (Hasberg) plates of increasing thickness, from 0.5 mm to 2.0 mm. The optimum v_f value on the 2.0 mm thick one is set at 6 mm/min, resulting in the minimum kerf taper, no detectable jet lag and sub-micrometric roughness (Figure 2). The tests are carried out on stainless steel in order to make a comparison with Wire-EDM possible, although μ AWJ can cut a much wider range of materials. The piercing repetitions are the most traumatic operations, but the novel gel-mixed abrasive flow counteracts the natural

trend of the abrasive to clog in presence of moisture. Indeed, since the abrasive is already fully wet, it does not suffer this issue. The jet can be started with the mixing chamber filled of abrasive gel, so that the already abrasive-loaded jet impinges the material. This feature turns useful when processing brittle or delaminating materials, as well as it is an effective safety system for the cutting head. The long-lasting cutting operation on benchmark pieces verifies the jet steadiness characteristics. A 90 mm long curved cut (the "A" logo, from WatAjet S.r.l., Politecnico di Milano spin-off company) is

performed in 15 minutes by scaling down at 75 % the smallest component achievable with state of the art μ AWJ. As a result of these tests, the average kerf width is reduced to about 0.16 mm, which is the 65 % of the state of the art, as demonstrated in Figure 2. A significant quality enhancement is highlighted by the valuable roughness reduction, with R_a and R_z values both about 42 % of the state of the art. The v_f needed for achieving these results is reduced to 6 mm/min, about the 17.5 % of the state of the art, which is a small drawback compared to the outstanding μ AWJ cutting quality, easily to balance by using multiple parallel cutting heads.

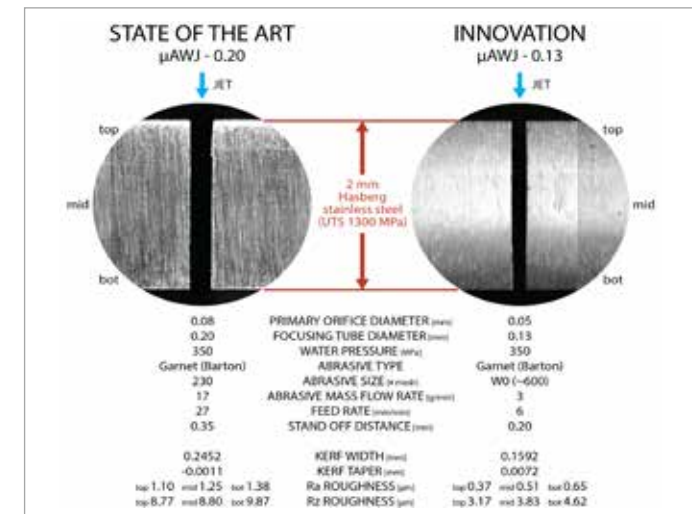


Fig. 2 - The μ AWJ performance comparison between the state of the art and the innovative solution.

SCHEDULING IN HYBRID FLOW SHOP MANUFACTURING SYSTEMS

Chunlong Yu

Supervisors: Prof. Quirico Semeraro, Prof. Andrea Matta

Hybrid flow shop (HFS) is a common production system architecture applied in many industrial fields. The scheduling problem in HFS attracts many attentions due to its strong relevance to industry. But, a gap between research and industrial application exists because of the complexity of real production systems. For example, typical consideration of identical parallel machines does not hold in practice when the machines are based on different processing technologies; common throughput-oriented objective functions loss their priorities in make-to-order environments; last but not the least, the multi-objective nature of production scheduling requires the ability to improve several KPIs simultaneously. Nowadays, researches are dealing with the scheduling problems taking into considerations more critical features of the production systems and more practical objective functions. This work aims at solving the scheduling problems in HFS with practical features. The research is motivated by a real-world case in the sheet-metal manufacturing company which is looking for technique to improve the production performance

via advance scheduling system. The research can be divided into three research phases, each tackles different aspect of the decision-making procedure in production scheduling. At the first phase, with the consideration of unrelated machines and machine eligibility constraints, the goal is to optimize the total tardiness for guaranteeing on-time delivery. At the second phase, sequence-dependent setup, a critical feature presents in many HFS systems, is included into the HFS model, and the goal is to optimize multi-objective of total tardiness and total setup times. This allows the manufacturing companies respecting due-dates while reducing non-value-added activities. Generally, the solution for multi-objective scheduling problem is a set of alternatives non-dominated by each other. To select the final solution, a decision-making process is needed. At the last phase, the group decision making problem is tackled. This helps a group of decision makers with different expertise and preference to reduce their opinion incompatibility and to reach a common solution. The main results of this research are as following:
R1: Develop an efficient genetic algorithm for hybrid flow shop

with unrelated machines and machine eligibility constraint to optimize total tardiness. A new decoding method is proposed to tackle the deficiencies of conventional methods on solving the defined problem. More technically, the proposed decoding is able to, on one hand, improve the influence of the job permutation on the schedule construction procedure; on the other hand, it can avoid introducing unnecessary machine idleness to obtain tight schedules. The proposed decoding method is integrated with a genetic algorithm for optimizing the job permutation. The genetic algorithm is calibrated for the defined problem both in terms of GA operators and parameters with full factorial design of experiments. Effects of different building blocks of the genetic algorithm are analyzed. A sound comparison experiment is made on instances with different size and different correlation patterns to generate the processing time matrix. This comparison is made between the proposed algorithm and state-of-art algorithms calibrated for the defined problem, and variants of the proposed algorithm with different decoding methods. The performance of different algorithms with different

computing budget are studied as well. Results show the efficiency of the proposed algorithm on the problem.

R2: Propose algorithms to solve the hybrid flow shop scheduling problem with unrelated machines, machine eligibility constraint and sequence-dependent setups with multi-objective of total tardiness and total setup times. The decoding method proposed in R1 is extended to different versions applying different machine selection rules, in which the sequence-dependent setup information is utilized. The performance of different decoding versions are analyzed. Then, a multi-decoding framework is proposed for genetic algorithm to use different decoding methods simultaneously. More technically, the idea is to treat the decoding method type as a decision variable to optimize during the evolution procedure. To this end, hyper-chromosome and the corresponding genetic operators are developed. This framework, (1) allows the genetic algorithm adjusting the applied decoding method during the runtime according to user preference; (2) allows the multi-objective

genetic algorithm to search different objective space regions simultaneously to obtain a wider non-dominated front. Comparison experiments show the usefulness of the multi-decoding framework in solving multi-objective scheduling problem, either via prior approach with given user preference or via posterior approach where a Pareto-optimal set is to be approximated.

R3: Develop a consensus reaching model to tackle the group decision making problem using objective space preference information. The proposed model allows the decision makers to input their preference directly in the objective space, by specifying the indifference zone within which solutions are considered of equal satisfactory. This generates several benefits: first, it allows to handle a larger alternative number compared to conventional preference-space-based approach because the use of preference relation is avoided; second, it allows the coupling of proposed consensus reaching model to state-of-art preference articulation methods which utilize and output objective space information; thirdly, the use of indifference

zones allows to represent the vagueness in human decision-making meanwhile facilitate the procedure to obtain common solution. To reduce incompatibility between two decision makers, the consensus model links the opinion transition paths between their indifference zones on which intermediate alternatives are located and suggested to the decision makers; then, to make group consensus, a recent proposed peer-to-peer opinion adjustment strategy is applied. The proposed model is tested by numerical experiments with randomly generated group decision making problems of different features. Moreover, a case study has been performed, in which we applied the proposed consensus model to an assembly line configuration problem in a pharmaceutical company.

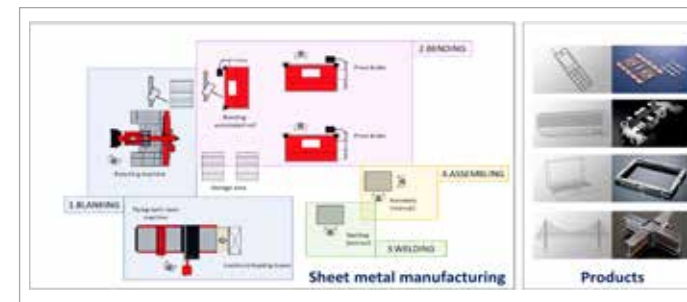


Fig. 1 - The hybrid flow shop system used in sheet metal manufacturing and the final products

ANISOTROPY AND IN HOMOGENOUS PLASTIC DEFORMATION IN FLAT STEEL PRODUCTS

Mandana Zebarjadi Sar - Supervisor: Prof. Carlo Mapelli

The low carbon steels due to use for many applications such as the structural components in the part of building constructions and automobile parts need to have high formability. However this type of steel do not reveal flat surface after uncoiling process. The lines form perpendicular to the direction of subjected stresses during decoiling of the steel strips. These lines known as fluting or Coil breaks deteriorate the smooth and shiny appearance of the curved strip surface. The presence of these lines not only decreases the flatness of the steel strips but also reduces the ductility of low carbon steel.

Different methods have been used to eliminate this defect from low carbon steels such as use of temper rolling and rolling leveler on the steels' surface. The removal of fluting by these methods are done with introduction of residual stresses. These stresses are larger value when the temper rolling is used and the fluting effect do not appear for longer time. Smaller rolls also can induce more residual stresses and can be more effective for the reduction of coil breaks in a long time. Although these solutions are suggested for elimination of fluting, these lines are appeared on the surfaces after passing time. Use of non-aging steels is another method

which prevent the return of fluting phenomenon after aging. The Nitrogen and Carbon atoms forming carbides and nitrides are removed from solid solution of these steels using microalloyed elements of Aluminum, Vanadium, Titanium, Niobium and Boron if they are added in sufficient stoichiometric ratio to Carbon and Nitrogen.

Considering the solutions employed previously, in this thesis it is focused on applying a method aiming at elimination or reduction of fluting intensity for a long time. For this purpose, hot rolling, cold rolling, annealing and temper rolling is substituted with intercritical region rolling of mild steel and boron contained steels. For this purpose the intercritical region rolling of mild steel and boron contained steels were applied. The symmetrical and asymmetrical rolling processes on Mild steel were employed. The production of steel with minimized or removed fluting intensity were investigated modifying thermomechanical conditions (rolling temperature and rolling reduction, rolling velocity ratio) of rolling process. In both rolling processes, the fluting intensity had low value when the rolling process was done at highest rolling temperature due to the presence of less diffusion

path (pipe diffusion) to form Cottrell atmosphere and fluting marks. They were removed from specimen's surface when the rolling was performed at higher rolling reduction in all temperature conditions by inserting high mobile dislocations to release the bounded dislocations from Cottrell atmosphere.

The Boron bearing steel also was investigated and it was rolled by two different rolling processes in diverse thermomechanical conditions. The results showed boron plays a main role in removing the fluting marks. Comparison of the mild steels and boron steels deformed in the same thermomechanical conditions showed the flat strips without any fluting marks can be obtained by use of boron steels rolled in intercritical region. This phenomenon happened through extracting Nitrogen from solid solution and inserting mobile dislocations.