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PhD Yearbook | 2023

Chair:
Prof. Andrea Bernasconi

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. The research topics of our Programme fall in the category Mechanical, Aeronautical & Manufacturing Engineering of the QS World University Rankings, where Politecnico di Milano currently ranks 7th in the world.

As for career perspectives, a recent survey (run by Politecnico in 2022) showed that our PhD Candidates are 95% employed after one year, in national and international companies and academic and non-academic research institutions, engaged in innovation, research and technical development. On average, the survey showed that people earning our PhD title are paid 35% more than the corresponding employees with a master title.

Within our Programme all Doctoral Candidates follow a minimum path of three-years, which includes specific courses and lectures, held by Faculty members and foreign professors and experts: in 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 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. In this view, their scientific profiles are suitable for prestigious positions at national and international level within universities and research institutions, large industrial and consulting companies, SMEs. In the following pages 37 abstracts belonging to PhDs of the 31st (2), 32nd (1), 33rd (4), 34th (24) and 35th (6) doctoral cycles (defended in 2022 and 2023) are proposed.

They represent a good overview of the international vocation of our PhD Programme, with a third of them having being developed by international fellows. Female presence accounts for almost 17%.

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, and in an additional interdisciplinary area. All doctoral thesis displayedin 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, Rotodynamic, 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 fibers), 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 etc.) 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: 3D Vision, Additive Manufacturing for 3D printing, Advanced Manufacturing Laboratory, Cable Dynamics, Laboratory for measurements for biomedical applications (LAMBDA), Characterization of Materials, DBA (Dynamic Bench for Railway Axles), Vehicle Dynamics, Laboratory for testing of mechanical components on real components or structures, La.S.T. – Laboratory for safety of transport systems, Material Testing and Analysis, Mechatronics, Measuring devices and calibration, Power Electronics and Electric Drives, Process Metallurgy and Simulation, Reverse Engineering, Robotics, SIP (Structural Integrity and Prognostics), Virtual Prototyping and Human Modelling Laboratory, Wind Tunnel, Water Jet.

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), Alliance4Tech (www.alliance4tech.eu) and ENHANCE (https://enhanceuniversity.eu/), three 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 Horizon 2020, Erasmus Mundus and China Scholarship Council.

We have ongoing agreements with MIT (Progetto Rocca), Delft University of Technology (Double PhD), RWTH Aachen (Double PhD and Cotutelle), University of Zagreb (Double PhD).

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, École Polytechnique Fédérale de Lausanne (CH), Norwegian University of Science and Technology (NTNU), University of Southampton (UK), Technical University of Denmark (DK), Pennsylvania State University (US), Chalmers University of Technology (SE), Technische Universität Berlin (DE), Technische Universität München (TUM), Warsaw University of Technology (PL), Politècnica de València (ES), Xi'an Jiao Tong University (CN), Tongji University (CN).

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APPLICATION OF COLD SPRAY AS AN ADDITIVE MANUFACTURING AND REPAIR METHOD

Amir Ardeshiri Lordejani - Supervisor: Prof. Mario Guagliano

Co-Supervisor: Prof. Sara Bagherifard

Gas dynamic cold spray, commonly referred to as cold spray (CS), is a novel solid-state metallic powder deposition method. Particle-substrate adhesion in CS relies on high impact velocity of the micron-scale particles that are carried through a de-Laval nozzle by a heated gas stream. Reliance of CS adhesion on kinetic energy rather than high temperature, makes it capable of achieving a dense deposit with low oxidation at high manufacturing rate and with mechanical properties close to those of bulk material. These characteristics make CS a compelling method for various applications such as additive manufacturing and repair. However, implementation of CS for any application requires careful tuning of its process parameters. These parameters depend on specific variables and desired target properties, such as powder and substrate material, substrate's geometry, as well as deposit's porosity, chemical composition, and growth.

The following research activities were carried out to develop and validate different tools required for enhancing technical maturity and flexibility of CS for various applications. Each research aims to propose a solution to a challenging aspect of adapting CS for additive manufacturing, presented in the form of fast and reliable methods for analysis of the relation between process parameters and deposit characteristics.

The first part of research was focused on developing a numerical framework for evaluating the effect of different process parameters on particle's window of deposition. The study involved developing and validating a single-particle impact finite element (FE) model that can accurately simulate the state of adhesion of a particle considering different variables including its size, morphology, temperature, velocity, hardness, angle of impact, and oxide content at any given velocity. This model is indispensable for identification of optimum process parameters without bearing the cost and time necessary for experimental campaigns.

The developed model was then used to study CS deposition of CrFeNi medium entropy alloy. Being a solid-state deposition method, CS can preserve the key intrinsic characteristics of the feedstock powder, and in this case those of carefully designed high and medium-entropy alloys. However, high hardness of these materials translates to a comparably high critical velocity. The described numerical framework has been used to precisely analyze the effect of these distinctive aspects on CS deposition parameters and identify the optimum values.

Next study involved developing a large-scale, multi-particle impact FE model using Coupled Eulerian-Lagrangian approach.

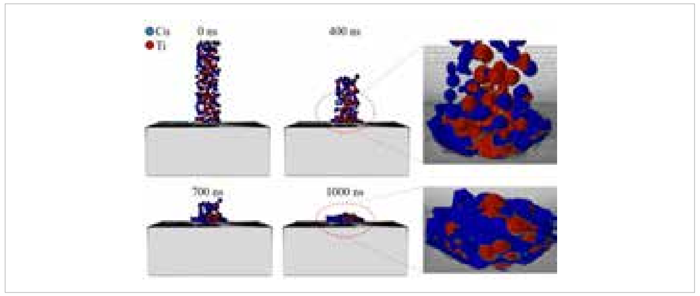

Fig. 1 - A FE model for simulation of multi-particle impact during CS deposition of multi-material feedstock

The developed model was then employed to simulate deposition of two composite powder feedstocks of Ti-Cu and Ti-Al, for manufacturing of bio-compatible structures and controlled fabrication of porous free-standing structures, respectively. The FE analysis results were post-processed using the developed codes to analyze the spatial distribution, connectivity, and morphology of each constituent material and the formed porosity. The results were successfully assessed against experimental data, confirming capability of CS for deposition of multi-material feedstock to achieve a controlled and designed composite deposit.

In the next step, a numerical model was developed to estimate deposition efficiency and chemical gradation of multi-material CS deposits. Based on deposition efficiency and flattening ratio of all possible material combinations on each other, this model can accurately estimate the variation of chemical composition of deposit across its thickness. The model was successfully applied to CS deposition of Al-Zn composite powder feedstock and results matched the experimental measured values.

Next part of the research was focused on developing a mathematical model to predict CS deposit profile growth and inversely, control and optimize the toolpath strategy to tailor the CS deposition for different cases. The developed model was employed to determine the optimum toolpath strategy required for repairing five types of damage cavities and connecting different configurations of welding butt joints with CS. Each combination was tested, and their deposit profiles were extracted. Simulated and acquired profiles were in very good agreement. It was also deduced that geometry of the substrate may affect the impinging gas regime and result in a consequent deviation of deposition efficiency from the theoretical value.

The peening effect of the CS deposition process induces a favorable compressive residual stress through the deposit and substrate thickness.

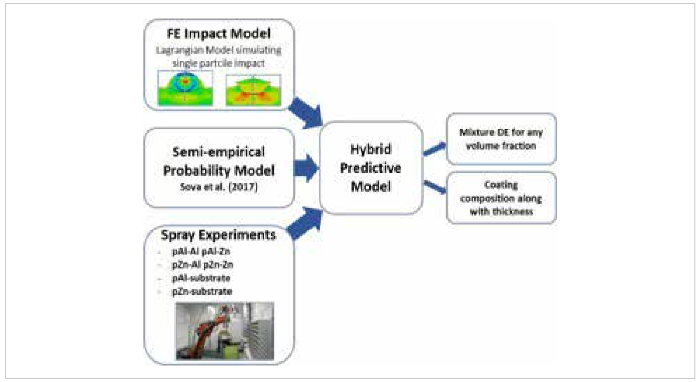

Fig. 2 - An overview of the numerical model for estimation of chemical gradation and deposition efficiency for CS of multi-material feedstocks

However, magnitude and state of this stress at the substrate-deposit interface, both of which evolve with increase of deposit thickness, strongly affect the stability of the deposit in terms of maximum achievable thickness before delamination. Utilization of CS for additive manufacturing and repair strongly depends on its capability to manufacture large scale parts. Therefore, the last part of research was focused on developing 2D and 3D multi-scale FE models to analyze the evolution of thermos-mechanical residual stress during CS deposition. The method relies on incremental addition of splat layers followed by introduction of sequentially coupled thermo-mechanical stress fields. The process was successful in predicting the overall trend of residual stress evolution and distinguishing between stress fields induced by different toolpath strategies.

The outcome of this PhD research can be summarized as developing a toolset necessary for expanding the applications of CS, with a focus on those necessary for implementation of CS as an additive manufacturing and repair method. The developed toolset can significantly increase the robustness and flexibility of CS, especially for industrial applications, by decreasing the uncertainty and borne cost and effort required to optimize the process parameters, otherwise done through costly iterative trial and error approach.

Keywords: Gas dynamic cold spray, Additive manufacturing, Repair, Finite element analysis, Process parameters

DEVELOPMENT OF HIGH-STRENGTH ALUMINUM ALLOYS FOR LASER POWDER BED FUSION

Filippo Belelli - Supervisor: Prof. Riccardo Casati

Despite the widespread use of Laser Powder Bed Fusion (LPBF), only few high-strength Al alloys are suitable for this process due to the occurrence of hot cracks during solidification. In this thesis, strategies to design Al alloys processable by Laser Powder Bed Fusion were successfully developed and applied to 2xxx and 6xxx series alloys. Novel Al alloys were designed to stimulate proper solidification behavior and to achieve improved mechanical properties by means of tailored heat treatments. CALPHAD-based simulations revealed a useful tool for the selection of alloying elements able to suppress hot cracks. Processability and performance of novel Al alloys were assessed by an extensive experimental work. The work was carried out within the framework of SAMOA (Sustainable Aluminum additive Manufacturing fOr high performance Applications) EIT Raw materials upscaling project, and the alloy design was carried out in compliance with the European Commission guidelines for critical raw materials. Specifically, the content of Sc and Si, which are defined as "Critical Raw Materials", was minimized or avoided.
Two different strategies were identified to suppress hot cracks: (i) the addition of grain refiners (Ti, B and Zr) and (ii) the formation of an abundant eutectic phase mixture at the end of solidification. The former route promotes the formation of a fine equiaxed microstructure capable to accommodate thermal stresses and avoid solidification cracking. Al-Cu-Mg-Ni-Fe-Ti-B and Al-Mg-Si-Zr alloys were designed and developed following this route. The second approach was applied to the Al-Cu-Mg system. By increasing the Cu content, an abundant eutectic phase mixture is stimulated and revealed capable to backfill and "heal" incipient cracks that nucleate at grain boundaries during last stages of solidification.
The strategies were applied to four main case studies, which are summarized in the following:
a) An Al-Cu-Mg-Ni-Fe alloy (2618 grade) was modified with different amounts of Ti and Bto improve the processability and high temperature resistance of the alloy. Samples withno hot cracks and relative densities higher than 99.7 % were produced by LPBF.
II
Microstructural features, aging response and mechanical properties of the alloys were studied and compared with those of the Al-Cu-Ti-B-Mg-Ag (A20X), a commercial alloy for high temperature applications specifically developed for LPBF.
b) An Al-Mg-Si alloy (6182 grade) was doped with Zr following two different procedures. The first relies on mechanical mixing of Al powder with ZrH_2 particles, whereas the second one is based on the alloying of the molten Al with Zr during the gas atomization process. The pre-alloyed Al-Mg-Si-Zr alloy showed relative density higher than 99.6 %, no hot cracks within its microstructure and mechanical properties comparable with those of the extruded 6182 counterpart. On the contrary, the use of ZrH_2 particles led to high fraction of gas pores, which are ascribed to the entrapment of molecular hydrogen in the melt pool during solidification.
c) The effect of Cu on the processability of a 2024 Al alloy was investigated. Cu is responsible for the eutectic Al-Al_2Cu reaction at the end of solidification. An abundant eutectic phase mixture was revealed capable to enhance the solidification cracking resistance of the material. A refined microstructure was found in samples with more than 10 wt.% of Cu, featuring no hot cracks and relative densities higher than 99.5 %. Similarities and differences with respect to Al-Cu alloys produced by conventional welding techniques were highlighted and discussed.
d) An Al-Mg-Zr-Sc alloy with reduced content of Sc was processed by LPBF. Its microstructural features, aging response, crystallographic texture and mechanical properties were investigated. Simulations of $Al_3(Sc,Zr)$ precipitation were performed to predict the yield strength of the aged alloy. Tensile properties of the alloy were compared to those of Scalmalloy, a commercial Al-Mg-Zr-Sc alloy featuring a higher amount of Sc.

A STUDY ON DRIVE-BY MONITORING, A TECHNIQUE TO SUPPORT DECISION-MAKING ON BRIDGE MANAGEMENT

Lorenzo Benedetti - Supervisor: Prof. Marco Belloli

Infrastructural networks are at the heart of countries' development worldwide. In this framework, bridges play a crucial role. Ageing represents a growing threat to these structures, and the current policies in matters of monitoring and maintenance do not address it effectively enough. In particular, today's best practices are not compliant with resource availability.

This work begins with an analysis of the problem of bridge monitoring, focusing on system needs and policymaking flaws. The basis for this is a broad literature review and personal experience gained through projects I worked on during my PhD. The findings emerging from this preliminary study motivated the search for new techniques to bridge the gap and support decision-makers in prioritising interventions. Drive-by monitoring is deemed a promising tool for quick and cheap data collection, helpful in performing the first-stage screening of our infrastructural networks. As represented in Figure 1, the idea behind this technique is to sense bridge vibrations by putting sensors inside crossing vehicles.
This thesis approaches the topic by providing a literature review aimed at presenting what has been done so far and which are the challenges to bringing drive-by monitoring to a real-world application. The result of this analysis has been the choice of a set of operational parameters to study their impact on the performance of the technique.

The work is based on a fully data-driven methodology, founded on two experimental case studies – Figure 2 – designed to address research questions related to the variables of interest.

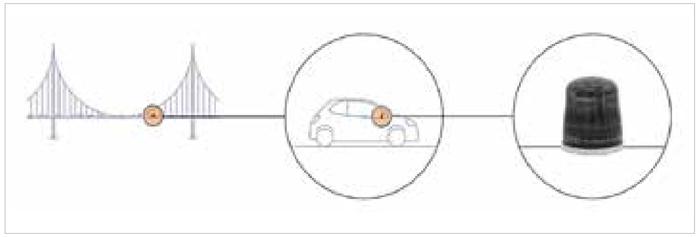

Fig. 1 - Schematic representation of the idea behind the technique of drive-by monitoring.

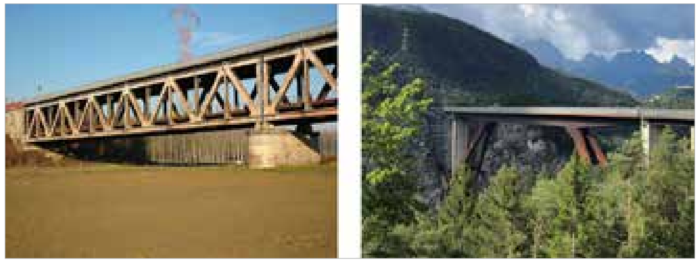

Fig. 2 - The two case studies. On the left the Bressana bridge, on the left the Cadore bridge.

Indirect frequency identification is performed on the first bridge to investigate optimal sensor placement. Also, a wavelet-based algorithm is tested. The second case study analyses the effect of vehicle dynamics, sensor performances, travelling speed, and spatial localisation accuracy by estimating mode shapes. To understand the impact of big data, both case studies explore the relationship between number of trips and accuracy of the results.

The positive outcomes of the research on the vehicle dynamics effect, tested through a comparison between cars and e-scooters, combined with the promising contribution of big data, guided the last case study. The latter proposes a scenario of crowdsourced data from shared micromobility to scan urban bridges. The analysis is based on a real data set of usage, made of nine million e-scooter trips in twelve US cities. The results suggest the feasibility of this application.

ROBUST PROGNOSTICS APPROACHES FOR MACHINE TOOLS UNDER VARIABLE OPERATING CONDITIONS

Luca Bernini - Supervisor: Prof. Paolo Albertelli

Introduction

Manufacturing productivity targets are nowadays demanding for maximum reliability and availability of machine tools (MTs), whose breakdowns and failures need to be fully avoided. Currently, industrial maintenance policies are based either on reactive or preventive strategies, leading to high repairing costs or to excessive maintenance actions, respectively. Prognostics and Health Management (PHM) is based on prediction of Remaining Useful Life (RUL) of components, thus becoming more and more attractive in industrial environments. Thesis activities ramified into three branches: cutting tool prognostics, process and tool monitoring by the analysis of machined surface images, prognostics of machine tool auxiliaries (i.e., the hydraulic unit).

Challenges

The main limitation on the applicability of current literature solutions is the inflexibility with respect to working conditions, being typically trained with run-to-failure data obtained in fixed and stationary operational conditions. This aspect leads to two main shortcomings: the need for experimental tests in all the expected working conditions of the system (not affordable in industrial applications) or the applicability of such approaches only in the experimented conditions (critical for most of the manufacturing companies since MTs rarely reproduce the same task for their entire life, only for mass-production industries).

Objectives

Based on the identified challenges, the research objectives were to develop:

1) PHM solutions requiring minimal experimental effort, both for cutting tools and machine tool auxiliaries prognosis.
2) PHM solutions which are robust or independent from the variability of operating conditions.
3) adaptive prognosis solutions flexible enough to adjust with respect to unseen degradation patterns.

Methodology

The proposed solution consisted of a modular approach (Fig.1) suitable for many metal cutting processes (i.e., milling, turning, and drilling). The solution relied on system and/ or process modelling. Cutting tools prognostics was based on the use of mechanistic force models to extract process independent features (SFC). Prognosis algorithm exploited a single run-to-failure and adapted to different degradation trends through its hybrid nature (statistics and AI fusion).
The analysis of machined surface images was conducted using a convolutional neural network, conceived to learn from a limited dataset. The algorithm classified images distinguishing between surfaces produced by healthy or worn tools, and classifying the process parameters.
Auxiliaries' prognostics was based on fault emulation by a digital twin of the system, to avoid the use of experimental run-to-failure tests. The digital model of the system was simulated under different working conditions and fault combinations, to train a data-driven multi-classifier diagnostic module and feed the prognosis module.

Results

TOOL WEAR - The evolution of SFC during a run-to-failure test is shown in Fig. 1c. As can be seen the SFC were correlated to tool wear. Self-starting control charts were applied as a real-time monitoring tool (with the aid of AI clustering techniques, to deal with unmodelled phenomena) to detect failures from SFC evolution, like cutting edge chipping, notch wear and maximum allowable flank wear. The prognosis solution showed good adaptivity in predicting cutting tool RUL. The performances were good overall: only 6 combinations out of 25 train-test run-to-failure pairs didn't allow to correctly estimate tool remaining useful life (when initialising just on one run-to-failure). Three of them resulted in tool life underestimations (i.e., false positives), which represented a safer error condition with respect to overestimation.
SURFACE ANALYSIS – The developed deep learning approach was cross-validated upon a dataset of 100 milled surfaces processed under different cutting parameters. The approach allowed performing inference on the cutting process, by analysing the technological signature left on the workpiece. The approach classified correctly both cutting parameters and undesired conditions (cutting tool chipping and excessive run-out) with an average accuracy of 81% (compared to 76% of the literature reference algorithms).
HYDRAULIC UNIT - The diagnosis of faults on modelled data was accomplished together with component failures RUL prediction. Prognosis provided good results in linear degradation cases, with increasing prediction capability while reaching the component failure.

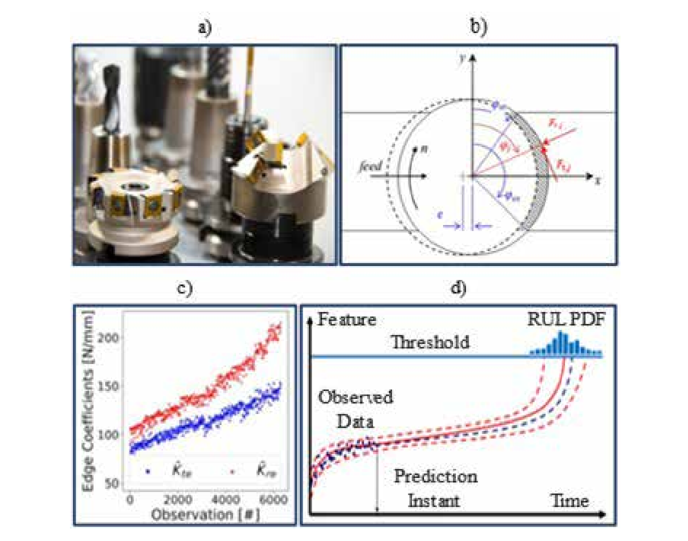

Fig. 1 - a) Cutting/machine tools variable operating conditions; b) Process/System modelling; c) Wear dependent features, cutting condition independent; d) Adaptive RUL probability density function prediction

Conclusions

The developed solution for cutting tools allowed building an unsupervised real-time monitoring framework for cutting tools, accompanied with an adaptive tool prognosis strategy. The solution is robust, based on cutting phenomenology, and suitable for industrial scenario, relying on a negligible experimental effort. Furthermore, it can be coupled with a surface quality analysis approach from machined surface images, enabling tool diagnosis and process inference.
The developed digital twin allows simulating the machine tool auxiliaries in variable operating regimes and with faulty components. Training of data-driven classifiers and hybrid prognosis was performed on digital twin simulations, avoiding the need for experimental run-to-failures.

ENGINEERING METHODS AND TOOLS TO SUPPORT THE DIAGNOSIS AND TREATMENT OF CARDIOVASCULAR DISEASES

Michele Bertolini - Supervisor: Prof. Giorgio Colombo

In the last decades, a fast and impressive development of tools and information systems in mechanical engineering was observed. Among them, Additive Manufacturing (AM), numerical simulations, Augmented and Virtual Reality (AR/VR) and Reverse Engineering (RE) technologies have reached such a degree of maturity that can be systematically extended and applied also in the medical field, in order to optimize and improve the quality of diagnosis and therapy. The resort to these engineering technologies opens the way to an innovative approach, which takes into account patients' anatomical variability, specifically in pathological conditions. Personalised medicine relies on the so-called patient-specific modelling, namely the creation of 3D digital models of the anatomical district of interest, starting from bioimages acquired from the patient.
Even in different declinations, the common thread of this PhD project is given by patient-specific modelling, applied to cardiovascular anatomies. The main objective consists in the development of dedicated engineering strategies able to support clinicians in patient-tailored approaches, in a synergy between different engineering methodologies and clinical expertise. This project, partly developed through active collaboration with clinicians, wants to provide an example of how innovative engineering methodologies originally developed in other fields can have a significant impact also in the cardiovascular field. In an increasing complexity path, the culmination is represented by the development and testing of an innovative physical cardiovascular simulator for a transcatheter heart valve repair procedure.
After some introductory hints about the anatomy, physiology and pathology of the cardiovascular system, the work starts with a state of the art about bioimages segmentation, namely the procedure through which 3D digital anatomical models are obtained.
The following part is focused on the evaluation of the accuracy the segmentation procedure can guarantee, when applied to blood vessels. Indeed, because of its crucial role played in the project, it is important to have a clear idea of the correspondence between segmented models and real anatomies. This is strictly related to the following evaluation of how the segmentation process can affect hemodynamic parameters, when extracted from Computational Fluid Dynamics (CFD) simulations conducted on these reconstructed models.
The next section is especially devoted to the heart, the central of the cardiovascular system. The first goal here is the implementation of a workflow that, starting from the stack of medical images, comes through segmentation until the hand-held printed model. In this way, the main criticalities in the process, starting from the challenges of this kind of segmentation, to the preparation of the model for printing, until the choice of the best printing technology and material, are delineated. This is accompanied by an evaluation of the level of agreement between printed results and digital models. On the basis of a RE approach, printed models are re-acquired with a laser scanner and these acquisitions are compared with the original Standard Tessellation Language (STL) files.
Afterwards, research moves to flexible resins, to print a compliant heart model. Starting from the already introduced segmented heart models, different solutions are tested, trying to replicate as much as possible a realistic mechanical behaviour for the print, in such a way it could effectively serve for training and surgical planning. Here careful resins selection, with a differentiated hardness assignment within the same model, plays a crucial role.
As already hinted, a major point deals with the development of a 3D printed training simulator for the repair procedure of a heart valve, the mitral one, when regurgitant, so it cannot close properly anymore. The previously acquired know-how turns out to be decisive for the generation of a highly realistic physical simulator, for the MitraClip™ Procedure (MCP), the most widely adopted transcatheter minimally invasive approach to repair the regurgitant Mitral Valve (MV). This is a recent and technically challenging procedure, with a steep learning curve. However, current training is typically performed on simplified models, which do not consider anatomical features, realistic materials or procedural scenarios. The aim is to propose a novel 3D printed, anatomy-based training simulator, which takes into account these aspects, thanks also to the active collaborations of experienced end-users. During the project, this simulator was designed, manufactured and tested with MitraClip equipment. It was assessed to be feasible to practice in a realistic fashion different procedural aspects including access, navigation, catheter steering and leaflets grasping. In addition, the model was found to be compatible with clinical procedural imaging equipment. Future studies will assess the effect of the proposed training system on improving training.
Developments of this thesis work can be grouped into three main categories, namely translation to clinical practice, research on materials and integration with complementary technologies.
For the first point, increasing research on automatic algorithms is fundamental, to overcome the bottleneck represented by the time and competencies required to segment and post-process anatomical models, which still prevents a wider spread in operative environments.
Despite the considerable improvements in recent years, there is not yet a material able to realistically replicate the complex mechanical properties of biological tissues, also because of the wide variability of patients' properties. The recent introduction of new resins and research on Functionally Graded Materials (FGM), as also in perspective the increasing interest in 3D bioprinting, could help in this.
Eventually, even more interactive and realistic medical experiences could be obtained by combining 3D printed models and simulators with extended reality. For example, the integration of the developed MitraClip simulator with AR technologies could be an interesting step forward and enrichment of the clinical training protocol.

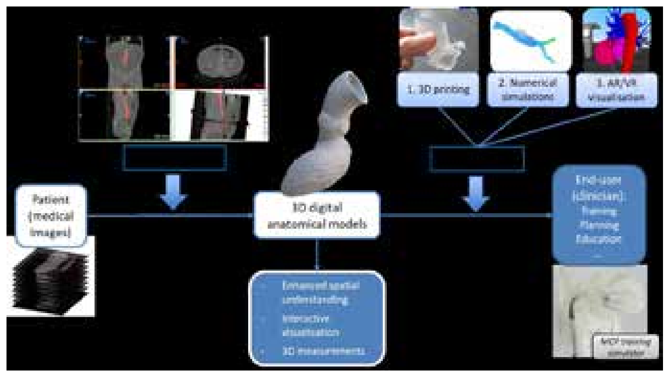

Fig. 1 - Backbone of the work: the generation of 3D digital cardiovascular models with applications in clinical practice

NANOPARTICLES-MEDIATED PHOTOTHERMAL THERAPY AND LASER ABLATION FOR CANCER TREATMENT: NUMERICAL MODELING AND MONITORING OF THE THERMAL EFFECT

Leonardo Bianchi - Supervisor: Prof. Paola Saccomandi

Laser ablation (LA) is a thermal therapy that exploits the conversion of laser light into heat to induce localized thermal damage in tissue. LA represents an attractive technology to treat tumor lesions owing to the possibility of being performed with a minimally invasive approach, hence reducing tissue trauma, and targeting the tumor site also in proximity to delicate anatomical locations. These advantageous characteristics, along with the associated low morbidity rate and cost-effectiveness, make LA a possible alternative procedure to conventional treatment methods. Especially, LA is gaining acceptance for treating patients that are not eligible for traditional surgical excision. Nevertheless, the main technical challenge preventing the widespread adoption of LA in the clinical routine is due to the complexity of effectively treating the target tumorous region, while avoiding collateral damage to the surrounding healthy tissue.
To overcome this hurdle, technological expedients and methodologies have been proposed. The use of highly laser-absorbing nanoparticles to increase the treatment selectivity, the adoption of temperature monitoring strategies for assessing the tissue thermal effect, and the development of accurate mathematical frameworks to predict the treatment outcomes, have opened new horizons for photothermal treatments.
In this regard, my Ph.D. project presents a combinational strategy based on: (i) monitoring the thermal outcome during photothermal therapy (PTT) assisted by rod-shaped gold nanoparticles (GNRs), (ii) the measurement of the tissue physical properties influencing the heat transfer, (iii) the development of a numerical model of the therapy, with the final aim to provide insights for the optimization of photothermal procedures (Fig. 1).
Regarding monitoring GNRs-mediated PTT, a first *in vitro* evaluation was performed to determine GNR cytotoxicity, cell internalization, and the proper treatment settings to attain decreased tumor cell viability thanks to the combined action of GNRs and laser irradiation.
In vivo experiments were then carried out in subcutaneous breast tumor models. High-performant thermographic imaging was exploited to investigate in real-time the superficial temperature due to laser irradiations, at different wavelengths of the therapeutic window (i.e., 808 nm, 940 nm, 975 nm, and 1064 nm), combined with GNRs. For comparison, each adopted GNR type was selected to exhibit an absorption peak respectively matching the stimulating radiation wavelength. The thorough thermal analysis of the measured temperatures allowed for assessing the laser wavelengths associated with a possible higher treatment selectivity, i.e., higher temperature differences when GNRs were administered compared to when tissue was exposed to radiation without GNRs. Additionally, the estimation of the time constants of the temperature evolutions provided useful insights into the diverse heating kinetics ascribable to the laser-tissue interaction at the different wavelengths.
Furthermore, to assess the internal tumor temperature evolution during GNRs-mediated PTT, the feasibility of fiber Bragg grating (FBG) sensors-based thermometry was explored. Femtosecond laser-inscribed custom-made FBG sensors allowed multiple sensing points within the tumor lesion to accurately describe the evolution of internal tumor temperature. Besides, they allowed the reconstruction of high-spatially resolved two-dimensional thermal maps. The good metrological features of the adopted sensors, i.e., short time response, high thermal sensitivity, millimetric resolution, 0.1 °C accuracy, along with multiplexing and multipoint measurement capability, foster the employment of these sensors for monitoring nanoparticle-assisted PTT.
Concerning the measurement of the physical properties of biological tissue, the thermal and optical properties were the principal focus of the investigation due to their implication in the photo-thermal processes. After a comprehensive literature review, it was noticed the lack of studies characterizing the thermal properties up to temperatures typical of ablative procedures. Hence, in this Ph.D. project, the thermal properties (thermal conductivity, thermal diffusivity, and volumetric heat capacity) of several biological tissues (i.e., heart, lung, liver, brain, pancreas) were measured in a controlled environment from nominal temperature up to >90 °C, by means of transient hot-wire method adopting a dual needle probe. Regression models based on the measured values were proposed to be utilized in mathematical frameworks of the therapy to maximize the accuracy of the prediction; the measurement uncertainty of each thermal property in the considered temperature range was estimated. Additionally, the optical properties, i.e., absorption and reduced scattering coefficients, of biological tissue (pancreas) were characterized using time-domain diffuse optical spectroscopy in a broad wavelength range (600 nm - 1100 nm). The attained results may provide indications on the laser wavelengths to be employed in the case low or high tissue attenuation is desired, and quantitative values to be used in the simulation of laser-based therapies and for the realization of tissue-mimicking materials.
Finally, an innovative numerical model was developed based on the bioheat transfer equation. The model was devised to consider the dynamic variation of the thermal and optical properties of biological tissue during the procedure, which has a major impact on the thermal outcome. Moreover, it also simulated the presence of the physical temperature sensors, i.e., FBG sensors, as in a real experimental scenario. Simulations were performed to determine the peak temperature trend, volumetric heat distribution, and thermal damage to evaluate a possible temperature-controlled system of interstitial LA. Indeed, the power of the laser light was controlled based on the measurement provided by the FBG sensors to confine the thermal damage in a specific tissue region. The numerical model allowed for the evaluation of different sensor locations on the final thermal outcome and tissue damage. The model was then experimentally validated, showing an accurate prediction of the temperature evolution for the different sensor configurations. The attained results suggest the applicability of the model for the investigation of different sensor-based controlling strategies for photothermal procedures.
Overall, the developed numerical model may serve as an effective tool for the investigation of different parameters affecting thermotherapies. Besides, the monitored tissue thermal effects ascribable to laser irradiation at different wavelengths and the measured physical properties may provide further insights into the in-depth study and optimization of photothermal treatments.

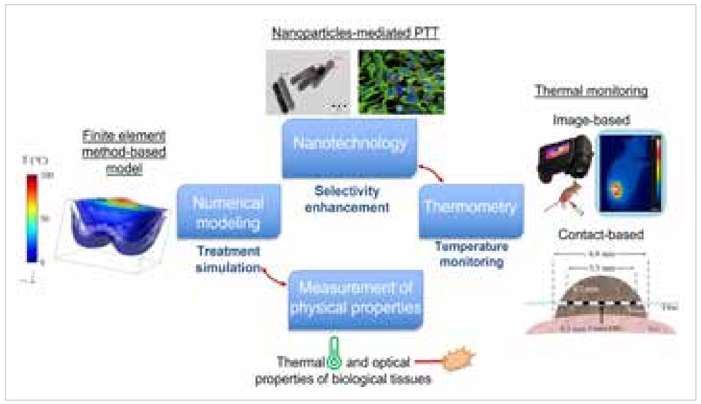

Fig. 1 - Technological strategies and approaches utilized in this Ph.D. project toward the optimization of LA for tumor treatment: i) use of nanotechnology approaches to increase the treatment selectivity (nanoparticles-mediated PTT), ii) temperature monitoring during treatment through image-based and contact-based techniques, iii) measurement of the physical properties of biological tissue, iv) development of a numerical model, based on the finite element method, to simulate the treatment.

ADAPTIVE ROBOTIC LASER BEAM WELDING: ONLINE VISUAL CORRECTION OF ROBOT TRAJECTORY AND CONTROL OF WOBBLING FOR SEAM TRACKING AND GAP BRIDGING

Davide Maria Boldrin - Supervisor: Prof. Barbara Previtali

Co-Supervisor: Prof. Ali Gökhan Demir

High-brilliance laser beam welding (LBW) is a joining technology known for its quality and speed, and can weld thick materials with high irradiance and reduced heat inputs. On the other hand though, the sharp laser tools (often in the range of 0.1 mm - 0.5 mm) require as small errors both in joint preparation and in weld execution, and the process is little tolerant to imperfect _t-up conditions (gaps) and inaccurate laser tool positioning. The combination with anthropomorphic arms is common in industrial practice but the low accuracy of such manipulators has restrained applications to simple weld geometries, not exploiting their dexterity, i.e. their attitude to follow complex trajectories in space. Seam-trackers have been proposed as systems to absorb positioning errors with online compensations of robot motion but have similarly fallen short on weld path complexity, focussing mainly on linear joints on planar workpieces. Moreover, the susceptibility to gaps has con_ned LBW mainly to applications of hard automation with dedicated _xtures whereas small-batch production and simpler _xtures have been long deemed less feasible. Dynamic beam-shaping (wobbling) can be used to relax both issues: with an online control of laser-material interaction, better gap-bridging is possible; moreover, thanks to the wider virtual spots, the accuracy required to the positioning is also relaxed.
A combination of these two techniques (seam-tracking and wobbling), although desirable, has not been implemented in research nor industry in a detailed way. The current work, therefore, discusses the design and implementation of an integrated control system that combines the two techniques for enhanced process exibility.
At the basis of this work lies a robotic LBW cell with dynamic beamshaping capability. A dedicated coaxial vision system and a custom machine vision algorithm for robust seam detection compose its sensing. On top of it, a double control system for simultaneous seam-tracking and gap-bridging is implemented.
The increased adaptability of the system is successfully assessed on curved trajectories with variable gaps and its application to an industrial case of structural beam welding is _nally discussed.

Keywords: Robotic laser beam welding; adaptive process; visual control; seamtracking; dynamic beam-shaping; gap-bridging

CROSSWIND EFFECTS ON TRAINS AERODYNAMICS

Elia Brambilla - Supervisor: Prof. Daniele Rocchi

The interest in trains aerodynamics has grown exponentially in the last twenty years. With the increase of trains speed, their mass reduction and the advent of high-speed trains, new aerodynamic issues developed and became constraints for rolling stock manufacturers and railway infrastructure managers. This work explores the trains (both high-speed and conventional) aerodynamic behavior in open air, with particular attention on how the presence of atmospheric wind can modifies their aerodynamics and safety, in term of overturning risk and Characteristic Wind Curves (CWCs, i.e. the maximum atmospheric wind values that the train can safely support). Full-scale experimental tests and Computational Fluid Dynamics (CFD) simulations highlighted the slipstream characteristics of high-speed trains (i.e. the air field dragged by the train passage, Fig. 1) and the large influences also of mild wind (up to 5 m/s) on the phenomenon, with consequences on the trains homologation procedure. URANS unsteady simulations turned out to be able to reasonably reproduce the phenomenon of slipstream (in term of average value and wind gust), also in presence of wind. An approach based on the splitting of simulation domain was tested, in order to make high fidelity simulations approach (like DDES) computationally possible on full-scale trains, giving encouraging results.

Wind tunnel tests (Fig. 2) and multibody calculations showed that, in presence of strong crosswind (up to 35 m/s), conventional trains have same overturning risk compared to high-speed trains. Due to the large number of conventional lines, the train shape optimization is a key crosswind countermeasure for this train type, as other common countermeasure in the high-speed lines like anemometers alarms or windbreaks may not be feasible. For conventional operative speed (i.e. up to 160 Km/h) with a 20% improvement in the aerodynamic coefficients, 10% higher CWCs can be obtained. Attention must be paid on the numerical determination of the train aerodynamic coefficients, as the CFD models that give good results on high-speed train geometries, don't have the same performance on conventional train geometries, resulting in large discrepancies from the coefficients measured in wind tunnel.

In case of high-speed lines, it is possible to protect the trains runs with windbreaks barriers. An innovative numerical procedure, based on wind tunnel tests (Fig. 3), moving mesh CFD simulations and a statistical data processing, was developed to evaluate CWCs in presence of windbreaks and windbreaks with gap. Results for Italian scenario showed that the windbreaks presence decreases 3 order of magnitude the overturning probability with respect the open-air case. In addition, the presence of also large gap (30 m) does slightly affect the mitigation performance, as the overturning probability increase 3 times with respect the continuous barrier case.

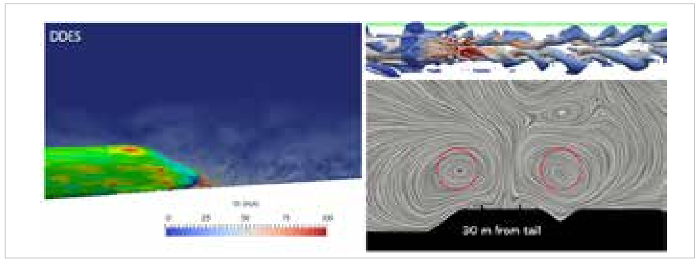

Fig. 1 - CFD simulation of high-speed train slipstream.

Fig. 2 - Wind tunnel test of a conventional train.

Fig. 3 - Wind tunnel test of a high-speed train in presence of windbreaks.

GAP (IMAGE-GUIDED COMPUTATIONAL AND EXPERIMENTAL ANALYSIS OF FRACTURED PATIENTS)

Federica Buccino - Supervisor: Prof. Laura Maria Vergani

We're currently living in an aging society threatened by the burden of fragility fractures. Fragile fragmented bones. Fragile patients. Fragile psycho-social and economic balances.
As Europe (EU) population ages, the incidence and contribution of fragility fractures to the overall healthcare spend continue to increase, raising a big red flag. Every year, 2.7 million fractures occur across the EU6 nations with an associated healthcare cost of €37 billion. This annual expenditure is predicted to increase by 23% (to €47 billion) by 2030. In addition to the cost issue, the physical and emotional impact must not be overlooked. These aspects are linked to the concept of frailty, defined as an increased vulnerability due to long-term hospitalization for fracture treatment, impaired quality of life and disability. The impact of fragility fractures suffers from an imbalance due to an evident gender gap: the number of women exceeding a fracture threshold is six times higher than in men. Beyond the immediate distress, healing time, and recovery associated with a fracture, an initial fracture significantly increases the risk of subsequent fractures and can trigger a negative spiral of healthcare dependence, escalating expense, and impaired quality of life, despite the existence of treatments and programs for secondary prevention of fragility fractures.
Nowadays, an additional high impact wake-up call rises from the outbreak of Covid-19 pandemic: a slowdown in bone formation processes is hypothesized as a direct outcome of the infection, which, together with the increased sedentary lifestyle of the bedridden hospitalized patients, could lead to a reduction in bone mass and strength.
All these contributing factors highlight the need and urgency to address right now the fragility fracture crisis: early diagnosis and effective treatment are the keys for targeted and preventive therapeutic strategies.
Despite the evident health- and economic-related interests about bone fractures, their comprehension, prevention and treatment are still limited to the macro-scale level, where their occurrence is already catastrophic. This is mainly due to the puzzling numbers of parameters to be considered when dealing with bone fractures, such as bone structural and morphological features and its complex hierarchical organization driven by intricate remodeling processes. This multi-scale complex and dynamically evolving arrangement is reflected in fracture patterns; indeed, damage occurs at different scales.
Common clinical tools for the evaluation of bone mineral density (BMD) such as dual X-ray absorptiometry (DXA) perform just a meso-scale analysis and are limited in their ability to consider the presence of bone fractures. In the case of vertebral fractures, BMD can only predict the 70% of them, raising the motivation to combine the diagnosis with measures of bone quality, that cover geometrical and material features of the macro- and meso-architecture. At the micro-scale a complete comprehension and knowledge of bone damage and its effects are completely lacking. For the identification of micro-architectural features and the understanding of their role in fracture occurrence, high-resolution imaging techniques such as micro-computed tomography (micro-CT) or synchrotron radiation could potentially be used in combination with artificial intelligence tools for image processing and subject-specific computational models. Despite the rising curiosity in their application, according to the 3R principle that proposes the replacement, reduction and refinement of animal experiments in favor of tests on surgical wastes and in silico models, these approaches are still on a preliminary stage.
The lack in comprehending bone fragility fracture occurrence therefore translates in a dramatic prevention and treatment deficiency.
Consequently, there is an imperative need to recognize fragility fractures as a public health priority, and to establish fracture prevention and management as an integral component of healthy aging.
In this context, "image-Guided computational and experimental Analysis of fractured Patients" (**GAP**) Doctoral Thesis project comes into play, providing interdisciplinary solutions for multi-scale comprehension of bone fractures, towards the definition of preventive patient-specific strategies (Figure 1). The over-arching **high-risk high-gain aim** of the current work is to bridge the gap between the research and the clinics by approaching the fragility fracture crisis from three sides: the elucidation of bone damage onset with a critical eye on the micro-scale via high-resolution synchrotron imaging, the identification of the pathology-induced alterations precisely at the scale where pharmacological treatments act and the implementation of multi-scale computational models for the definition of local stress intensification sites.
GAP methodological strategy has the potential to overcome the silent paralysis of EU healthcare system, threatened by the burden of fragility fracture economic and psycho-social consequences.
With this long-term aim, we tested under compression 144 samples belonging to healthy and osteoporotic femoral heads, capturing local mechanical properties variation to meso-scale morphological alterations. Among these samples, ten are selected to be tested inside the synchrotron and scanned at different time-frames (corresponding to progressively increased applied compression) for assessing real-time meso and micro-scale damage progression. We demonstrate that manual segmentation processes in the detection of micro-scale bone features can be overcome by means of convolutional neural network-based approaches, that represent a potential for increasing the size of the analyzed trabecular regions. The possibility to compare intra-sample and inter-sample variability both in presence of healthy and osteoporotic bone samples is a hint for discussing the variability in the local architecture and its eventual alterations. Micro-cracks analysis is approached through a methodical translation of fracture mechanics concepts to human bone micro-fracture. These findings bridge gaps between micro-scale crack visualization and precise quantification of micro-scale morphological features and structural phenomena. This opens the doors, then, to the forthcoming definition of micro-scale fragility indexes, as a connection between research routes and clinical strategies for early detection of bone fractures.

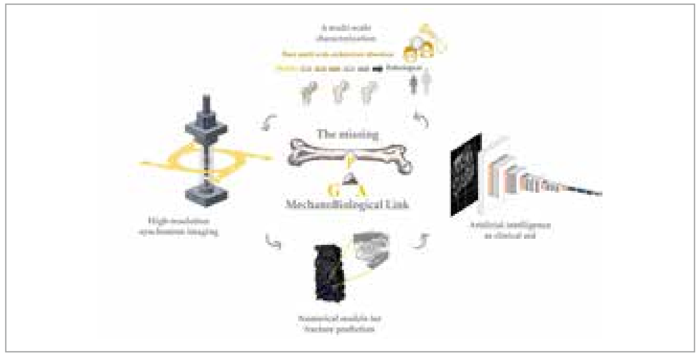

Fig. 1 - GAP multi-disciplinary methodological approach towards bone fragility prevention.

IN-SITU MONITORING IN AM: NOVEL SOLUTIONS FOR PROCESS QUALIFICATION

Matteo Bugatti - Supervisor: Prof. Bianca Maria Colosimo

Additive Manufacturing (AM) is known to offer unprecedented capabilities for producing functional mechanical parts that offer improved performances at just a fraction of the weight. However, typical AM components are characterized by complex shapes and features that are difficult to manufacture and increase the likelihood of incurring in the formation of defects. Moreover, qualification with standard non-destructive inspection (NDI) techniques can be challenging and create difficult conditions for the verification of part quality requirements. To foster the adoption of AM to a larger audience, the AM industry needs to develop new solutions to improve the process stability as well as new methods to qualify the part and support the NDI of complex components. In-situ process monitoring is a key tool for this purpose because it allows exploiting the layer-by-layer manufacturing scheme of AM to acquire data during the building process and, via in-situ signature and process defect correlation, it can be employed to detect instabilities for in-process part qualification. However, the development of in-situ monitoring is still at an early stage and several limitations exist in (i) the number and type of sensors available to acquire relevant process signatures, i.e. observable process characteristics, (ii) the correlation between process signatures and defects formation in the final part and (iii) the way the in-situ data are processed to provide real-time feedback about process quality. In this work, all these research topics are addressed by exploring new methods for in-situ monitoring and data processing that target the typical defects that form when building complex features. The industrial applicability of all techniques developed in this work was also carefully evaluated to develop methods that can be effectively applied and transferred to an industrial environment to provide real-time feedback to the process user.

Keywords: Additive Manufacturing, In-situ process monitoring, geometrical complexity, defects

IN-SITU MONITORING FOR DEFECTS DETECTION AND CORRECTION IN ADDITIVE MANUFACTURING PROCESSES

Fabio Caltanissetta - Supervisor: Prof. Bianca Maria Colosimo

Additive Manufacturing (AM) is one of the major technological game changer of the last decades. It allows the production of complex-shaped, lightweight bioinspired parts with high thermomechanical performance in a large variety of materials ranging from metals to composites and ceramics. The significant investments of many companies in different sectors, namely aerospace, automotive, oil and gas and healthcare, are a clear proof of the technological relevance of AM technologies in the industrial panorama.
Regardless of the specific AM technique, the lack of process stability and repeatability is still considered a major issue for the technological outbreak, as it can strongly impact process defectiveness, which is a crucial factor for poor mechanical performance, increased costs due to the expensive raw material and long processing times.
For this reason, the attention of the scientific and industrial communities is currently focused on in-situ monitoring solutions, which can in principle prevent and mitigate material waste and part failure. This research field has been indeed expanding at a fast rate in the last few years, with an exponential growth especially focusing on AM technologies that recently came under the spotlight. Among them, Extrusion-based AM processes are receiving a renewed attention for their flexibility, the possibility of printing large scale products (higher than 1 m3) in a large variety of materials (techno-polymers, metals and ceramics), primarily for machinery and aerospace sectors.
So far, many studies on in-situ monitoring of Extrusion-based AM processes focused mainly on proposing new sensing acquisition setups with the main objective of studying the process evolution. Few preliminary works have combined big data mining with machine learning and statistical process monitoring solutions to fully address in-situ defect detection.
Regardless the AM technique, assuming a defect is automatically detected by the in-situ monitoring solution, few approaches have been proposed for inline defect mitigation, correction and or removal.
These research challenges are the bases for this PhD thesis, which is meant to discuss novel solutions for defect detection in Extrusion-based AM process and to present a brand-new patented prototype for inline defect correction.
Two main strategies will be considered for statistical process monitoring and control for in-situ defect detection.
The first one makes use of the dynamic process signatures (i.e., process features evolving during the printing process) to characterize the process stability as related to the temporal changes of the process fingerprint. The second dimension of research mainly focus at the layerwise level, taking advantage of images collected at the end of the printing layer in order to analyze the part quality at each stage.
The first approach for dynamic defect detection presents a new solution for modeling and controlling the spatial maps of the temperature evolution, since this is a major driver of material bonding quality thus affecting the final mechanical performances. This work was partially carried out during the period abroad at the Massachusetts Institute of Technology - MIT, together with Prof. Anastasios John Hart and Gregory Dreyfus (MIT), working on a case study of Big Area Additive Manufacturing (BAAM) from the Oak Ridge National Laboratory.

The second solution for SPC based on layerwise images, consists of a novel method for automatic flaw detection when stochastic textured surface has to be analysed. Several new elements characterize this second research results, as out-of-control detection of local defects in highly textured surfaces can be a complex task that currently lacks appropriate solutions. In this case, novel methodology based on random trees and distributions similarity measures will be combined with statistical process monitoring to face this open challenges.
Although applied to Extrusion-based technology, defect detection of layerwise images is a general approach that can be applied to other AM processes, like Powder Bed Fusion (PBF).
With reference to PBF, the PhD thesis will eventually present a novel approach for in-situ and in-line defect correction, to move a step forward in the direction of zero-waste, first-time-right AM. The proposed solution originated on a newly patented prototype named "Penelope" representing the first highly-sensorized AM machine which integrates a rectilinear grinder devoted to the defective layer removal. The capability of detecting major dimensional and geometrical defects will be first discussed and the in-situ acquisition system performances will be characterized. This part of the study will determine which magnitude of dimensional defects can be detected by the in-situ setups and what are the best illumination condition and segmentation algorithm for an accurate inline measurement.
Finally, the effects of layers grinding will be discussed.
More in details, the possibility of restoring the powder bed, of eliminating chip contamination, as well as the capability of preserving mechanical performances and products quality will be deepened. All the experimental campaigns were specifically designed and tested in the AddMe Lab laboratories of Politecnico di Milano1
Even if not included in the discussion of this PhD thesis, a final chapter will briefly describe an additional activity carried out during the PhD, focusing on multimaterial L-PBF.

SMART WHEELSET: HIGH-SPEED WHEELSET DEFECT IDENTIFICATION BY MEANS OF AXLE-BOX ACCELERATION MEASUREMENTS

Stefano Cii - Supervisor: Prof. Gisella Tomasini

In recent years, an increasing interest in the Internet of Things (IoT) has grown in almost every technical field of our society. The miniaturization of electronic components, together with the exponential growth of microprocessor computational power, allows a higher number of devices to be instrumented with sensors and to be connected each other by means of the Internet. This opens interesting new horizons also for the railway field. The possibility of introducing sensing electronic in mechanical components is very promising both to increase the safety and security level and to improve the maintenance of mechanical component itself.
Objective of the present PhD thesis is the design, realization and test of a Smart Wheelset for the Italian high-speed train ETR1000. A smart wheelset means a complete and embedded system characterized by a set of sensors on board, provided with a wireless communication system able to perform an early identification of the wheel defects, by means of proper algorithms. For the present research, the measurements coming from a 3-axial accelerometer are considered, but the possibility to install other sensors to be integrated in the same system, thanks to a great flexibility of the system, can be of great interest in this field.
In this PhD thesis the focus of the work will be on the development of algorithms aimed at the identification, from Axle-Box Acceleration (ABA) measurements on-board, of two main defects that may occur on a High-speed train wheelset: Wheel-Flat and transversal Crack in the resistant cross section of the axle.
Wheel-Flat is a local defect of the wheel profile. Usually, it is caused by a blockage of the wheel during emergency breaks. The presence of a Wheel-Flat generates periodic impulses on the track (1 time for each complete revolution of the wheel), leading to damages both on the infrastructure and on the vehicle itself and reducing the comfort on board of the vehicle during the running dynamic.
The presence of a wheel-flat, especially at high speed, can seriously endanger the vehicle dynamic leading, in the worst cases, to possible derailment of the vehicle.
Cracks on the wheelset usually develops along the resistant cross section of the axle. Cracks start from a local defect on the surface of the axle (geometry defects are often observed in correspondence of the junction between wheels and the axle where a shape change is observed, or they are caused by ballast hitting and damaging the surface of the axle) that propagates while the wheelset rotates, and the axle undergoes successive stress cycles. Cracks are very dangerous for the safety of running dynamic since they slightly affect the mechanical system until the crack reaches a critical extension and the sudden failure of the wheelset occurs, leading to very severe consequences.
The early identification of these two defects can have very significant advantages: it allows to perform predictive maintenance of the mechanical component and to improve security and safety of the high-speed line, avoiding unexpected stoppage of the line or even, in the worst cases, accidents.
The results shown in this thesis are obtained thanks to a collaboration between the Mechanical Department of Politecnico di Milano and LucchiniRS that owns a full-scale wheelset test bench in Lovere, named BU300, able to reproduce the dynamical behaviour of the wheelset up to a speed of 300 km/h.

COMPOSITE PHASE CHANGE MATERIALS BASED ON THERMALLY- ACTIVATED IMMISCIBLE ALLOYS: FROM DESIGN TO FUNCTIONAL CHARACTERIZATION

Chiara Confalonieri - Supervisor: Prof. Elisabetta Gariboldi

Phase Change Materials (PCMs) are functional materials which undergo a phase transition under specific conditions.
In thermal applications, they can store thermal energy as latent heat associated to an endothermic transition (e.g., melting), releasing it when the phase change is reversed. This heat is an extra energy boost at constant temperature that is added to the sensible heat stored in a temperature range. PCMs can behave as heat reservoirs to keep a constant temperature over time (e.g., in solar energy systems, textiles for extreme cold conditions, space satellites or building envelops) or as heat sinks which support cooling systems (e.g., in electronic devices or industrial applications). The phase change can also induce variations of microstructural distribution and/or material properties (e.g., thermal diffusivity), thus providing extra functions to the material.
This doctoral dissertation focuses on metallic PCMs based on immiscible alloys and exploiting a solid-liquid transition. These composite materials (C-PCMs) consist of an active phase (the actual PCM) undergoing the phase transition and a passive phase providing additional features, like structural properties, enhanced thermal diffusivity and sensible heat, as well as form-stability of the system preventing shape changes and loss of material when active phase is molten.
The proposed systems are binary (Al-Sn, Al-In, Al-Bi, Cu-Bi) and ternary alloys (Al-In-Sn, Al-Bi-Sn) with various compositions, where Al and Cu behave as passive phase and the active phase consists of one or two elements. These systems span a range of transition temperatures between 100°C and 300°C.
Among the main advantages of metallic C-PCMs with respect to other material classes, there are high thermal conductivity, high energy storable per unit volume and good stability in material response over time and thermal cycles.
The aim of this doctoral research was studying a combination of theoretical and experimental methods to design and characterize metallic C-PCM systems, in order to accelerate their development and ease the match with design requirements.
The proposed method consists of performing preliminary thermodynamic calculations (with the CALPHAD method) on a set of potential C-PCM alloys and then producing only the ones which meet better the design requirements. Beside transition temperature and latent heat, the preliminary calculations give also reliable thermodynamic properties (e.g., enthalpy, density, specific heat capacity) for the composite system, that can be used in simulations considering either fully dense or porous materials. The analysis of material behaviour, theoretical and experimental, showed that some properties of interest follow opposite trends as function of composition, therefore the alloy design shall include an optimization of the composition in order to meet all the design requirements.
A significant part of the experimental work focused on the effect of production process on microstructure and properties, which cannot be evaluated with equilibrium thermodynamic calculations. In order to obtain a homogeneous dispersion of the active phase in the passive one, powder metallurgy processes (powder mixing, compression, sintering) and rapid solidification with powder bed laser melting were applied. The set of experimental tests for an extensive C-PCM characterization involved the analysis of microstructure, composition, thermal properties, and mechanical properties. An Al-Sn alloy with 20% of Sn in volume was tested as representative immiscible alloy. Its thermal and mechanical responses were correlated to microstructural features. Further, the effect on microstructure and properties of thermal cycles across active phase melting temperature was evaluated to simulate possible operative conditions. The results showed that phase distribution, which can be from coarse to fine depending on process parameters, has a strong impact on properties and stability over thermal cycles.

ADVANCED METHODS FOR EXPERIMENTAL ANALYSIS OF ADHESIVELY BONDED JOINTS UNDER MODE I CRACK PROPAGATION

Rosemere de Araujo Alves Lima - Supervisor: Prof. Andrea Bernasconi

Co-Supervisor: Prof. Michele Carboni

The use of adhesively bonded joints as a replacement for the traditional bolted and welded joints in the aeronautical and automotive industries has increased in recent decades, mainly due to their high mechanical strength associated with low weight and no negative impact on the adherends' mechanical properties. Moreover, adhesives are particularly suitable for joining dissimilar materials. Nevertheless, these joints are more susceptible to environmental conditions and present a relevant variation of their mechanical behaviour as a function of defect occurrences. It is challenging to ensure their reliability and safety during the joint's in- service life.
In primary structural applications, it is crucial to know the typical behaviour of components and accurately predict their failure. So, it is essential to adopt intensive periodic inspections to operate non-destructive testing techniques and implement advanced methods for in-service structural health monitoring of materials and components, especially considering adhesively bonded joints.
Structural health monitoring methods present the main advantage of real-time or on-demand components' structural integrity assessment. It requires the diagnosis of the structure by identifying, locating and quantifying damaged areas and the prognosis of its remaining useful life. Moreover, a condition-based maintenance plan can be implemented instead of preventive service interruptions, thus saving operational costs.
Several methods have been strongly encouraged for assessing the structural integrity of adhesively bonded joints, such as strain measurement, dynamic responses, scattering of guided waves, impedance variations and acoustic emission. Even so, there are still open points regarding understanding the relationship between the essential features for crack development and damage propagation within adhesive joints' bondline.
Therefore, this research aimed to study the link between different sensing solutions and the damage initiation and propagation within the joint's bondline. For that, quasi-static and fatigue mode I crack propagation tests were performed.
Two different ductile adhesives were used to bond metallic double cantilever beam specimens. It is worth mentioning that high-strength steel was chosen as the adherend material to avoid any crack competition, as it happens, for example, in the case of composite materials.
The backface strain approach was adopted, using Optical Backscatter Reflectometry distributed sensing. Acoustic emission methods were applied to monitor the adhesively bonded double cantilever beam specimens during the tests.
Digital image correlation and visual evaluation were also used as complementary techniques to track the crack propagation and correlate the crack positions with the acoustic emission and optical fibre responses.
Since the acoustic emission method is also very sensitive to background noise, artificial neural networks associated with unsupervised pattern recognition algorithms were used to cluster and classify the acquired data. After that, the acoustic emission sources associated with damage propagation were then localised and further filtered in base energy levels.
Specimen's backface strain profiles were obtained from the optical fibre-based strain measurements, and it was observed that their peak positions had been shifted while cracks within the bondline propagated.

Digital image correlation and visual evaluations could give information about the onset of plasticisation and the crack-tip positions (Figure 1), respectively. Finally, the peak positions obtained from the optical fibre's strain profile and the located acoustic emission sources were compared with the results obtained from digital image correlation and visual evaluation.
The results showed the feasibility of both methods in monitoring crack propagation in quasi-static and mode I fatigue crack propagation tests. The studied adhesives presented a non-negligible process zone length ahead of the crack tip, estimated by digital image correlation and visual evaluation.
For the quasi-static tests, the backface strain sensing could identify the onset of the plasticisation ahead of the crack-tip within the bondline, thus allowing for detecting the onset of damage before the complete failure of the adhesive. The same was observed for the high-energetic group of the localised acoustic emission sources. It is worth mentioning that the acoustic emission method required a more complex post-processing analysis due to the big data, and the final data was considerably scattered.
The fracture zone length was shorter for the fatigue tests.
By processing the optical fibre results by the same method applied to static tests, it was possible to identify the crack-tip position. Moreover, the strain peak values obtained during the tests were found to be a promising indicator of the crack propagation stage (stable or high-speed) within the adhesive.

STIFFNESS VARIATION DEVELOPMENT TO SUPPRESS CHATTER VIBRATION IN LARGE BORING MACHINES AND STUDY OF ITS POTENTIALITY IN COMBINATION WITH OTHER CHATTER AVOIDANCE STRATEGIES

Fabrizio Defant - Supervisor: Prof. Paolo Albertelli

Introduction

Nowadays, industries are asking higher productivity and performances from manufacturing systems, which leads to arising problems of unstable chatter vibration in metal cutting. Chatter is detrimental for both the machine and the workpiece health and due to its complexity it is difficult to be managed. During the years many strategies to predict, avoid and handle chatter have been developed. However, these tools are often relegated to the academia due to the complexity of methodologic frameworks and technical setups. This research exploits the synergy between the academia and the industry, to boost the development of the novel and promising stiffness variation and its combination with other chatter suppression strategies.

Challenges

The exploitation of chatter suppression strategies requires tools to evaluate quickly stability maps, which are available only for simplified cutting models. The main research challenge is the development of a general end efficient methodologic framework to study stability maps under many hypothesis. In addition, the direct identification of the experimental linear time periodic dynamics is critical to apply the methodology in industrial environment. The technical application should be easily adaptable to an existing machining system without affecting the machine usability. Therefore, a smart solution to vary continuously the dynamics is another key aspect to guarantee the successful exploitation of the developed technology.

Objectives

- Development and implementation of an industrially feasible technical application of stiffness variation in an operative machine tool.
- Development of an efficient methodology to study the stability of the milling process when the dynamics is linear time periodic, the spindle speed is varied periodically and the tool has special geometries with variable pitch and helix angle.
- Development of an efficient procedure to directly identify the linear time periodic dynamics by minimizing the experimental setup and effort.
- Experimental validation of the methodologic framework and experimental evaluation of the stabilization introduced by stiffness variation and its combination with a variable pitch tool in a relevant industrial environment.
- Provide comprehensive guidelines for optimal stiffness variation parameters and technological application selection.

Methodology

The proposed Harmonic Solution is obtained by applying the linear time periodic (LTP) system dynamics theory to the dynamic cutting force equation. The exponentially modulated periodic test signals and the Harmonic Transfer Function (HTF) introduce the possibility of dealing with LTP dynamics in the frequency domain, enabling fast and accurate prediction of stability maps. Furthermore, the approach applies also to the most general cutting force equation, which considers the effects introduced by time periodic, multiple and distributed delays. Therefore, the general and efficient Extended Harmonic Solution is presented:

$$\mathbf{P} = \frac{1}{2}\frac{a}{L}K_t\left(\sum_{j=1}^{Z}\sum_{l=1}^{L}\mathcal{A}_{Dj,l}\mathcal{D}_{j,l}\right)\mathcal{H}\mathbf{P}$$

This formulation can deal with processes characterized by any combination of stiffness variation, spindle speed variation and special geometries tool with variable pitch and helix angle. Meaningful approximation of the stability maps are evaluated within a minute maintaining a general formulation that applies to many combinations of chatter suppression strategies and standard processes.

The main idea of the technical application is to modulate the stiffness exploiting the synchronous movement of the ram and the boring bar in boring machines. Even if it this approach may not be applicable for general milling machines, it can be easily implemented on boring machine, also as a retrofitting of existing systems.

The dynamic behaviour is identified experimentally according to a direct least square approach. A novel procedure to reduce the experimental setup is presented and validated, taking in to account a train of random impulses as excitation, which should be properly distributed on the fundamental period of the system.

The overall approach is validated by means of cutting tests and the performances introduced by the stiffness variation and of the combination of chatter suppression strategies are assessed experimentally. Finally, the developed knowledge is shared through comprehensive guidelines for optimal stiffness variation parameters and technological application selection are provided.

Results

- The Extended Harmonic Solution enables the evaluation of precise stability maps with a marginal computational effort, when systems are characterized by linear time periodic dynamics, periodically varied spindle speed, tools with variable pitch and helix angle and combinations.
- The linear time periodic dynamics behaviour in terms of the HTF is assessed thorough rapid impulses response measurement, thanks to an extended direct least square identification framework.
- The developed methodological framework is validated experimentally considering the technical application implemented on a machine tool involved in production.
- The technical application of stiffness variation and the combination with a variable pitch cutter demonstrate an abrupt increase of the absolute stability limit by +50% and the stable area ratio by +37% (Fig. 1).
- Optimal stiffness variation parameters are amplitude between 10% and 25%, while the ratio between the stiffness variation and the tooth pass frequency should be from 2 up to 30.

Conclusions

The developed Extended Harmonic Solution enables an efficient evaluation of stability map considering the combination of multiple chatter suppression strategies, which is exploitable in their development and optimization. Furthermore, the direct least square identification of the Harmonic Transfer Function introduces the possibility to evaluate quickly practical applications of the innovative stiffness variation technique.

The stiffness variation was implemented for the first time on an industrial machine tool exploiting the synchronous movement of the ram and the boring bar. The capabilities were assessed experimentally achieving outstanding results. Stiffness variation increases the absolute stability limit by +33% and the stable area ratio by +19%, which grows up to +50% and +37% when a variable pitch cutter is added.

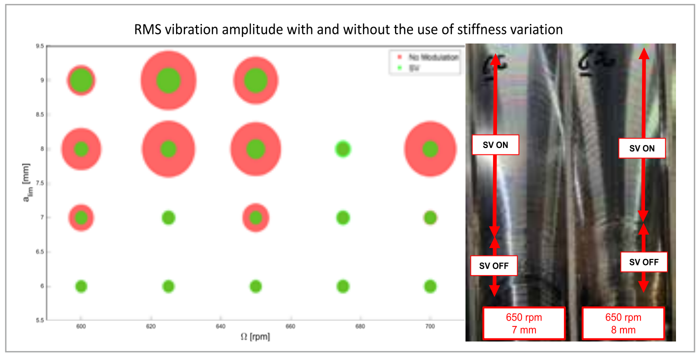

Fig. 1 - Experimental evaluation of the capabilities introduces by the stiffness variation and a tool with variable pitch in terms of the rms vibration amplitude and cutting surfaces

A FRAMEWORK FOR THE VALORISATION OF SLAG AS A BY-PRODUCT OF ELECTRIC ARC FURNACE (EAF) STEEL

Mohammadtaghi Falsafi - Supervisor: Prof. Tullio Antonio Maria Tolio

Scrap-based steel production is one of the major routes in the European and Italian steel industry, with an increasing production outlook. Slag is the major steelmaking by-product, accounting for around 15% of the production weight arising several challenges to the sector in terms of sustainability due to a high proportion of landfilling. The thesis analyses the value chain of slag from electric arc furnace (EAF) (black slag-BS) and secondary metallurgy (white slag-WS) and proposes a new framework for valorising it and a new configuration of the ecosystem.

To this aim, the research methodology is designed by aggregating different methods and tools to build up the appropriate framework for slag management from the overall challenges of the steel sector. In the first step, through extensive literature analysis, slag features, technological advancements for its treatment, applications, legislation, and its value chain within the circular economy and industrial symbiosis opportunities are investigated. The results of the literature analysis are used for the definition of semi-structured interviews, being conducted with 15 key managers (strategic or operational) from steelmaking companies, technology providers, and associations to design the as-is situation of the sector and elaborate on the challenges and expectations for the future.

The analysis in the second step is then followed by interviews with five Italian steelmakers, accounting for around 30% of Italian scrap-based steel volume focusing on various value chain features, namely technology, legislation, production volume, and economic aspects. The results show how the decisions about vertical (by internal treatment) and horizontal integration (by external actors) in the material flow (both BS and WS) can facilitate circularity in this sector. In the studied cases, vertical integration highly affects the economic aspect, while horizontal integration positively impacts the market and technology. We also address the importance of raw material self-sufficiency in closed-loop supply chains and collaborative supply chain networks.

Based on the interviews in the second step of the study, challenges preventing the WS treatment and application include volume instability, volatile composition, and slag disintegration. Accordingly, the third step analyses the WS value chain and proposes a new framework where the potential of technologically innovative applications requires changes in the treatment processes towards a pre-treatment phase (focusing on cooling practices) to prepare the slag for the main treatment. To this aim, the thesis investigates the opportunities for WS use through the lime production process and develops a mapping of technological approaches.

The output of the analysis with the experts results in the definition of the criteria to evaluate the possible alternative solutions for WS treatment and use. For this reason, the Analytical Hierarchy Process (AHP) has been adopted to consider multiple criteria (qualitative and quantitative) such as market, technology, legislation, supply chain, and environmental and economic sustainability and compare and prioritise alternatives based on the experts' opinions. The results show economic sustainability has the highest importance, while CO2 emission and water consumption significantly impact the WS value chain.

To analyse the impact of the model, the alternatives considering the treatment unit owners and locations, pre-treatment and treatment processes, and collaboration aspects have been defined. Based on the specific case study analysed in this work, a value chain where a third-party recycler attracts the pre-treated WS and carries out the treatment process is shown to be more advantageous than the other alternatives. Also, we show how a collaborative system is fundamental, where a third-party recycler is preferred to a consortium of producers collaborating for slag recycling. The developed framework can also be used for other regions to create awareness about ways to valorise slag and evaluate possible alternatives.

ACTIVE NOISE CONTROL IN A SUPER SPORTS CAR CABIN

Cesare Lupo Ferrari - Supervisor: Prof. Daniele Rocchi

The passenger cabin acoustics greatly influence the perception of vehicle quality. The acoustic excitation inside the passenger cabin of a car consists of two main components: the tonal sound generated by the powertrain, related to the combustion and the engine firing, and the broadband noise due to the tyre rolling and the vehicle aerodynamics. In super sports cars, the first contribution is significantly greater and can mask the second one. In the spectrum, this contribution is found at low frequencies and it is therefore possible to improve the sound quality through an active control system. This thesis analyses, studies, designs and implements an active noise control system installed on board a super sports car.
Regarding the study of active controls, several alternatives are analysed in order to choose and develop the most efficient and computationally light algorithm. These options have been first simulated, then implemented and tested in simplified environments, such as a noise control system in an impedance tube (one-dimensional case) and in an anechoic chamber (three-dimensional case with no external reflections) in order to evaluate the effect of parameters tuning on the performance of the control.
To best adapt and customise the algorithm to the case under study, it has been necessary to completely characterise the vehicle acoustically. A super sports car, in fact, differs from other cars, which have already been studied in the literature, due to its fast dynamics and sudden transients - which can lead to frequency variations of up to 80 Hz/s - and for sound levels inside the passenger cabin that reach peaks of over 90 dB. For these reasons, tests have been performed for static characterisation, such as the evaluation of natural frequencies, vibration modes and reverberation time; but also, dynamic tests to estimate the actual noise emission of the powertrain during different driving conditions. A set of manoeuvres has therefore been selected both in transient (such as Wide-Open Throttle, Partial-Open Throttle or coast down manoeuvres) and steady state (such as constant speed manoeuvres) to characterise the vehicle as comprehensively as possible. In addition, these measurements have been used to validate a finite element model built to have a complete and accurate mapping of the acoustic field within the entire vehicle.
From these results, it has been possible to understand which components of the acoustic emission should be focused on and which algorithm should be used best. Thanks to various simulations of the algorithm implemented in the passenger cabin environment, it has been possible to define a multi-channel system capable of equalising the sound of engine orders using the car's loudspeakers and CAN bus signals. The algorithm, shown in Figure 1, has been developed starting from the well-known Fx-LMS algorithm to which modifications have been made to equalise the sound and to limit the power of the control action signal sent to the loudspeakers in order to avoid damaging and melting them during control applied to extreme manoeuvres.
Lastly, in order to validate the proposed adaptive algorithm and the simulations performed, the real-time control system has been built inside the cabin; measurements and tests have been conducted on the selected super sports car equipped with a naturally aspirated engine. The system, depicted in Figure 2, consists of the car's audio system loudspeakers used as actuators, error microphones positioned on the headrests, the CAN bus signal from the engine exploited as reference signal and the Digital Signal Processor to acquire all the data and to compute the control action.
In some manoeuvres, the experimental tests show good performance, similar to that obtained in simulations; in Figure 3, the results obtained with regard to a manoeuvre at constant speed are shown: on the left, the spectrogram of the acoustic field in the passenger cabin is shown when the controller is turned on; while, on the right, the Loudness trend is shown, when the control is activated. In the case of more extreme and more dynamic manoeuvres, on the other hand, the results highlighted the need to develop flexible solutions for the specific case study analysed.

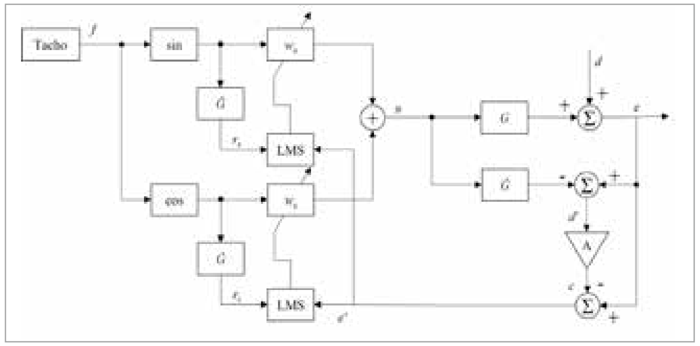

Fig. 1 - Block diagram of the modified single-order Active Noise Equaliser (ANE) algorithm

Fig. 2 - Sensors and actuators of the active control system used to equalise the sound field.

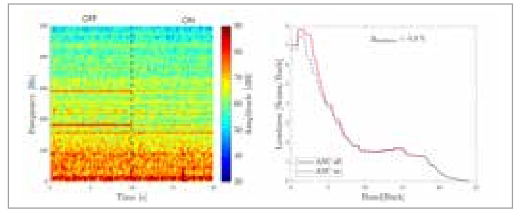

Fig. 3 - Left: Spectrogram of the sound field during a constant speed manoeuvre. During the first half the controller is off, then the controller is turned on. Right: Loudness comparison between on (blue dashed line) and off (red bold line) conditions.

PATIENT-SPECIFIC NITI STENTS PRODUCED WITH LASER POWDER BED FUSION PROCESS: DESIGN, MANUFACTURING AND CHARACTERIZATION

Valentina Finazzi - Supervisors: Prof. Barbara Previtali, Prof. Lorenza Petrini
Co-Supervisor: Prof. Ali Gökhan Demir

Additive manufacturing (AM) has shown great potential for the realization of patient-specific medical devices. For the production of metallic stents, Laser Powder Bed Fusion (LPBF) process has raised in the last years considerable interest in the research field. Currently, metallic stents on the market are mainly produced using laser cutting of tubular precursor. With LPBF, limitations deriving from tube precursor can be eliminated. In particular, the use of tubular precursors implicates that the stent dimensions are linked to available tubes, whose manufacturing cost is high when small diameters are required. A great opportunity given by LPBF process, and one of the targets of the present investigation, was the possibility to realize patient-specific devices.
In this work, dedicated LPBF process parameters were identified using a non-commercial $Ni_{50.8}Ti_{49.2}$ powder, allowing to achieve 99.6±0.2% apparent density and average roughness Ra of 3.1±0.1µm on wires with an average diameter of 453±11µm (Figure 1). After LPBF process, specimens surface showed sintered particles attracted by the melt pool surface tension during the scanning process. In addition, a layer of oxides was present on the specimens. For these reasons chemical etching was studied to improve the surface quality.

Heat treatment was studied to obtain superelasticity at body temperature on the produced samples. A austenite finish temperature of 31°C was reached and the samples showed superelasticity under tensile cyclic loading, in particular they showed a maximum stresses above 705 MPa and 6% elongation in tension (Figure 2), which is a promising result for superelasticity of NiTi produced by LPBF.

Design rules for the production of stents with LPBF process were identified and used to realize stent meshes which optimize the outcome of the powder-bed process (Figure 3). Both closed-cell and open-cell stents were realized, showing that a proper modelling technique is mandatory to exploit the geometrical benefit of LPBF process. In addition to tubular stents, more complex geometries were studied, with variable diameter or non-rectilinear axis to meet requirements for patient-specific application. Parametric design was investigated to build stent models which can quickly be adapted to the anatomy of every patient. Using CT data, a stent for the ductus arteriosus of a newborn baby affected by Hypoplastic Left Heart Syndrome was designed.

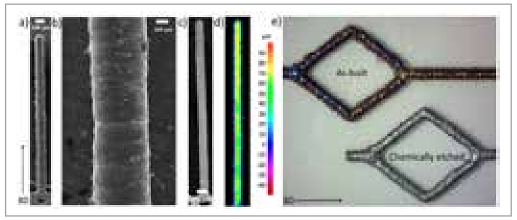

Fig. 1 - NiTi struts produced with LPBF process: a-b) SEM and c) cross-section images and d) surface reconstruction, e) before and after chemical etching.

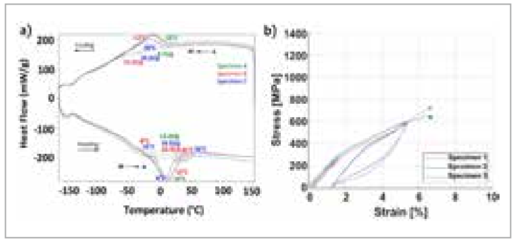

Fig. 2 - Differential Scanning Calorimetry thermogram and b) mechanical behaviour of NiTi samples produced with LPBF process and heat treated

Designing new stent geometry, Finite Element Modeling (FEM) is a powerful tool to assess the validity of the new designs in terms of biomechanical behaviour and considering the big differences between traditional and additively produced stents both in terms of material and geometric design, it was studied how to build proper FEM methodologies for LPBF processed devices. In particular, it was evaluated how the characterization of the additive material and the reconstruction methodologies of the geometric model affect the result. Since LPBF processed alloys have a different behaviour than the classical ones, material characterization was required to implement proper and realistic material properties in the analyses. CT reconstruction of LPBF processed stents has shown to be a good tool to catch the mismatch between nominal CAD and real device geometry and to build a realistic model for FEM. FEM methodologies were validated with tensile and crush experimental tests on LPBF processed stents and it was found that beam elements are a good solution, providing a suitable compromise between reliable results and computational time. The results of this work confirm how it is possible to use LPBF process to produce superelastic patient-specific stents. It was also highlighted that in order to make the most of the geometric potential of the process, a design with an eye to the peculiarities of the technology is essential. It has also been shown that the use of beam elements is an excellent solution for FEM of LPBF stents, underlying the need to implement measures related to the material and to the differences between nominal and post-process geometry.

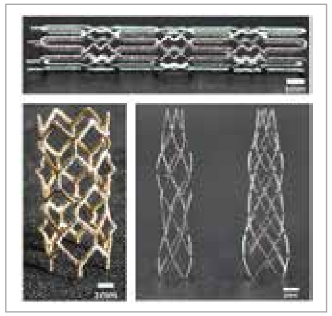

Fig. 3 - Some of the stents designed and produced during the PhD research.

DYNAMICS OF ROLLING ELEMENT BEARING

Shuai Gao - Supervisor: Prof. Paolo Emilio Lino Maria Pennacchi

Rolling element bearing (REB) is the core supporting component of various types of rotating machinery such as high-speed motor, aero-engines, spacecraft momentum wheels and other industrial equipment. The evaluation of equipment reliability and operation health status based on the dynamic characteristics of rolling element bearings is the frontier and mainstream research filed of mechanical system. As the rolling bearing running, it is necessary to provide proper load and the correct lubricating condition, ensuring the pure rolling of the rolling elements on the inner and outer ring raceways, otherwise the rolling elements may slide, or skid, from time to time. Causing severe wear and smearing of the raceways, rapid temperature rises of bearing, and thus reducing bearing operation stability and service life. Meantime, the bearing cage, a vulnerable component inside bearing, sustained frequent collision, which dynamic characteristics affects the bearing skidding degree, and the bearing running stability.
The whirling, wear and collision characteristics are main reasons for cage failure. Therefore, it is of great scientific significance and engineering practical value to carry out research on the dynamic characteristics and failure mechanism of rolling bearings based on the skidding behaviors and the dynamic characteristics of the cage.
Angular contact ball bearing (ACBB) is considered as the research object, a multi-discipline full-degree-of-freedom (DOF) nonlinear rolling bearing dynamic model (KH-TEHD) based on the analysis of kinematics, tribology, dynamics, and lubrication thermal effects is established, as shown in Fig. 1. Two experimental systems for investigating rolling bearing skidding and cage whirling stability are developed, respectively. A non-contact freestanding high-precision self-powered bearing skidding and cage stability sensor (HP-TEBSS), which is based on triboelectric generator technology, is proposed. The failure mechanisms of bearing cage wear, raceway parallel sliding and raceway gyro skidding damage are proposed based on the model and test results. The effects of load, rotational speed, lubrication state, cage pocket type, cage lubrication type and other factors on bearing skidding and cage whirling stability are taken into account. The following achievements have been obtained:
In the field of research and industry, the "over-skidding" behavior of bearing exhibits and is explained by the author for the first time. A three-phase analysis method based on the theoretical model is proposed to explain the discovery. The term "over-skidding" means that the revolution speed of the bearing cage is higher than the theoretical speed as the rolling element under pure rolling state. The KH-TEHD model considers the kinematic relationship of the REB components, the Hertzian contact theory of rolling elements and raceways, the mutual driving collision force and wear behavior between the cage pockets and rolling elements, lubricating driving force based on Bair-Doolittle-Cross elasto-hydrodynamic thermal shear effect, hydrodynamic pressure force of cage under oil-flooded lubrication, rolling element skidding shear, and oil churning thermal effect, the thermal deformation of bearing components under temperature rise. The Runge-Kutta and the Newton-Raphson methods are employed to solve the differential equations, which includes 5 DOFs inner ring deflection, 4 DOFs rolling element rotation and revolution, and 3-DOFs whirling and revolution of the cage.
To obtain the rolling element skidding of ACBB and the radial whirl profile of the cage, a non-contact cage whirling and skidding test bench, based on high-speed photographic technology, has been designed and constructed, as shown in Fig. 2. The whirl trajectory of cage center, bearing stability analysis, cage skidding rate (CSR), cage rotation speed fluctuation and wear characteristics under variable rotation speed, applied load and lubricating condition is discussed. The test cage is made of a porous oil-containing self-lubricating material which used in momentum wheel of spacecraft. The wear resistance and stability of the cage are crucial properties to the healthy state of the equipment. The test results are consistent with the simulation analysis of the dynamic model, which verifies the accuracy of the model.
Due to the large space requirement and the damage to the bearing structure, the traditional real-time monitoring methods which focus on bearing skidding and cage motion are difficult to be carried out. Combining with advanced energy harvesting technology, we propose and fabricate the non-contact floating freestanding HP-TEBSS for real-machine REB real-time monitoring. The measurement precision of instantaneous skidding and cage speed fluctuation can reach 36 times that of traditional eddy current sensors. Its superior accuracy and real-time performance are cross-validated by means of KH-TEHD model and commercial sensors.
A fabricated prototype is applied on the main bearing of the high-speed dual-rotor jet engine test bench, which proves its reliability under extreme working conditions, as shown in Fig. 3. The HP-TEBSS provides theoretical and experimental support for the development of intelligent bearings.
Based on the KH-TEHD model and established test platforms, the effects of operating conditions, lubrication state and bearing structure on CSR, over-skidding behavior and cage whirling stability are discussed. The theoretical analysis is consistent with the experimental results. The results show that the temperature rise in the Hertzian contact zone caused by the skidding, under high speed and light load, will reduce the friction driving force of the raceway, further resulting in the over-skidding phenomenon, which is significantly obvious in large-size ACBBs. The improvement of lubrication and the cooling effect help to alleviate CSR and avoid over-skidding. In addition, under high-speed and compound loads, the whirl stability and speed fluctuation of the self-lubricating cage are significantly improved. With the increase of the oil content ratio of the self-lubricating cage, the vibration level of the cage is significantly reduced, and the whirling profile tend to converge. Furthermore, as the pockets of the self-lubricating cage distributed in a circle and a square arrangement, the performance indicators of CSR, pocket wear rate, collision characteristics and whirl stability can achieve a balanced compromise.

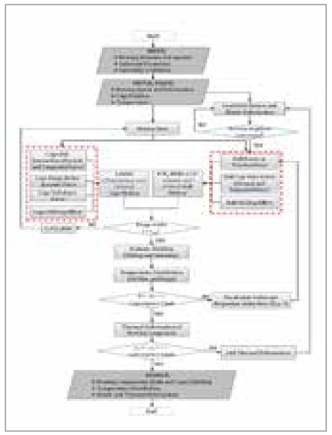

Fig. 1 - Structure of KH-TEHD model

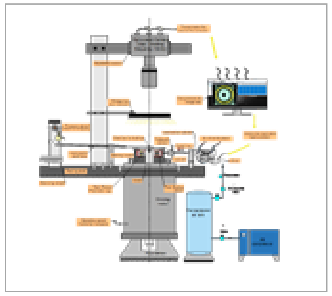

Fig. 2 - Cage whirling test bench

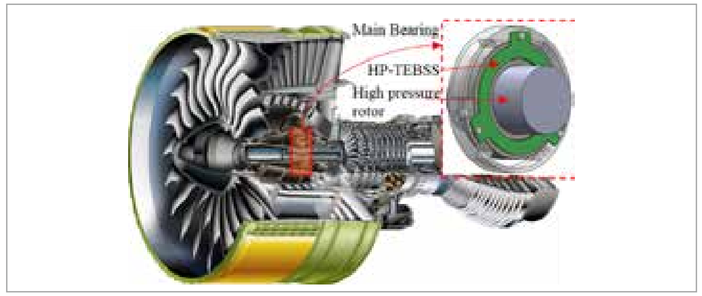

Fig. 3 - Application of HP-TEBSS

MODELLING AND MONITORING OF COMPOSITE STRUCTURES SUBJECTED TO EXTREME LOADS EVENTS

Álvaro González Jiménez - Supervisor: Prof. Andrea Manes
Co-Supervisor: Prof. Marco Giglio

The use of composite materials has completely redefined the technological limits in a large variety of engineering fields. Two of the sectors that has advantaged more from the application of these materials are the aeronautical and wind power industries. For the former, the high strength-to-weight and stiffness-to-weight ratio typical of composites has allowed to design aircrafts that can travel larger distances with heavier payloads. For the latter, the employment of composites materials, particularly on the blades, has significantly increased the upper limit of the turbines swept area, incrementing the energy that each individual turbine can harvest. However, the use of composite materials has created new challenges never faced with traditional materials. These challenges are mainly related to the complex failure mechanisms of composites, inherent to their heterogeneous and, sometimes, laminated nature. Consequently, in the past years several approaches have been proposed to understand, predict or detect damage of composite materials. Particularly, the structural healthy monitoring (SHM) methodology has demonstrated to be a firm candidate to solve the challenges presented.
An SHM system predicts the condition of the analysed structure based on data obtained from several sensors installed into the structure. In particular, SHM systems based on the propagation information of ultrasonic guided waves has been widely studied due to its suitability for the properties of structures commonly used in the aeronautical and wind power sectors. Within this frame of reference, the overall scope of this thesis is the creation of an ultrasonic-based damage diagnosis algorithm to detect, localise and, eventually, quantify the damage on composite structures. This would allow to increase the reliability and robustness of an SHM system. Specifically, in the first part of the thesis, a critical discussion of one of the most commonly employed damage localisation algorithms, namely the RAPID algorithm, is done in order to identify its intrinsic flaws. Successively, several solutions are proposed based on the post-processing of the RAPID output and the optimisation of the sensor positions. The second part of this thesis deals with the creation of a convolutional neural network-based algorithm able to perform a full diagnosis of the structure conditions by detecting, localising and quantifying the presence of damages in different types of composite material panels.

Keywords: Lamb waves, structural healthy monitoring, RAPID, CNN

FIBER-OPTIC SENSORS FOR MONITORING LASER ABLATION THERMAL OUTCOME IN BIOLOGICAL TISSUES

Sanzhar Korganbayev - Supervisor: Prof. Paola Saccomandi

Laser ablation (LA) is one of the tumor treatment techniques that can provide minimally invasive treatment in cases when conventional methods (surgical resection, chemotherapy, radiotherapy) are not recommended. The main principle of LA is based on the delivery of laser energy via a fiber optic cable to the tumor in order to induce local coagulation, necrosis, and apoptosis of cancer tissues. The main advantage of LA is based on two unique features that stem from the use of minimally-invasive fiber optic cable: immunity to electro-magnetic interference and flexibility of the applicator. Thus, the treatment can be used during magnetic-resonance and computed tomography imaging, and can reach deep-laying organs. Nevertheless, LA cancer treatment is still limited due to the difficulty to guarantee complete destruction of the tumor and prevent collateral damage to the healthy tissues. The main reasons for it are the lack of accurate monitoring techniques and the use of an open-loop approach, i.e., laser parameters are set before the procedure. In this regard, my Ph.D. project was focused on investigation and development in the two main areas: (i) real-time temperature-based control techniques for extra- and intra-corporeal LA; and (ii) innovative fiber optics sensing methods to measure intra-tissue parameters (temperature, refractive index) during LA procedure.

For temperature-based LA control, custom-made highly dense FBG sensors were utilized. FBG inscription has been performed using point-by-point femtosecond laser inscription (Figure 1 a) and FBG array characteristics (FBG spectra on Figure 1 b, c) were optimized for LA measurements. The developed FBG-based LA control techniques (Figure 2 a-c) are: (a) ON-OFF control for extracorporeal LA; (b) ON-OFF control for interstitial LA; and (c) proportional-integral- derivative (PID) control for interstitial LA. In addition, a pre-planning based on numerical simulations of the bioheat transfer has been developed to optimize the control parameters before the actual procedure (Figure 3 a for thermal damage results and simulations for contactless LA, Figure 3 b thermal distributions for interstitial LA). In general, the obtained results show that LA control allows controlling the margins of the ablated region, and, as a result, minimizes the damage to the surrounding healthy tissues. The novelty of the developed intraoperative platforms compared to currently available systems is that they also allow for quasi-distributed measurement of tissue temperature in two- and three-dimensional configurations, while retaining the minimally invasive nature of the procedure.

Regarding the new sensing methods for LA monitoring, the main investigated sensor was titled FBG (TFBG), a particular type of FBG with tilted FBG planes that allow coupling between the core and cladding modes. As a result, TFBG is sensitive to temperature, axial strain, pressure (as standard FBG), and also to outside medium parameters, such as surrounding refractive index (RI). In this regard, the experimental investigation of the increase of RI sensitivity by fiber etching has been performed. Analysis of step-wise etching and calibration in different RI solutions have provided the best trade-off between wavelength and amplitude sensitivity, intensity level, and fiber thickness.

In addition, TFBG sensing modalities during LA of ex-vivo hepatic tissues have been investigated. The first modality is a measurement of the RI changes of the ablated tissue during LA. The second one – is the temperature sensing modality based on the core mode analysis using conventional peak tracking techniques (maximum tracking, X-dB Bandwidth, centroid methods) and the developed reconstruction algorithm. The developed algorithm allows the measurement of quasi-distributed spatial temperature profile along TFBG. In general, the results show that the main reliable sensing modality of TFBG during LA is temperature monitoring, which can be significantly improved by the proposed algorithm.

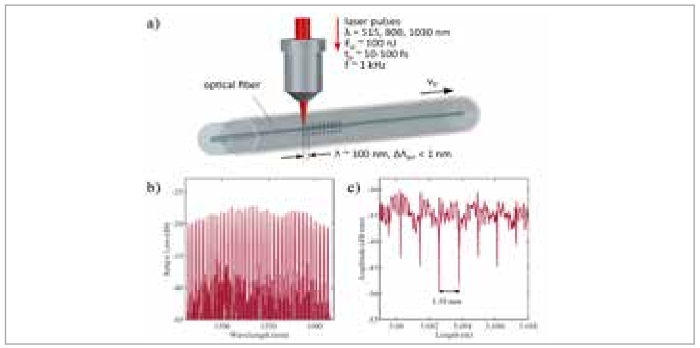

Fig. 1 - a) femtosecond laser FBG inscription; b) FBG array spectrum; c) time-domain spectrum

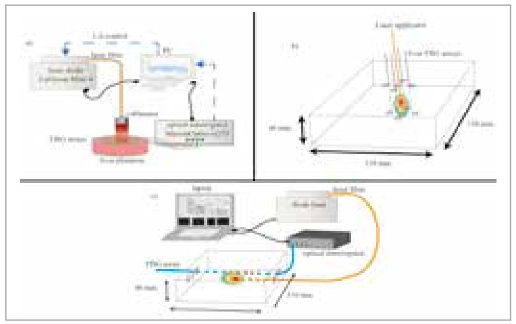

Fig. 2 - a) ON-OFF control for extracorporeal LA; b) ON-OFF control for interstitial LA; and c) PID control for interstitial LA

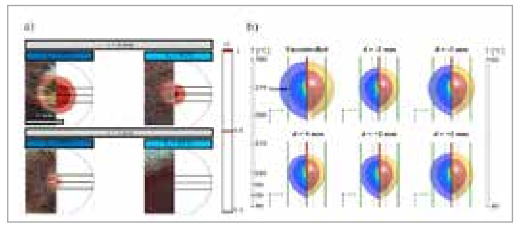

Fig. 3 - a) extracorporeal LA simulation; b) interstitial LA simulation

ROLLING STOCK-BASED DIAGNOSTIC SYSTEM FOR CONDITION MONITORING OF RAILWAY TRACK GEOMETRY

Ivano La Paglia - Supervisor: Prof. Roberto Corradi

Co-Supervisor: Prof. Alan Facchinetti

Maintenance of the railway infrastructure is essential to achieve safety, availability and proper operation of the rail service. It is currently mainly based on elapsed time or cumulated kilometres, by means of inspection trains (TRV) that periodically measure the infrastructure geometry and the dynamic behaviour of the vehicle. However, the increasing demand for railway transportation is progressively reducing the time available to carry out the inspections necessary to determine the conditions of the railway track. A modern approach relies on commercial vehicles as detector of defectiveness, by exploiting the influence that a defect can have on the dynamic interaction between the vehicle and the infrastructure. New generation trains are indeed usually already equipped with sensors for vehicle diagnostics that can be adopted also for infrastructure monitoring purposes. Therefore, the collection of data from sensors installed on commercial vehicles may represent a cornerstone for monitoring purposes, allowing to move from scheduled to condition-based maintenance. This doctoral thesis aims at identifying innovative railway infrastructure diagnostic strategies and defining an adequate measurement setup to be permanently installed on-board of specific commercial train, so as to perform continuous condition monitoring of the rail track. The designed system is meant to support the current maintenance strategy providing a continual flow of data in between subsequent diagnostic train runs. In this context, attention has been devoted to the train positioning topic at first, that is crucial for the development of a diagnostic system suitable for operating on commercial fleets. The algorithm exploits two signals commonly available on commercial trains, namely odometry and GNSS. It consists of two steps: a map-matching procedure for the projection of GNSS acquisitions on the digital map of the railway line, followed by a robust-fit to correlate the map-matched data to the odometry data. The acceleration RMS originated from several repetitions of train runs on the same railway line are perfectly overlying both in term of peaks and locations along the line, enabling the possibility to perform a trend analysis.
Along high-speed railway lines, maintenance interventions are often driven by the need to correct the longitudinal level (vertical track irregularity).
By comparing the RMS bogie vertical acceleration (Figure 1a, commercial vehicle) to the RMS longitudinal level (Figure 1b, diagnostic train), a significantly high degree of correlation can be observed. The two dataset can then be used to realize a track condition monitoring system. The methodology relies on two steps: the first is the training phase, that combines acceleration data from commercial trains with track geometry recorded from the diagnostic train to develop a linear regression model; the second takes advantage of this predictive model to perform

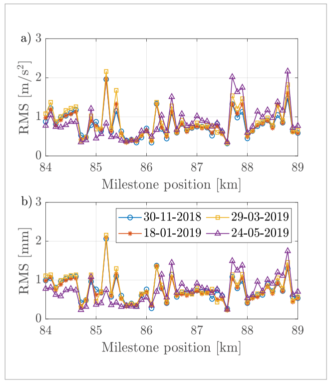

Fig. 1 - Geo-localization and time evolution of the synthetic indexes as a function of the milestone position. a) RMS bogie vertical acceleration; b) RMS longitudinal level in D1 range. Spatial windows of 100 m, vehicle speed of 300 km/h.

daily estimations of the track conditions. Various models are realized, suitable to estimate different track geometry parameters, as the rms and max values of longitudinal level, alignment and cross level defects, over windows 100 m long down to 25 m. Major attention is devoted to the MAX longitudinal level, that triggers maintenance operation along high-speed lines. RMS acceleration measured at the corresponding km are used as input to provide geometry estimations, that are compared to the direct measurement from the TRV. Accurate results are achieved, allowing both a correct monitoring of the evolution of track quality and limitation of the maximum prediction error. A distinct behaviour characterizes distributed defects (series of defects inside the 100 m window, Figure 2a) and isolated ones (one single defect, Figure 2b). To better account for the defect typology, multiple linear regression models are designed, using the crest factor of the longitudinal level (ratio of peak over rms) as a predictor.
Finally, the first acceleration data gathered by a commercial train equipped with the designed geo-localization algorithm were considered to verify the performance of the condition monitoring system. Promising results have been achieved in terms of predicted RMS and MAX longitudinal level, that confirm the possibility to adopt the commercial train to monitor the track infrastructure. The designed system can potentially increase data availability in between subsequent diagnostic trains run, that are scheduled every two/four weeks along high-speed lines, helping the management of track maintenance operations. Although track safety and integrity are well under control with the current strategy, the designed system installed on a commercial vehicle could provide different benefits. First, in case the diagnostic train is not available to operate on a specific railway line (due to maintenance of its own equipment, or in case urgent interventions are required elsewhere), an estimation of the track condition can be achieved. Moreover, provided that reliable estimations of the track conditions and of the degradation rate are made available, the time lapse in between the diagnostic train runs could be increased with benefits in terms of easiness of the intervention scheduling. Finally, in case of sudden changes in a portion of the railway line, daily estimations would allow the identification of possible critical track sections in advance with respect to the diagnostic train, allowing timely interventions and preventing dangerous situations.

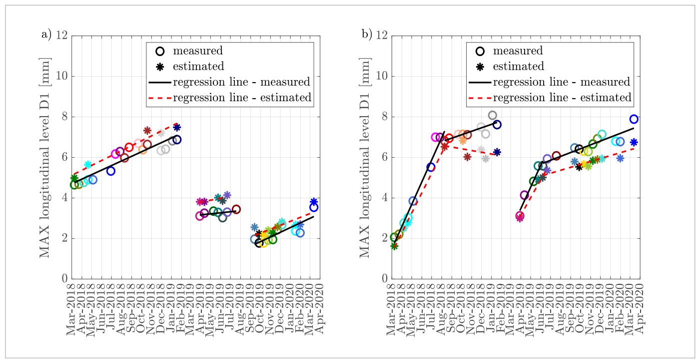

Fig. 2 - Comparison of time trends measured by the diagnostic train and predicted by the multiple regression model in terms of MAX longitudinal level D1. a) Distributed defect at km 47.3; b) isolated defect at km 80.6.

TRAIN-TRACK DYNAMIC INTERACTION MODELLING INCLUDING NONLINEARITIES OF RESILIENT TRACK COMPONENTS

Qianqian Li - Supervisor: Prof. Roberto Corradi

Co-Supervisor: Prof. Egidio Di Gialleonardo

Train-track dynamic interaction simulation is an extensively used and powerful tool for the study of various issues of railway transport. However, most of the available train-track interaction modelling does not take into consideration the nonlinearities of resilient track components, which are in fact widely acknowledged by railway engineers. The aim of the current study is to propose a methodology to account for the of resilient track components in the train-track dynamic interaction simulation in time domain. The rail support of an Embedded Rail System (ERS) is taken as the reference component and its frequency- and preload-dependent dynamic properties in vertical direction are studied.

The proposed methodology is composed of three groups of activities characterisation of the dynamic properties of the reference component through laboratory tests; development of a rheological model for the characterised non-linear dynamic properties based on the experimental results and integration of the developed rheological model to a track model; performing train-track dynamic interaction simulation (time domain) and studying the effects of the modelled nonlinearities on train and track responses.

The laboratory tests are carried out with an ad hoc test-rig. Air springs are placed over the rail head to apply static preloads. A hydraulic actuator and an impact hammer are employed to apply dynamic loading. A purpose-built dynamic force measuring platform is placed below the ERS. The dynamic properties (equivalent dynamic stiffness and viscous damping coefficient) determined with the test results show strong dependences on static preloads and dynamic loading frequency.
The proposed rheological model is in the form of a standard solid model and the parameter values are in function of static preload F0 and frequency of dynamic loading Ω with analytical expressions. The model parameters are identified with experimental results. It is verified that the identified model is able to reproduce the dynamic behaviour of the reference component both in frequency and time domain.

The validated rheological model is integrated into a finite element track model which thus account for the modelled non-linear dynamic properties. Train-track dynamic interaction simulations in time domain are performed with such track model, where moving vehicle (speed 200 km/h) and rail roughness excitation mechanisms (wavelength 0.2 – 2.5 m, excitation frequency 22 – 280 Hz) are considered, and the train and track responses are compared to the ones computed with a linear track model where a constant-value viscoelastic rail foundation is used. The modelled nonlinearities lead to remarkable differences of the rail vibration in the ranges of 50 – 70 Hz and 160 – 200 Hz, which correspond to the frequencies of wheelset-rail coupled mode of vibration and track cut-on frequency.

In conclusion, the non-linear dynamic properties of a resilient track component, the frequency- and preload-dependent dynamic properties of the rail support of a reference Embedded Rail System in vertical direction, are characterised by the performed laboratory tests. The developed rheological model is able to reproduce the non-linear dynamic behaviour of the reference component. The modelled non-linear dynamic properties lead to significant differences on train-track dynamic interaction simulation results. The current study has proposed a methodology to include the non-linear dynamic properties of resilient track components in the study of train-track dynamic interaction based on laboratory tests and appropriate modelling techniques.

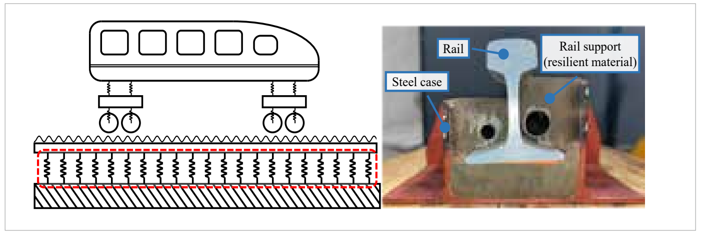

Fig. 1 - Train-track modelling containing resilient track components (highlighted by red box) and sectional view of an Embedded Rail System.

Fig. 2 - Purposely developed laboratory test rig to determine dynamic properties of the Embedded Rail System.

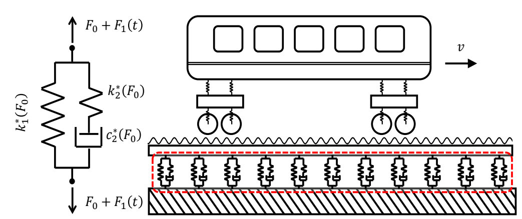

Fig. 3 - Non-linear rheological model of the rail support of the Embedded Rail System and time domain train-track dynamic interaction simulation model.

DEVELOPMENT OF AUTOMATIC UNSUPERVISED DAMAGE DETECTION ALGORITHMS FOR AXIALLY-LOADED BEAM-LIKE STRUCTURES

Francescantonio Lucà - Supervisor: Prof. Alfredo Cigada
Co-Supervisor: Prof. Stefano Manzoni

Structural health monitoring is the naturally suggested approach for the maintenance of structures, given the current availability of increasingly advanced sensors and computing capabilities. A transition from traditional approaches, based on human inspections, to continuous monitoring is made possible by the adoption of data-driven approaches, to identify relationships between the physical quantities measured by the sensors and the state of health of structures. Vibration-based approaches are among the most popular in the field of structural health monitoring, based on the concept that changes in structural properties due to damage are reflected in changes in the properties of the dynamic response. Damage-sensitive features can therefore be extracted from vibration signals and used in combination with machine learning techniques to develop automatic algorithms capable of identifying the onset of anomalies.

Despite the work carried out by the scientific community to develop algorithms and methods for damage identification, there are still few applications that have demonstrated the effectiveness of these approaches in real contexts, characterized by uncontrolled environmental and operational conditions. Although dealing with these factors play a key role in translating structural health monitoring algorithms from research to real world, they are often neglected since they are difficult to replicate in a laboratory environment. At the same time, when real operating structures are considered as a case study, it is very rare that data referring to a damage condition are available.

This article-based thesis, consisting of a cover essay and three attached articles, presents the development of an automatic strategy for damage identification in axially-loaded beam-like structures, widely used in civil, mechanical and engineering applications. Attention was paid to the case study of tie-rods, structural elements used to balance the forces discharged by arches and vaults of ancient and modern civil structures. The works presented in the literature are mainly addressed to the identification of the tie-rod axial load as a means to monitor the overall structural equilibrium. This problem is complex, due to the considerable uncertainty related to the structural characteristics and materials for already installed tie-rods. Although the failure of a tie-rod can have dramatic consequences, no approach that accounts for the presence of damage in the tie-rod itself was present in the literature. The author used the approach known as statistical pattern recognition to develop an automatic vibration-based data-driven algorithm that does not require the knowledge of any physical variable and does not need axial-load identification, separating this research work from all the other works in the literature regarding tie-rods.

The work details two fundamental aspects. The first is the definition of an appropriate vibration-based damage feature that allows distinguishing the variations associated with the normal variability of the structural parameters from those due to the onset of damage in axially-loaded beam-like structures. For this first aspect, two approaches, one based on modal parameters, the other on time series analysis, have been adopted. The two alternatives were evaluated not only for their ability to provide a damage-sensitive damage feature, but for their ability to be used efficiently from an economic point of view and to be robust enough for real-world applications. The second aspect investigated was the automation of damage identification, exploiting tools for outlier detection and unsupervised data clustering and developing an automatic data cleansing strategy, essential for implementation in uncontrolled environments.

After a first phase of simulations aimed at explaining and motivating the effective use of damage features extracted from the response for axially loaded beam structures (Figure 1), the algorithms were validated on data coming from an experimental set-up consisting of a series of nominally identical full-scale tie-rods (Figure 2).

The case study here presented not only considered realistic and uncontrolled operational and environmental conditions, but also allowed to obtain monitoring data of a structure subjected to real damage (figure 3). This aspect, very rare in the literature concerning structural health monitoring in general, has allowed us to define a case study that can serve as a benchmark for future research activities on the subject.

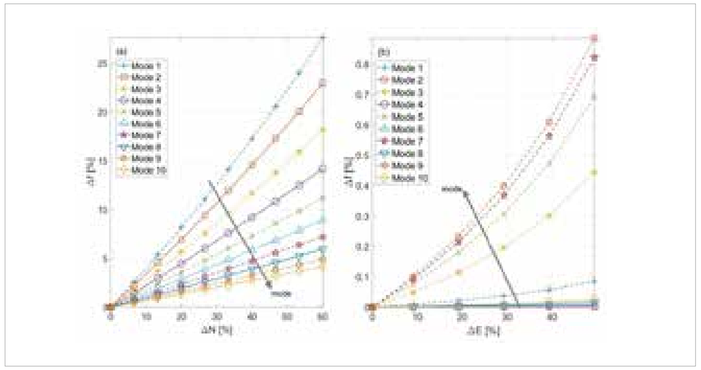

Fig. 1 - Changes in eigenfrequency values due to axial load variations (a) and damage (b). The effects can be distinguished if eigenfrequency values of multiple vibration modes are considered as a multivariate damage feature.

Fig. 2 - The experimental set-up

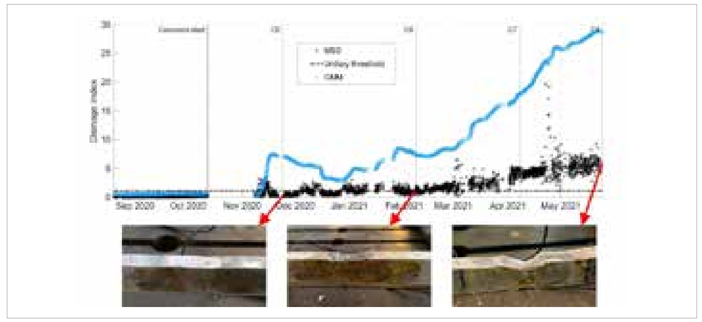

Fig. 3 - Detecting real damage: comparison between two proposed damage indexes, one based on the Mahalanobis Squared Distance (black crosses), the other on Gaussian Mixture Model (light-blue circles)

EFFECTS OF DIFFERENT POST-PROCESSING METHODS ON STRUCTURAL INTEGRITY OF LASER POWDER-BED FUSION AlSi10Mg

Erfan Maleki - Supervisor: Prof. Mario Guagliano
Co-Supervisor: Prof. Sara Bagherifard

Laser powder bed fusion (LPBF) as one of the most popular additive manufacturing (AM) technologies, offers prominent advantages in fabrication of the parts with complex structures and geometries. Layer-by-layer nature of fabrication in metallic LPBF materials besides the relevant complex thermo-physical phenomena and very high cooling rate (~10^6K/s) of melt pool resulted in formation of different internal and surface defects in these materials. LPBF materials have anisotropic and inhomogeneous microstructures, internal defects such as porosity formed by trapped gas, lack of fusion and key-hole effects, tensile residual stresses, and high surface imperfections. These defects have detrimental influences on mechanical properties and fatigue behavior of the LPBF materials. Formation of unmelted and partially melted feed-stock (powder), spatters and balling defects on the surface of the as-built fabricated parts can be specified as the major sources of surface imperfections. The parameters affecting the surface quality of as-built metallic LPBF parts have been categorized to feed-stock material specifications, design of part with different orientation and presence of down/up skins as well as the considered process parameters. Surface irregularities act as local stress concentration zones resulted in early crack initiation and failure under cyclic loadings. Hence, applying post-treatments can modulate negative effects of internal and surface defects in LPBF materials.

In this thesis, a wide range of post-processing methods including thermal treatment as well as mechanical, laser-based and chemical surface treatments were selected and their effects on mechanical properties of LPBF AlSi10Mg samples were investigated.

In particular, a notched geometry was designed for the samples to evaluate the effect of surface build orientation and how it affected the post-processing results. V-notched sample was designed as one of the bold advantages of AM is fabrication of the parts with complex geometries. Fig. 1 depicts the schematic illustration of manufacturing process of V-notched sample and the corresponded internal and surface defects in as-built state. The applied post-treatments include heat treatment (HT), shot peening (SP), ultrasonic nanocrystalline surface modification (UNSM), laser shock peening (LSP), severe vibratory peening (SVP), chemical polishing (CP) and electro-chemical polishing (ECP). Comprehensive experiments were carried out to study the effects of individual post-treatments as well as their combinations as hybrid processes on microstructure, surface morphology and roughness, hardness, residual stresses, wear and corrosion resistance and fatigue behavior of the LPBF samples. HT used for modulating internal defects by homogenization of the microstructure. Surface severe plastic deformation methods were applied for surface layer grain refinement and hardening, inducing compressive residual stresses, sub-surface porosity closure or reduction, as well as surface morphology and roughness modification. In addition, chemical surface treatments were employed for modifying surface imperfections. Finally, designed hybrid treatments were utilized to modulate both internal and surface defects. The applied post-treatment mostly focused on surface treatments, thus surface of the fabricated and treated LPBF samples characterized the in details using different approaches. For instance, as shown in Fig. 2, proper characterization of surface morphology of the as-built sample via different methods of scanning electron microscope (SEM), confocal observations, optical microscopy (OM) and micro-CT is presented. 2 main areas of smooth and notch can be seen in SEM images. In the notch area, 3 distinct regions of downward and upward faces as well as notch root with corresponded surface irregularities are shown. Downward face of notch had the highest surface roughness followed by upward face and notch root respectively.

The results revealed the high potential of the applied treatments to enhance the performance of LPBF materials under a variety of working conditions. The main physical and mechanical aspects, associated with each treatment, that contributed to the improved performance were identified and critically discussed. The results indicated that with a careful selection and design of hybrid post-treatments, considering each processes advantages and limitations, significant performance improvement can be achieved. The key is to focus on maximizing the synergy between surface roughness reduction, surface layer grain refinement and hardening, and inducing compressive residual stresses to improve wear and corrosion resistance and fatigue performance. Fig. 3 reveals the obtained fatigue tests results in fixed stress amplitude of 110 MPa which indicates fatigue life improvement up to more than 400 times after applying hybrid treatments of HT+ SP/SVP/LSP+ECP.

In addition, further than experimental studies, an alternative approach based on machine learning (ML) was used for fatigue behavior prediction and analyses of the post-processed LPBF AlSi10Mg samples. The obtained results reveal the high potential of ML for unlocking the role of post-processing on the fatigue performance.

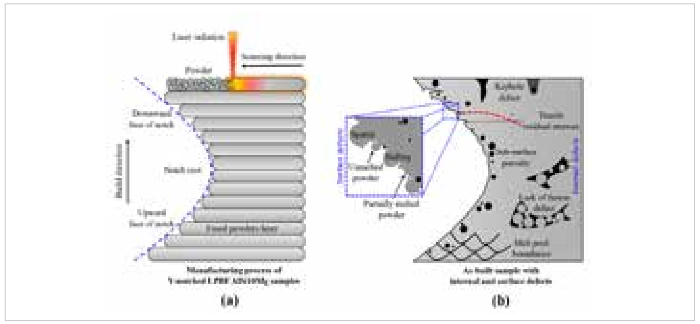

Fig. 1 - Schematic illustration of (a) manufacturing process of V-notched sample and (b) the corresponded internal and surface defects in as-built state

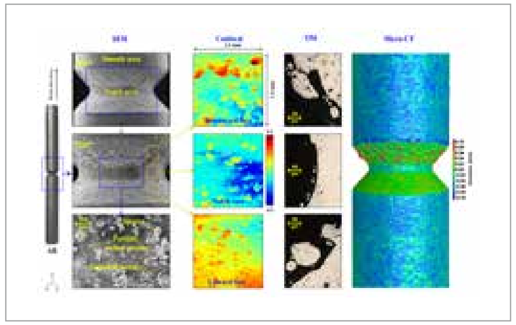

Fig. 2 - Specified surface defects in as-built notched LPBF AlSi10Mg via different methods

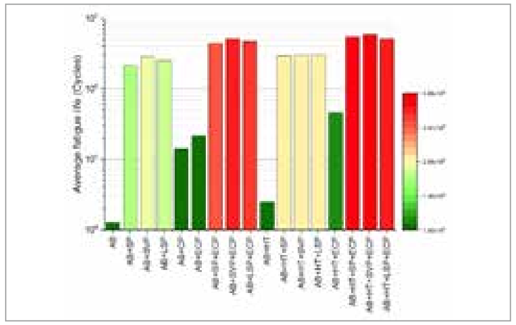

Fig. 3 - Obtained fatigue tests results in fixed stress amplitude of 110 MPa in all sets of samples.

A CONTACTLESS MEASUREMENT SYSTEM FOR HIGH TEMPERATURE SHAFT MANUFACTURING IN OPEN DIE FORGING

Valerio Marcotuli - Supervisor: Prof. Marco Tarabini

Introduction

The production of steel shafts has an important role in the manufacturing industry of mechanical devices. These products are usually made by open die forging and represent common commodities in heavy industry. It is important to monitor the dimensions of these products during the forging shaping, for reaching the desired specifications in the shortest time, avoiding excessive machining allowance.

The challenge is to obtain the shape that minimizes the finishing time process since, in some cases, up to 15% of the material has to be removed after forging. The fundamental parameters of these geometries are: 1) the section dimensions, generally roughly estimated indirectly by the forging dies, 2) the total length along the main axis and 3) the overall straightness along the main axis.

Generally, steel forging represents a hostile environment due to the presence of dust, hot temperatures, noises, and vibrations. Consequently, conventional methods and strategies for dimensional monitoring are not suitable in this industrial context.

Nonetheless, nowadays, most of the forging industries use contact measurements performed by an operator with hand calipers or mechanical gauges. This method is slow, potentially harmful and, above all, inaccurate since the measurement depends strictly on the operator's skills. Contactless dimensional measurement technology can be, in turn, a valid alternative for this purpose.

Proposed method

This research proposes an innovative measurement system independent from the factory machinery based on two contactless technologies (Figure 1): a 2D triangulation laser scanner for reconstructing the vertical section of the forging bar and a machine vision system based on a single camera with a filter in the red field (wavelength of 635 nm) for 2D and 3D measurements.

The laser scanner system is placed in correspondence of a section of the forging bar at 2-3 m of distance for acquiring different scans (point clouds) followed by a rotation of a cylindrical or prismatic hot bar. Then, a point cloud matching algorithm is able to reconstruct the geometry and estimate the geometrical parameters such as the maximum, mean, and minimum diameter in case of cylindrical forgings.

The machine vision systems can either estimate specific dimensions from a single frame by means of selectable computer vision techniques or create a 3D model of the workpiece by means of a 180° rotation. Differently from the laser scanner the camera is placed at a higher distance (>5 m) taking into account mainly the horizontal length of the forging since it usually is the dominant dimension of the workpiece (up to 15 m).

Experimental tests

Laboratory tests demonstrated that the laser scanner system was able to reconstruct the profile of cylindrical specimens (diameter in the order of 300 mm) in terms of maximum, mean and minimum diameter with an uncertainty of 2.2 mm (CI=68%). The system was also tested with prismatic specimens with the side dimensions in the order of 200 mm and returned an uncertainty of 0.9 mm (CI=68%). The machine vision system reported a measurement uncertainty of 0.7 mm (CI=68%) for the estimation of the diameter of a cylindrical specimen with a nominal value in the order of 70 mm placed at a distance of 1 m from an RGB camera in the laboratory.

The two sub-systems were also validated in the forging as real case environment. The comparison between manual caliper measurements and the laser scanner (Figure 2) estimations showed a diameter uncertainty of 4.7 mm (CI=68%) for cylindrical bars with a diameter between 300 mm and 1060 mm and an uncertainty of 2.4 mm (CI=68%) for prismatic bars with the side dimension between 340 mm and 500 mm.

The machine vision sub-system (Figure 3) was tested on cylindrical bars in the forging environment reporting an uncertainty of 9.8 mm (CI=68%) for diameters between 600 mm and 1200 mm, and a measurement uncertainty of 7.5 mm (CI=68%) for the length of specific parts of the bar up to 4 m.

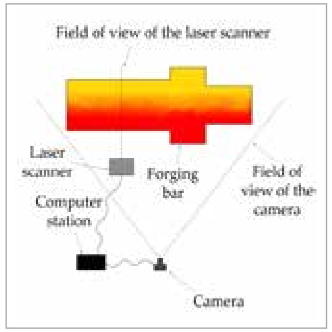

Fig. 1 - Schematic of the proposed measurement system

Fig. 2 - Laser scanner device measuring the section of a prismatic forging bar

Fig. 3 - Camera device measuring the geometry of a cylindrical bar

ENGINEERING FRAMEWORK FOR BINDER JETTING OF METALLIC, CERAMIC AND COMPOSITE MATERIALS

Marco Mariani - Supervisor: Prof. Nora Francesca Maria Lecis
Co-Supervisor: Prof. Raffaele Ardito

The research programme purpose was to define and validate an engineering framework based on the availability of liquid phase sintering for the development of binder jetting as an additive manufacturing method suited for different classes of materials. At each step of the framework diagram the relevant features and parameters to account for are listed and considered to predict the potential outcomes of the process. Three final scenarios are distinguished (full-, high- and low-density components), obtained following the guidelines on the powder properties and the specifics of the processing conditions (see Fig. 1).

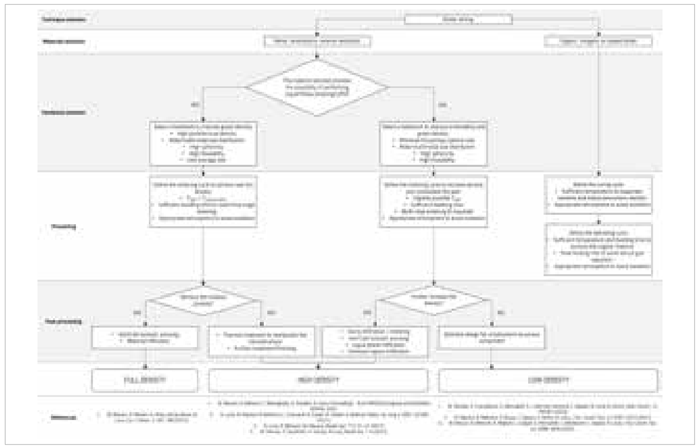

Fig. 1 - Engineering framework for the development of Binder Jetting with the identification of the possible outcomes

Multiple feedstocks were tested by varying the:

- Material type – AISI 316L stainless steel for metals, α-alumina, and sodium potassium niobate (KNN) for ceramics and tungsten carbide in cobalt matrix for composites.
- Morphology – irregular nanometric particles, spherical granules by spray drying and spherical dense particles by gas atomisation or plasma spheroidisation.

The feasibility study for tungsten carbide in 12 wt.% cobalt revealed that printing parameters may affect the distribution of ligand within the green bodies with relevant effects on the repeatability of the shaping phase. On the contrary, the sintering process is less dependent on printer settings and homogeneous results are achieved among the tested conditions from microstructural and mechanical perspectives. The large volume fraction of liquid provided by melting of the metallic matrix (cobalt) allows to accelerate densification and minimise residual porosity, which can be later removed by sinter-HIP process, thus achieving full density (> 99.6%). Therefore, materials experiencing persistent liquid phase sintering and designed for traditional powder metallurgy processes are ideal for this additive manufacturing technique and may provide acceptable mechanical performance for structural applications.
A comparative analysis on two feedstocks belonging to 316L stainless steel grade with different percentages of alloying elements allows to determine the nature of the diffusive mechanisms occurring during sintering. It is highlighted the relevance of Nieq not just on the final phase composition of the dense components, but also on the diffusion rates during sintering. Especially, the role of δ phase at high temperature is fundamental in providing a preferential path for volume-to-surface diffusive mechanisms, especially for species with high mobility as chromium. The effect of localised compositional inhomogeneities is combined with the carburisation process of the particles during debinding and early sintering, due to exposure to organic residuals acting as carbon source. The carbon concentration profile from surface to core regions affects local composition by increasing γ stability and, at the same time, by reducing solidus temperature, thus promoting supersolidus phase sintering.
Studies on α-alumina and sodium potassium niobate are reported for porous components. The impact of feedstock morphology is assessed both for the shaping and sintering steps. Alumina granulated and spheroidised powders produce optimal results in terms of geometrical accuracy of the printed parts, but both cannot grant high densification rates. Indeed, in the former case granules feature reduced primary particle size leading to intragranular densification, but green density is low and intergranular porosity is excessively large to be filled just by solid phase diffusion. In the latter feedstock, initial density is high, consistently with results achieved with gas atomised metallic powders, however surface energy has been already minimised during powder production and its contribution to densification is negligible. In both scenarios, the final components provide relevant open porosity with large specific surface areas, that can be exploited for a series of applications (filters, membranes, catalysts supports, insulators) benefitting from application-oriented geometries. Regarding sodium potassium niobate, as-synthesised irregular particles were printed, leading to scarce green densities due to their low flowability. Nonetheless, piezoelectric constants and properties were acceptable and electrical permittivity variations induced by residual porosity were correlated to increased Figures-of-Merit for 3-3 mode applications. This paves the way for geometrical customisation of porous piezoceramics configurations for sensing, energy harvesting and other applications.
Overall, it was observed that designing a correct feedstock for the process is of utmost importance. Relative density is strictly dependent on powder flowability and packing behaviour, which on turns is correlated to particles true density, shape and PSD. It was observed that well flowing powders with high sphericity, namely tungsten carbide, stainless steel and gas atomised alumina, have an optimal packing density in the 50-60% range. In such cases, a minimal amount of binder is required to achieve a sufficient consolidation of the green bodies (if particle-polymer adherence is acceptable). On the contrary, in the cases of poorly flowing feedstocks with low true density (e.g. granulated alumina, irregular sodium potassium niobate), the packing efficiency is low. Trapped macropores reduce capillary pressure on the binder, thus limiting infiltration within the powder bed, leading to the necessity of increasing the binder saturation to join all the particles within the printed volume. Therefore, it is evident that this manufacturing route is complex and the final components show memory effects of the subsequent steps of production on the macrostructure and/or microstructure. A careful optimisation of the thermal treatments and other post-printing operations may compensate for some defects (e.g. complete removal of closed porosity by HIP) but cannot solve structural issue generated by improper feedstocks or printing parameters. The presence of a heterogeneous porosity network, with relevant macro-voids generated by improper components shaping, may hinder full densification. Indeed, the competition among densification and coalescence leads to the rapid closure of sub-micrometric pores, as those within alumina granules and in intralayer regions, and possibly to the further growth of voids in poorly packed areas as the interface among subsequently deposited layers.

PROGNOSTICS OF ROLLER BEARINGS FOR INDUSTRIAL GAS TURBINE APPLICATIONS: A REAL-TIME APPROACH FOR AN EXISTING GAS TURBINE

Manfredi Mazzola - Supervisor: Prof. Paolo Emilio Lino Maria Pennacchi

Rolling bearings have key advantages for aeroderivative Gas Turbines (GT) compared to hydrodynamic bearings, such as efficiency, low friction coefficient and they can reduce the GT weight and footprint. However, rolling bearings life strongly depends on operating conditions and environment contamination, and unplanned failures lead to expensive and long-time repairs. Hence, rolling bearings create the customer need for a life prediction system to maximize plant productivity. Baker Hughes lost M$ in maintenance and contractual penalties due to roller bearings unplanned stops of aeroderivative Gas Turbine. And the Company decided to invest in alternative solutions, starting a real test case: the free power turbine ball bearing of the Company latest 70MW GT: the LM9000 (Fig. 1).
Currently, the bearing instrumentation on aero-derivative GT is composed by accelerometers on the turbine casing and chip detectors or Oil Debris Monitoring sensors. These systems are relatively cheap and easily replaceable. However, they are not highly accurate, and they can predict several false positives, without any prognostic ability.
The LM9000 ball bearing is one of the largest ball bearings in the industrial world (Fig. 2). It will operate under a wide range of operating conditions, and it is assumed that it will be subject mainly to fatigue life failure mode. In fact, in the last years, the Company introduced several improvements to maintain environment cleanliness and the ball bearing was nitrided to further improve its resistance to contaminants. Hence, the aim of the thesis consisted in developing a simple and reliable real-time prognostic system, based on standard instrumentation.
The system allows a prognostic assessment of the ball bearing life, with a simple algorithm and architecture. Moreover, it is based on cheap and easily replaceable sensors since it is based on standard instrumentation. On the other hand, it needs an accurate and validated models embedded, and it cannot predict non-linear failure modes such as hard particles contamination, corrosion, etc.
The core of the prognostic system is represented by three key models developed during the PhD project. Firstly, it was created an axial load model estimating the load acting on the ball bearing during its mission, based on two engine parameters: the speed and the compressor discharge pressure. It was built through a deep DOE, running thousands of operating points. The accuracy of the model was verified on the first engine prototype, comparing the axial load estimations to the measurements, in several operating conditions.
Secondly, a life model was developed to estimate simultaneously the ball bearing life. The bearing life curves represent the core of the model, and they are based on GE Aviation proprietary software. They are embedded in a 11x16 matrix, expressing the bearing L10 life versus the rotor speed and the axial load. The software predictions were validated on an advanced test rig, comparing predictions and measurements in terms of bearing temperatures, cage speed, skidding, in operating and off-design conditions.
The third model is represented by a simple algorithm to calculate the bearing residual life. It consists of three calculations performed in contemporary: the instantaneous L10 life, the average L10 life, and the residual life calculations. The instantaneous L10 life depends on the operating conditions, and it is calculated at each time step through the life matrix defined in the previous paragraph. The average L10 life estimation is a recursive average between the instantaneous life and the previous values of the average life. It provides the evolution of bearing L10 life over time. Finally, the residual bearing life is simply the L10 averaged minus the running hours until the considered time step. As stated, all these models are based on the same engine standard parameters, so they enable the prognostic system to operate in real-time.
The prognostic system was installed on the second LM9000 prototype. It was able to operate real-time, and to continuously predict the residual life for the ball bearing. It provided reasonable estimations of residual life, according to the variation in the rotor speed and in the ball bearing load. The results are shown in Figure 3, where it is possible to notice the variation of the instantaneous life (blue line) and residual life (orange line) with the axial load (yellow line). In this example, rotor speed was maintained constant. The values in the plot are hidden to respect the intellectual property of the Company.
In the next years, the prognostic system will be installed on the next LM9000 GTs, and it will be tuned through the failure data coming from the sites. The Company will use the prognostic system to prevent unplanned stops and to optimize the maintenance stops, with expected potential savings of M€ per year.

Fig. 1 - LM9000 Overview

Fig. 2 - LM9000 Free Power Turbine Ball bearing

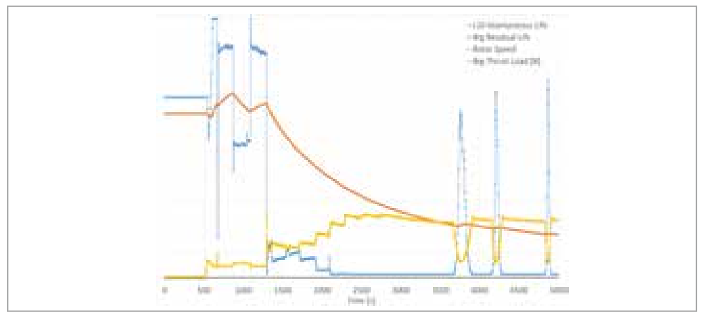

Fig. 2 - LM9000 2nd prototype, full day mission February 2022

DESIGN FOR MASS PERSONALIZATION IN DIGITAL MANUFACTURING CONTEXT

Mehmet Ozdemir - Supervisor: Prof. Gaetano Cascini

The advancements in digital manufacturing lead the shift toward smart, data-driven, and flexible production systems that allow providing on-demand and one-off products efficiently.
This shift in industrial production enables Mass Personalization (MP) to answer individual customer needs affordably, which is gaining increasing attention of businesses as a means to take the competitive edge. MP envisages profound product variability through manufacturing process flexibility, along with active customer participation in design to answer specific needs effectively. However, a challenge exists with the scarcity of design methods and tools dedicated to Design for Mass Personalization (DfMP). Existing methods and tools are mostly aimed toward modular product configurations, which are limited to component-level product variety and present only given options to customers. Therefore, conventional design methods fall short to address the product variability and customer involvement that can answer the specific needs of individual customers. Addressing these challenges, this thesis aims to develop a prescriptive design methodology for MP, focusing on the utilization of manufacturing flexibility in the process of designing a personalizable product; and an effective customer co-creation process that answers to specific needs.
The proposed design methodology guides the designer through the development process of a user-modifiable design and demonstrates how to facilitate the user involvement in reaching a personalized design. It proposes a flexible and adaptable seed design architecture, and an interactive customer co-creation process. The overall design process is structured with a DfMP framework (Fig. 1) that outlines a design process where the designer facilitates customer co-creation over a modifiable seed design.
To effectively create design variability based on the capabilities of flexible manufacturing processes, a novel seed design architecture is proposed. This architecture defines the variety and commonality through design features and by combining the common and varying design features with the information on limitations and dependencies of variability, the seed design allows keeping control over complexity while offering an almost continuous variety. The seed design development process is guided in two phases to form a variable seed design and manage its variability for customer co-creation. The first phase guides the designer in the process starting from addressed categories of needs to the identification of varying design parameters. Through filtering with a set of constraints, the variability of the parameters is expressed as a solution space, and these are translated into a design space where the user can operate.
The second phase starts with investigating the dependencies between design parameters and personal requirements, which are then used to devise a design solution algorithm. As a means to facilitate the interaction between the user and the design, the proposed methodology uses an algorithm that modifies the design parameters based on the user input, considering the dependencies and constraints. Hence, the algorithm enables the interaction of the user with the design in real-time, while ensuring a reliable final design. Generic principles of the algorithm that can be adapted to each design case conclude the seed design development. The output of the proposed design process is a seed design with certain variability and the means to co-create a personalized design with the user. The overall design process is then completed by each individual user reaching a personalized design.
The first case study includes the functional, ergonomic, and esthetical personalization of a shoe that is manufactured by 3D printing and digital knitting. This case study applies the methodology to a personalized footwear design case with a knitted upper and a 3D-printed sole. Besides the fit and the appearance, the variability of certain functionality of the knitted upper is investigated through the variation of yarns and knit patterns. The study follows the prescribed design process by identifying the design parameters for personalized fit, appearance, and comfort, and by forming solution and design spaces. Finally, the design solution algorithm for this case and an example co-creation process on a user interface are illustrated. The study is supported by interviews with experts to evaluate the design process and content of the study. The potential of the proposed design methodology is largely confirmed by the experts.
The second case study demonstrates the functional personalization of a saxophone mouthpiece to tailor the performance for musicians. The mouthpiece is where the sound is produced in the saxophone and its design is highly influential on the performance. Therefore, the choice of a mouthpiece is a very personal decision and there is an existing demand of saxophonists seeking the one that provides the sound they wish or fits their playing habits. Towards building a seed design, this study included an acoustical analysis to obtain quantitative relations between mouthpiece design and performance. To that aim, twenty-seven 3D-printed mouthpieces with nine varying design parameters are tested using an artificial blowing machine, to determine their effects on four selected mouthpiece features. The influence of the design parameters on the mouthpiece features, based on statistical analysis, is implemented in a seed design, where a largely coupled design case emerges. Following that, a user study with five saxophonists is devised to verify the outcomes. The proposed co-creation scenario is successfully tested with saxophonists personalizing their mouthpieces through a graphical user interface, and then testing the 3D-printed personalized mouthpieces.
Finally, an industrial application case on FARO dental lights is exampled to illustrate the use in a practical setting of a commercial product. This case also demonstrates the potential of the design methodology for the hybrid cases where there are both personalized and modular components.
Overall, the case studies show the potential of the methodology to deal with coupled mass personalization cases and provide for the specific needs of customers. The three main objectives of this thesis on creating variety, customer involvement, and prescriptive design guidance and tools for MP are achieved by devising a design methodology for MP and testing it through case studies. The outcome of this research contributes to the design thinking in MP to exploit the flexibility that emerging digital manufacturing technologies provide, to enable meeting diverse customer needs efficiently and effectively. A systematic approach to DfMP will allow expanding MP to more products and act as a foundation for the customer co-creation-oriented design in the context of this emerging paradigm.

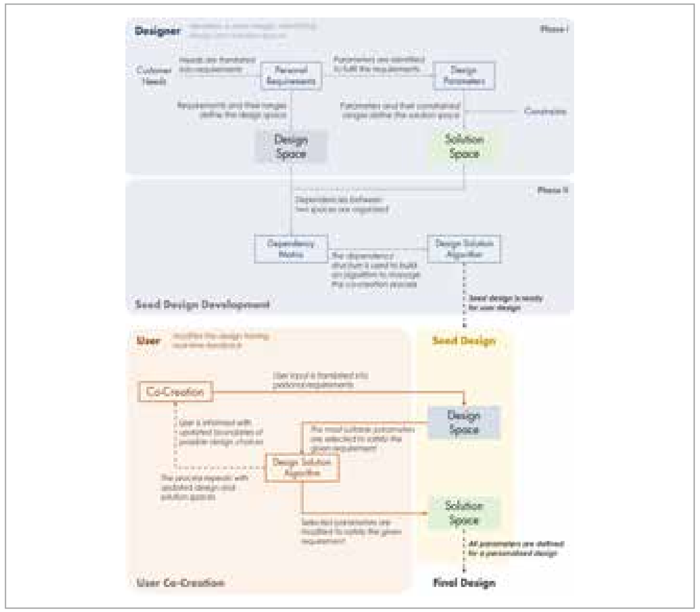

Fig. 1

OVERCOMING MIXED REALITY ADOPTION BARRIERS IN DESIGN THROUGH A COMPUTER VISION-BASED APPROACH FOR CONTENT AUTHORING

Eduardo Andrés Piñones Zuleta - Supervisor: Prof. Gaetano Cascini

Co-Supervisor: Prof. Giandomenico Caruso

Prototypes are fundamental in the product development process as different types of prototypes can take different roles depending on the needs of the developers and the expected decision outcomes. Due to this, several technologies have been developed to support the prototyping process. Among them, physical prototypes enhanced through dynamic digital elements, also known as mixed prototypes, have been demonstrated to be valuable technology in product development. However, mixed prototyping has yet to achieve a successful technology adoption due to a highly complex content authoring process. In this context, this thesis aims to reduce the existing adoption barriers of mixed prototyping and allow subjects involved in the design process to take advantage of the benefits of this technology. The main objectives are:

O1: To develop a workflow and supporting tool that can be used to streamline the mixed prototyping content authoring process.

O2: To develop a workflow and supporting tool that reduces the 3D modelling competence requirements to conduct the mixed prototyping authoring process.

O3: To develop a workflow and supporting tool that allows subjects with low competence in 3D modelling to achieve a mesh segmentation of similar quality to one made by an experienced user using standard tools.

The research process comprised five stages to assess the previously mentioned objectives. The first stage comprises two descriptive studies of the practice and research contexts, gathering information to support the design decisions, detect the existing research gaps and define the research questions. Using this information, a new workflow to support the mixed prototyping content authoring process is presented in the second stage. The third stage defines a validation plan to verify the contributions of the proposed approach and answer the research questions. The fourth stage comprises the execution of the validation plan with the analysis of the obtained results. Finally, the fifth stage discusses the overall results of the experimental activities.

This thesis presents an integrated workflow of content authoring for mixed prototyping (See Figure 1) spanning from the availability of a physical prototype to exporting a 3D model suitable for mixed prototyping. The main contribution is a texture-based mesh segmentation algorithm to generate part-based segmentations of reconstructed surface models. The integrated workflow is composed of multiple sequential stages. First, a physical prototype preparation stage ensures that the object has texture information that can aid the segmentation, that is, high-contrast features that define the boundaries of the output segments. Next, surface reconstruction creates a digital replica of the object with its texture information. The model is prepared for the projection system by applying the required transformations (e.g., rotation, location, or scale). Then, a feature detection algorithm is used to extract the information related to the boundaries of the segments from the original texture and uses it to select the corresponding vertices in the 3D mesh. Finally, all the polygons within the detected features are individually assigned to the main segments detected, and new UV maps are generated for each segment. Hence, producing a 3D model that complies with all the requirements of mixed prototyping.

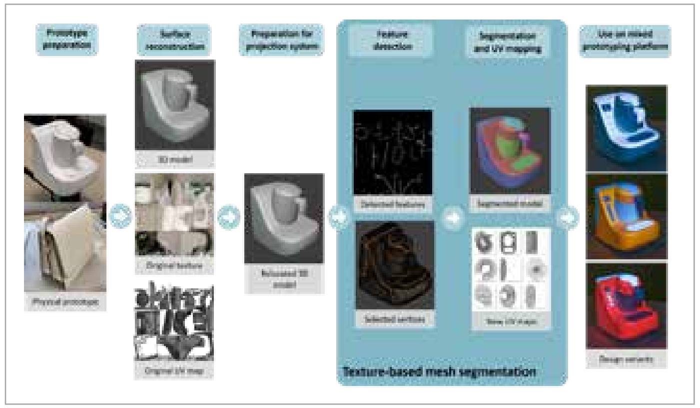

Fig. 1 - Proposed content authoring workflow

The validation plan comprises three testing stages. The first testing stage focuses on the technical suitability of the proposed approach. Consequently, the research activities begin with a simple setup, adding new variables and increasing the complexity of the input at each step. Finally, the proposed solution was tested with multiple prototypes with a wide range of geometrical features and segmentation requirements. The results demonstrated the technical suitability of a texture-based mesh segmentation approach to process models used in mixed prototyping and its integration within the complete content authoring workflow.

The second testing stage extends the evaluation of the functionality of the texture-based mesh segmentation approach to unmodified physical prototypes, i.e., using already existing texture features. Moreover, it also focuses on the proposed approach's usability and ease of use of the developed implementations. The results show that computer vision is a suitable method for feature detection in this context and that the resulting segmentation using the proposed approach is acceptable in mixed prototyping. Additionally, the subjects, who had low expertise in 3D modelling, chose parameters that generated a properly segmented 3D model for mixed prototyping without manually intervening in the mesh. Hence, demonstrating the capability of the approach to reduce the 3D modelling competence requirements for mixed prototyping content authoring.

The third testing stage compares the results of the texture-based mesh segmentation method against the standard tools available in 3D modelling software. The comparison was focused on the quality of results relative to reference segmentations made by advanced users, the time required to execute the segmentation process, and the perceived ease of use of each method. The results show that the segmentations generated through the proposed approach are slightly less accurate than the manual segmentation. Nevertheless, they could still be suitable for applications where a low error level is acceptable. Moreover, the proposed approach demonstrated significant benefits regarding time reduction, resulting in an average processing time of nearly 1/3 the time required for manual segmentation. Finally, regarding the perceived ease of use, the subjects perceived the proposed method as easier to use than the standard modelling tools to execute the mesh segmentation.

Overall, the multiple research activities to validate the proposed texture-based mesh segmentation approach demonstrated its suitability to support the mixed prototyping content authoring process. The three main objectives of this thesis were achieved, with only a small cost in the accuracy of the results to gain considerable improvements in processing time and reduction of the 3D modelling knowledge required to conduct the authoring process.

The outcomes of this research contribute to understanding the potential that a texture-based mesh segmentation can have and the limitations of that must be considered. This thesis is a step forward to reducing the existing adoption barriers of mixed prototyping and allowing users to take advantage of the benefits of this technology.

NUMERICAL AND EXPERIMENTAL ASSESSMENT OF WIND LOAD ON PERMEABLE DOUBLE SKIN FAÇADES

Giulia Pomaranzi - Supervisor: Prof. Alberto Zasso

The evolving performance requirements of modern buildings make their design a complex process that encompasses different fields. Among them, the energetic issue currently acts the leading role. In this framework, the building façade system plays a major role in the overall energy efficiency of the building and, for this purpose, new typologies of building envelopes are currently appearing in the architectural trends to help meet energetic requirements. One of the most popular examples is the Permeable Double Skin Façades (PDSF), able to provide shielding against direct sun irradiation and create a ventilated cavity useful to increase building comfort. Being the cladding system directly exposed to environmental action, the design of a PDSF must include an accurate assessment of the wind loading too. If compared to the single façade case, wind interaction with a PDSF poses several peculiar difficulties, which have been still very little investigated by the scientific community. In particular, as clarified by Figure 1, the multi-scale nature of the problem, dictated by the large geometrical scale separation between the pores and the overall building size, makes the application of both experimental and numerical methods typically adopted in wind engineering not straightforward. Neither the standards are currently providing any design guideline for such a problem. This work aims at investigating the aerodynamic behaviour of PDSFs and at identifying the role of the outer permeable layer in the aerodynamics of the building, with the final aim to provide a novel validated design procedure for a reliable prediction of the wind's interaction effects both on the external as well as on the internal façade. The general outline of the thesis is summarized in Figure 2. A set of experimental tests based on wind tunnel tests on rigid scaled model allows putting light on the potentialities coming from the adoption of a PDSF. Specifically, time-domain analysis of pressure time histories allows quantifying the shielding effects provided by the porous façade on the inner skin pressure distribution. If compared to the single-layer case, the reduction of design pressure could be up to 60%; besides this, an increased correlation between pressure signals in the separated flow region is obtained when they are recorded on the inner skin of the PDSF. Another important finding from the experimental part is the investigation of the PDSF's role in the global aerodynamics of the building: with reference to the vortex shedding excitation, it is found that the PDSF configurations are able to compromise the generation and transmission of synchronized vortexes and so to realize the VS suppression.
The experimental approach is surely able to provide an accurate description of the expected loading of the inner skin of the PDSF along with the global wind loads significant to the structural design. However, it is much harder to get a description of the loading condition on the outer façade. Relying on a scaled model makes impossible to represent angle-dependent behavior expected for the outer skin or to have a detailed description of the forces exerted on the porous layer. To overcome such limitations, a reduced-order model able to fully represent the aerodynamic behaviour of the permeable structures is implemented in the CFD framework through the porous media approach, allowing it to describe the complex aerodynamics of the outer façade. According to the porous media approach, the porous screen is represented in the computational domain through a porous slab, instead of meshing the effective screen geometry. In the cells of the porous slab, a momentum resistance term Sm is applied according to the Darcy-Forchheimer (D-F) model, neglecting viscous effects:

$$\mathbf{S_m} = -\frac{1}{2}\rho|\mathbf{U}|\mathbf{F}\mathbf{U}$$

This term is dependent on an inertial loss term F, recreating a pressure drop that is proportional to the velocity vector. In the most general formulation, it is described by a 3x3 matrice to account for the anisotropy of the porous medium. Its implementation in the OpenFoam environment is addressed along with the identification of the tensor components. Focusing on a sample of expanded metal, typically used in the PDSF, a set of preliminary numerical simulations is performed to identify the tensor's components that are then used as input in the D-F model. A comparison between the explicitly model results and the ones from the porous media model is finally carried out, providing significant results in view of the PDSF application: both the mean pressure and velocity fields are well caught by the CFD reduced-order model. Although the ideal identification of the reduced-order model parameters and the model's overall validation should come finally from full-scale experimental data, the CFD model lays a strong groundwork to address the PDSF - wind interaction problem.

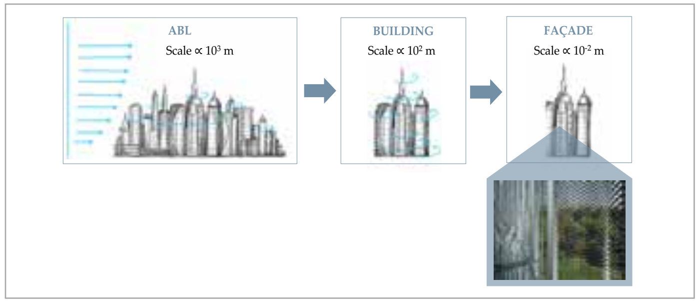

Fig. 1 - Wind effects on a PDSF: the multi-scale problem

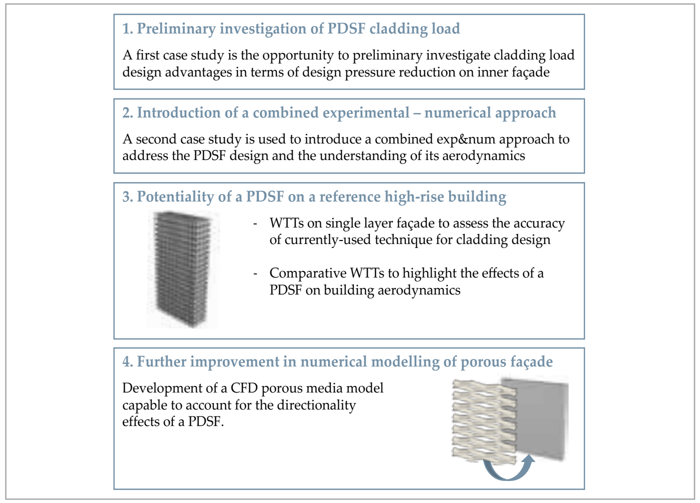

Fig. 2 - General outline of the PhD thesis

CHARACTERIZATION OF MOLYBDENUM PRODUCED BY LASER POWDER BED FUSION FOR THE HIGH-TEMPERATURE ION SOURCES OF THE INFN SPES FACILITY

Pietro Rebesan - Supervisor: Prof. Maurizio Vedani

The Laser Powder Bed Fusion (LPBF) process provides significant opportunities to design novel geometries, complex internal structures, lightweight components, and customized parts.
Currently, the most common metallic materials manufactured by the LPBF are iron-based, titanium-based, aluminium-based, nickel-based, cobalt-based, copper-based alloys, and some pure metals such as titanium, gold, silver, and some others. However, the currently in use cutting-edge alloys do not exploit the enormous opportunities inherent in the technique at all. The development of alloys specifically designed for the LPBF process is fundamental in order to exploit the full potential of AM technology.
This thesis aims to develop and characterize materials that are not yet commercially available with license tools or well defined and characterized by state of the art for the LPBF process. The selection of the materials is related to the National Institute for Nuclear Physics experiments and projects. This study is focused on additively manufactured refractory metals, especially molybdenum.
As a refractory material, molybdenum is regarded with high interest for high-temperature applications.
The concurrent use of powder bed Additive Manufacturing (AM) technology can provide significant design and production advantages.
Initially, the pure molybdenum was additively manufactured using an AISI 304 building-plate. Adhesion issues were found at the interface between the two materials from the early stage of the production process. Interface analysis was performed to investigate the possible origins of the failure. The investigation showed that large cracks could propagate and lead to the separation of the printed part from the substrate when the dilution of Mo on the AISI 304 platform was approximately in the range of 40÷50. The brittle intermetallic sigma phase was extracted and analysed by XRD on Mo-AISI 304 interface specimens. It is assumed that the sigma phase impaired the interface strength, providing a preferential route for brittle crack propagation (see Fig. 1).
Once the adhesion issue was solved using a pure copper substrate, the process parameters tuning led to produce almost fully-dense AM Mo blocks (density of 99.5±0.5 %). Fine-tuning of the parameters also involved the Single Scan Tracks analysis, which is aimed at continuous and homogeneous melt-pools production. High-density Mo specimens were characterized at room- and high-temperature in terms of thermal and mechanical properties, then compared with conventionally manufactured Mo samples. The thermal diffusivity measurement at room temperature confirmed that AM Mo has a thermal conductivity value that is roughly half that of standard Mo. Stress relieving heat treatment improves the thermal conductivity by approximately 13%. The estimation of emissivity and thermal conductivity carried out in the 600÷1600 °C temperature range led to a similar result. The Vickers microhardness measured on fully dense specimens (212 ± 18 HV0.15) is similar to that of commercially available Mo. Tensile tests were performed at both room temperature and 600°C. The effect of building direction and post-processing machining of AM specimens was also investigated for tests at room temperature. Although the AM samples exhibited a very similar density to standard Mo, the AM Mo mechanical properties resulted generally lower.
Finally, the process parameters tuning was performed for secondary parameters, related to geometrical performances, such as the evaluation of geometrical integrity as the thickness changes, the production of complex geometry, and the overhang angle study. As a result of this characterization step, the first AM molybdenum component was successfully produced (see Fig. 2). This component is the anode of the FEBIAD (Forced Electron Beam-Induced Arc Discharge) Ion Source of the Selective Production of Exotic Species (SPES) project. The physical performance of the AM anode was evaluated thanks to the proof-of-concept test carried out at the ISOLDE project's off-line system at CERN. The comparison between the ionization efficiency estimated with the totally conventional FEBIAD ion source and the one evaluated with the traditional ion source with the AM Mo anode confirms that the LPBF technology is compatible with the production of devices of such kind, thus opening up the possibility of fully exploiting its technological advantages, for instance, exploring new design solutions for the entire ion source assembly.

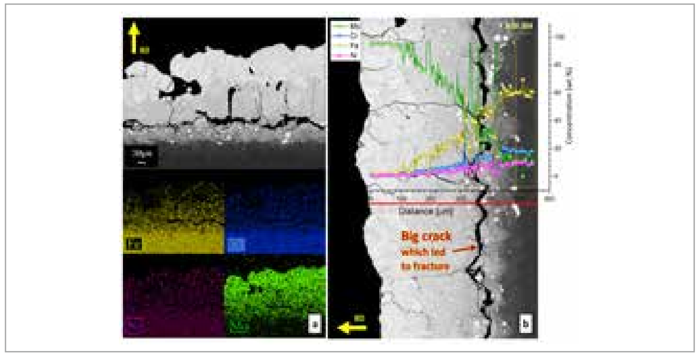

Fig. 1 - (a) EDS elemental mapping and (b) EDS elemental line analysis performed on AISI 304 and Mo interfacial surface parallel to the building direction (BD).

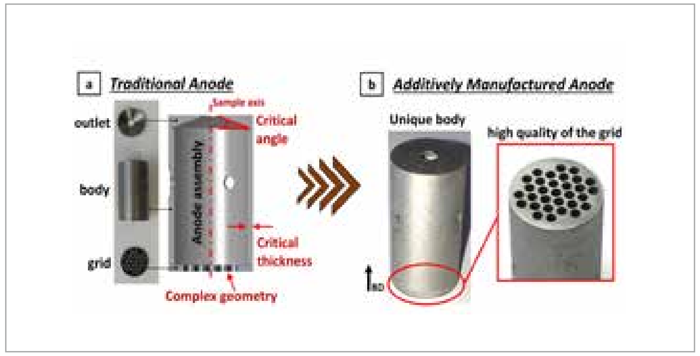

Fig. 2 - (a) Traditional anode with highlighting of the critical features vs. (b) Additively manufactured anode with magnification of high quality grid.

COMPUTATIONAL MODELS FOR FATIGUE OF ADDITIVELY MANUFACTURED MATERIALS OBTAINED BY L-PBF

Francesco Sausto - Supervisor: Prof. Stefano Beretta

The continuous rise of interest in Additive Manufacturing (AM) technology from the industries, particularly by space and aerospace firms, is pushing the scientific community to propose innovative and reliable computational models for assessing the reliability of the obtainable parts and components with this revolutionary technology. Although AM is a mature technology featuring the advantage of manufacturing mainly whatever complex geometries, the obtainable parts are still affected by several drawbacks that limit their massive employment in critical environments. Some of these drawbacks that negatively affect the produced parts by AM are the presence of volumetric defects, a typically rough external surfaces and the process induced residual stresses. Fracture mechanics approaches (deterministic) showed to correctly estimate both the fatigue strength and the finite life of components containing defects (both volumetric and superficial) and affected by the presence of residual stresses. The drawback of such models is that probabilistic simulations, in which a lot of variabilities have to be taken into account, are unmanageable from the required time and numerical burden point of view. Hence a fast and accurate methodology able to take into account the typical variabilities of parts produced by AM represents a stringent requirement during the design phase.

In the first part of the work an alloy employed in energetic field was studied, an AMed Inonel718. This investigation aimed to the characterization of the fatigue performances of this alloy at the typical loading condition required during the service of a turbo jet engine. Different printing orientations were investigated, highlighting an anisotropic fatigue behaviour of the alloy due to both a different mean size of the defects at the failure origin and a different cyclic mechanical behaviour due to a preferential orientation of the microstructure as schematically reported in Figure 1.

The second part was focused on the investigation of the residual stresses that affect a low-weight alloy which is widespread used in space applications, an AlSi10Mg. Both the effect of defects and residual stresses, in different superficial states of the tested specimens, were carefully analysed and a fracture mechanics-based approach was employed for the description of the experimental results. It was found that the measurement of the residual stresses of the "virgin" specimens gives satisfactory estimations respect to the experimental results, but the accuracy of the numerical models can be increased if one considers the effect of the cyclic loading on the residual stresses relaxation. The same AlSi10Mg was tested under torsional loading conditions. The failure mechanisms were found to be strongly related with the geometry of the defect at the failure origin, with a pure Mode I propagation for cracks emanating from spherical defects and an initial Mode II followed by a Mode I propagation in case of elongated defects. The two found mechanisms were schematically reported in Figure 2, with some representative defect morphologies that trigger the initial fatigue crack.

The multiaxial fatigue problem of AMed alloys was figured out in the third part of the work, in which the experimental results of Ti6Al4V material were analysed with a fracture mechanics approach taking into account the defect size at the failure origin. A critical plane approach was employed to determine the crack propagation direction along the specimen thickness. It was found that, due to the big size of the defects coming from the rough external surface, all the specimens failed on the maximum principal plane direction irrespectively of the loading path.

Some of the experimental investigations and the obtained numerical results were finally adopted for the development of a comprehensive probabilistic fatigue software. This software, named ProFACE, was initially developed in 2018 in PoliMI to assess the failure analysis of complex components manufactured by AM. Its capabilities were hence extended to handle the presence of superficial roughness and the effect of residual stress. After an initial tuning of the required material parameters, this software was used to estimate the fatigue life of a component-like specimens obtaining a fairly good estimations of the experimental tests, Figure 3.

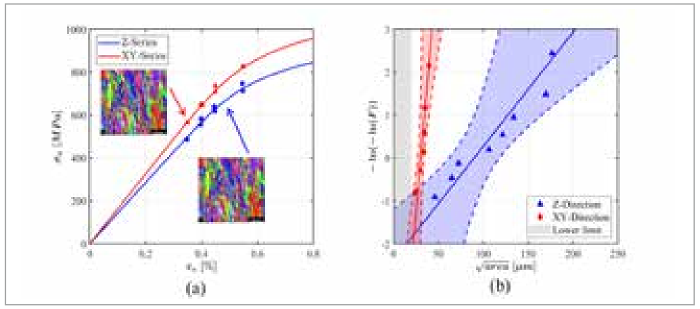

Fig. 1 - Anisotropic behaviour of the Inconel718 from both the point of view of a) cyclic behaviour and defects size. Both of the source of anisotropic behaviour come from the printing orientation.

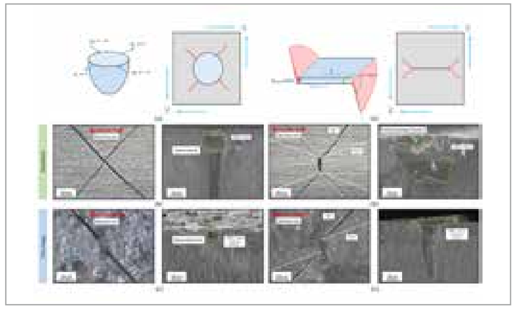

Fig. 2 - Failure mechanisms under torsional loads triggered by the different defects' morphologies which feature the tested AlSi10Mg alloy.

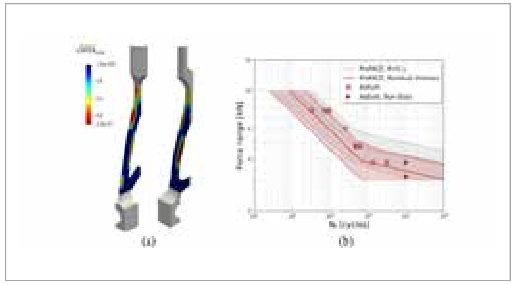

Fig. 3 - Numerical results of ProFACE against the experimental results of the fatigue tests of component like specimens: a) critical defect maps; b) F-N numerical curves against the experimental data-points.

DESIGN AND EXPERIMENTAL TESTING OF A LARGE-SCALE WIND TURBINE MODEL INSTALLED ON A FLOATING STRUCTURE

Federico Taruffi - Supervisor: Prof. Marco Belloli

Floating Offshore Wind Turbines (FOWTs) are recognized both by academia and industry as a potential solution to reduce the Levelised Cost of Energy (LCoE) of wind energy and as the key technology to exploit the high-quality wind resource available far from coastal areas.
Installing a FOWT on a multi-purpose platform (MPP), a floating platform hosting different technologies for contemporary energy and food production, instead of a traditional floater can bring advantages, such as the sharing of the infrastructure, like the platform itself, the mooring system, and other service systems, among the onboard Offshore Renewable Energy subsystems, improving the redditivity.
In this scenario, the H2020 funded "The Blue Growth Farm" project aims at developing an offshore farm that combines aquaculture with wave energy converters and a wind turbine. The concept platform is a barge-shaped floater hosting a moonpool for fish farming, that is the primary activity to be performed on the platform; then, wave energy converters are exploiting wave motions and platform motions for energy production. Last, a multi-megawatt wind turbine is exploiting wind power. The development of the MPP concept is going to be supported by experimental data collected on a 1:15 model deployed at the Natural Ocean Engineering Laboratory (NOEL) in Reggio Calabria (Italy). Actually, the platform was deployed for ten months in the waters of the Messina's strait (see Figure 1), in front of the city of Reggio Calabria, and the experimental campaign was targeted to the inspection of feasibility of the whole system as a combined food and energy production platform.
Considering the MPPs low Technology Readiness Level (TRL) and the high complexity, model testing is indeed of fundamental importance. In particular, large-scale models deployed in a natural outdoor environment are a valid complement in understanding the real features of the system and in updating or validating codes. Focusing on wind turbines, adopting a large scale presents some adavantages. Large-scale wind turbine models deployed in natural environment represent a key link between small-scale laboratory tests and full-scale prototypes. In particular, adopting a large scale allows to better reproduce the aerodynamic behaviour of the rotor, that in laboratory scale experiments is usually impaired by low-Reynolds effects. Moreover, such models can be built to be very similar to full-scale prototypes.Moreover, while implying smaller cost, design and installation effort than a full-scale prototype, large-scale models are technologically very similar to prototypes from the point of view of construction, technology involved and operation, allowing to reach higher TRLs, about 5-7.
Another advantage in large-scale

Fig. 1 - Picture of the 1:15 prototype deployed in the test site at NOEL (Reggio Calabria, IT) for a 1-year test campaign.

modelling is represented by the chance to operate in a natural environment, so exposed to uncontrolled environmental actions, further enhancing the fidelity of the experiment.
In this framework, the present work focuses on the design, testing and validation of a large-scale wind turbine model, based on the DTU 10MW reference wind turbine, installed on the scaled MPP (see Figure 2).
The typical strategies used for wind turbine models for tests in wind tunnel and wave basin are adapted to the peculiar natural laboratory requirements, integrating the scaling issues with the one related to safety and the structural assessments.
A probabilistic approach is used to evaluate wind and wave conditions in the site selected for the tests and these data are used both as input in the aeroelastic design of the tower, in the aerodynamic design of the rotor and for an assessment to extreme events. The correct aerodynamic performance is accomplished through the adoption of a performance-scaling design methodology. The structural design of the outdoor prototype blade is defined by structural requirements. The machine is implemented in order to grant the same functionalities of a real turbine: the control strategies aim at reproducing the full-scale turbine performances. Differently from small-scale models, also safety issues must be taken into account in order to grant a proper behaviour of the wind turbine even under extreme wind and wave events.
It is of interest to assess that the physical model performance reflects the design specification. The aerodynamic design was validated comparing the performances in terms of power coefficient and thrust curve reproduction with the numerical model used in the design phase. For what concerns the experimental thrust curve, the complexity of the large-scale model together with the natural environmental conditions make it necessary to perform indirect measurements: these are accomplished by means of deformation measurements records at tower base and blade root and then compared between each other and the target (see Figure 3).
The controller correct operation is verified for stationary conditions and dynamic behaviour, the latter by means of gain sensitivity analysis. From the analyses performed, it is assessed that the behaviour of the wind turbine model is correctly respecting the parameters established during the design phase in terms of structural dynamics, aerodynamics of the rotor and power controller dynamics.

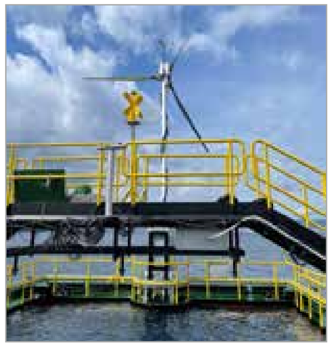

Fig. 2 - Onboard view of the wind turbine model.

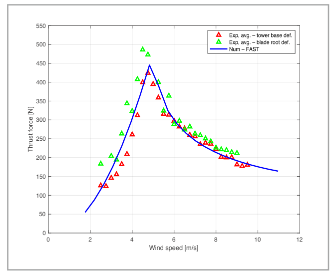

Fig. 3 - Comparison between experimental thrust curves, obtained by means of tower base and blade root deformation measurements, and design curve.

NOVEL DATA-DRIVEN/MODEL-BASED AUTOMATIC HEALTH CHARACTERIZATION FOR FAULT DETECTION, DIAGNOSIS, AND PROGNOSIS OF MACHINERY AND ITS CONTROL

Syed Muhammad Tayyab - Supervisor: Prof. Paolo Emilio Lino Maria Pennacchi

Rotating machines are essential part of today's industry. Rolling element bearings (REBs) and gears are important components of these machines, therefore, efficient condition monitoring of REBs and gears is crucial for smooth operation and availability of the machines. Fault detection and diagnosis of these components requires experts' involvement. Most of the times, human intervention cannot respond efficiently and effectively to huge amount of measured data. To perform the fault detection and diagnosis process automatically and to relieve the experts from this challenging task, different machine learning (ML) based techniques have been introduced by the researchers.
For automatic/intelligent fault detection and diagnosis of REBs and gears using ML models, accurate features containing enough information regarding the health state of the said components are required to be extracted from vibration signal.
For this purpose, vibration signal is divided into small segments to generate enough training data to train the ML model. Mostly the segment size is selected randomly by the researchers, however, using optimal segment size can be crucial in real world applications where mostly limited amount of training data is available. Moreover, to make this process suitable for online monitoring it must be computationally efficient. Thus, fault detection and diagnosis of REBs and gears, by selecting most suitable features to improve the accuracy and to make this process computationally efficient, is a challenging task for the researchers. Therefore, importance of appropriate segmentation of vibration signal for features extraction, and subsequent features selection with the help of genetic algorithm (GA), for accurate and computationally efficient fault detection and diagnosis of REBs and gars is studied using K-nearest neighbours (KNN) model as classifier. Selecting very small size of segment for features extraction to increase the amount of training data, adversely affected the features quality as those features did not contain enough information to depict correct health state of components and subsequently fault detection and diagnosis accuracy of ML model was affected.
For Fault detection and diagnosis using ML models, usually it is assumed that the operating conditions under which the models are deployed to make predictions are same to those operating conditions under which the models were trained. However, in real world applications different operating conditions such as speed and load may be encountered.
Features which are extracted from vibration signal are sensitive to change in health state of machine's components and depict changes with changing health state of the components. These features can also be sensitive to operating conditions and may alter due to change in operating conditions as well, consequently, misleading the ML model and causing inaccurate fault detection and diagnosis.
In real world applications it is usually not possible to obtain training data from all possible operating conditions. As a result, fault detection and diagnosis under different operating conditions is a challenging task for researchers. Therefore, an effort is made to find robust features which are less sensitive to operating conditions but can discriminate between different health states under different operating conditions for accurate fault detection and fault severity level identification of spiral bevel gears which have rarely been used as benchmark for defect diagnosis studies due to difficulty in their fault detection which is attributed to their high contact ratio and complex vibration signal. Performance of ML models is significantly improved under different operating conditions by eliminating the misleading features, which are more sensitive to operating conditions, and selecting the robust features which are comparatively less sensitive to operating conditions but are fault discriminative.
Even though use of classical ML models for fault detection and diagnosis has reduced human involvement in this process, however, it involves correct features extraction and selection, which still requires filed experts' involvement to some extent. In order to further reduce human intervention in this process, deep learning (DL) based techniques have been introduced by the researchers. DL models have capability to perform end to end diagnosis and do not require manual features extraction and selection. However, challenge of fault detection and diagnosis under different and variable operating conditions exists for DL based techniques as well.
Therefore, a novel method is proposed for defect diagnosis of REBs utilising the combination of order tracking, and image classification and recognition capabilities of deep convolutional neural network (CNN) model.
Order maps are generated from nonstationary vibration signal by resampling the signal synchronously at constant angular intervals to convert it into a stationary signal in order domain and subsequently computing Short-time Fourier Transform.
Order maps show consistent patterns under variable speed but show unique patterns for different types of defects. The sensitivity of order maps for changing load is studied experimentally for deep groove ball bearings and it is found that they remain consistent under varying loads if the bearings are properly loaded.
A deep CNN model having the capability to automatically extract fault discriminating features from order maps is proposed.
The proposed method undertook fault detection and diagnosis on REBs under variable speeds and loads with high accuracy and outperformed other CNN, KNN, ANN and support vector machine (SVM) based methods.
Although deep CNN models have gained much success in the field of automatic fault detection and diagnosis using vibration characteristic images due to their excellent image classification and recognition capabilities.
However, training the deep CNN models from scratch is computationally much expensive and require a lot of training data as well. Therefore, application of these techniques may not be feasible in real world applications if limited amount of training data is available and hardware limitations exist. This issue can be mitigated to some extent by using pretrained CNN models on other types of data sets through transfer learning. However, it may still be computationally expensive and may require much time in the absence of graphic processing unit (GPU). Alternately, instead of using CNN model as end-to-end classifiers, they can also be used to extract meaningful features form the vibration representative images and those features can be used as input to classical ML models. Moreover, there are other image classification methods which have not been used widely in the field of fault detection and diagnosis of REBs. These image processing (IP) based methods can be computationally much efficient as compared to using CNN models as end-to-end classifiers. However, fault detection and diagnosis accuracy may be compromised. Therefore, using spectrogram images, a comprehensive performance comparison between these IP based techniques is carried out to find a trade-off between defect diagnosis accuracy and computational expense. Based upon the comparison, a hybrid-ensemble method involving decision level fusion is proposed for defect diagnosis of REBs.
Performance of all these IP based techniques involving different combinations is also compared in case of minimal training data availability and for diagnosis under slightly different operating conditions to ascertain their generalizability and ability to correctly diagnose despite availability of minimal training data. The performance of the proposed hybrid-ensemble method remained outstanding for the defect diagnosis of REBs even though being computationally far less expensive as compared to CNN models while using them as end-to-end classifiers.

CONSTRAINED OPTIMIZATION OF MICRO INJECTION MOULDING PROCESS

Gianluca Trotta - Supervisor: Prof. Quirico Semeraro

Tutor: Prof. Paolo Emilio Lino Maria Pennacchi

Micro injection moulding (μIM), among micro manufacturing technologies, is the leading process able to produce, on large scale, polymeric micro components and micro devices (Fig. 1). The growing industrial interest in this technology is pushing towards the definition of a reliable process through the observation of affordable process variables that can be easily measured and optimized.
The idea behind the PhD work is to observe, with an experimental approach, both the weight variable, which is a continuous variable, and the related flash defect (Fig. 1), which is instead a categorical variable. This approach is very useful because it follows, and somehow combines, the industrial methodology, which always prefers a direct observation of part to classify the quality and eventually the defect due to personal sensitivity and experience, with the scientific field that instead, with a statistical approach, seeks to identify reliable models for assessing the quality of the product.

The optimization problem can be focused only on the optimization of Tmelt and Phold because they both influence the objective function and the constraint.
In detail, as Tmelt and Phold increase the weight increases (and therefore the quality), but at the same time also the defect probability increases[1] The utility function used in this work (fig. 2) can help to find a compromise between part weight and the probability of flash formation, for this reason in the optimal condition there is a small but non-zero probability of flash formation (fig. 3).
The present work focused on the evaluation of part weight as an affordable variable to be easily implemented in an industrial environment to estimate the quality of the moulded part.
The quality of the produced components in μIM process is still an open question to which researcher are still trying to give an answer. Some defects, such as flash formation, are more usual than standard injection moulding due to the extreme process conditions of the micro injection moulding process and arise when the part weight is maximized.

In the proposed work:

- It has been defined a procedure to identify an optimality region for the maximum weight of the moulded part in which the risk of generating flash is minimized.
- The procedure was applied to a technological problem and, additionally, the procedure was generalized to also consider a stochastic constraint.
- The selection of the optimal level of the process parameters was carried out using a utility function. The utility function aims at finding a compromise between the maximization of the weight and the minimization of the probability of flash formation.
- The bootstrap technique and data depth approach has been used to identify the optimality region of the part weight constrained by the region related to the probability of flash formation.
- The result of this novel approach is a greater variability of the main process parameters, namely Tmelt and Phold, and this means a greater variability of the micro injection moulding process without falling into the risk of producing waste parts.
- The use of a utility function that correlates two variables of the same process has proved to be fundamental for the construction of the optimality region.

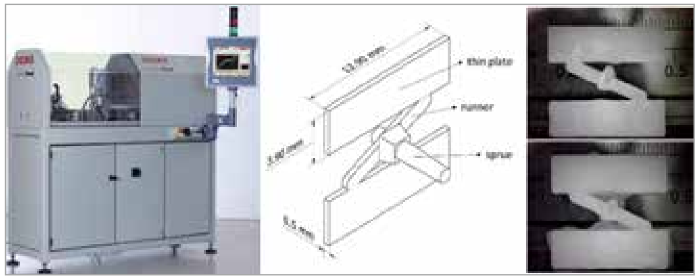

Fig. 1 - Micro injection moulding machine and test specimen details on flash defect analyzed

1. Trotta G., Cacace S., Semeraro Q. (2022). Optimizing process parameters in micro injection moulding considering the part weight and probability of flash formation. Journal of Manufacturing Processes, 79,250-258; Trotta G., Cacace S., Semeraro Q. (2022). Process optimization via confidence region: a case study from micro-injection molding. Journal of Intelligent Manufacturing, 33(7), 2045-2057.

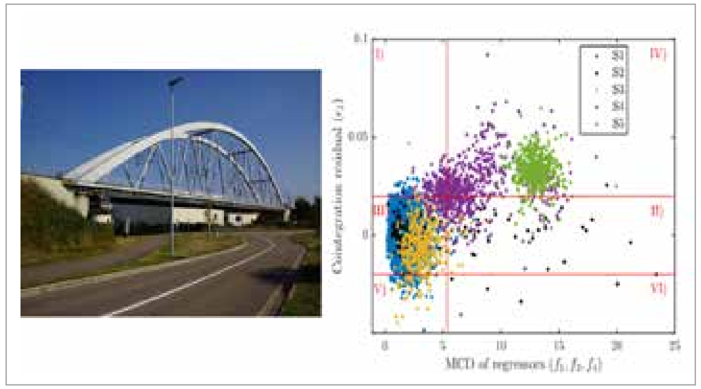

Fig. 2 -Workflow of the Generalized Optimal Region procedure (GORp)[2] to identify the optimality region

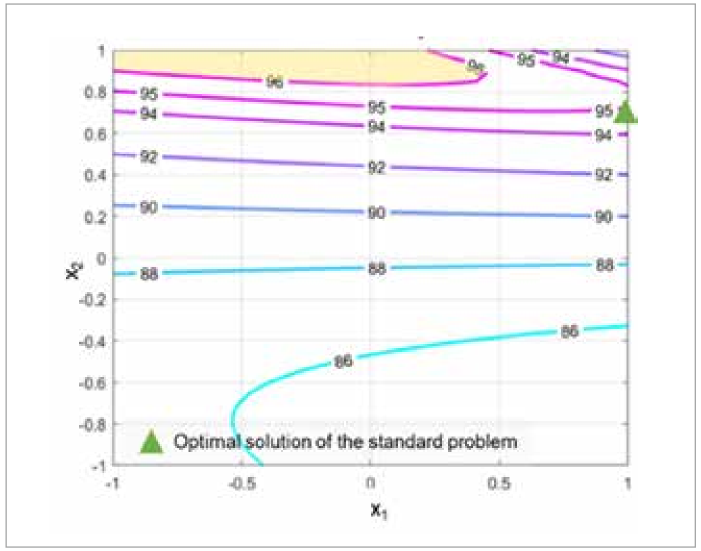

Fig. 3 - Optimality region (yellow) for the micro-injection process[2]

2. Trotta G., Cacace S., Semeraro Q. (2022). Process optimization via confidence region: a case study from micro-injection molding. Journal of Intelligent Manufacturing, 33(7), 2045-2057

ADVANCED MONITORING AND DATA PROCESSING TECHNIQUES FOR LARGE-SCALE CIVIL STRUCTURES

Simone Turrisi - Supervisor: Prof. Emanuele Zappa

Structural Health Monitoring (SHM) has become increasingly popular in the last few decades, thanks to advanced research activities combined with the rapid developments of sensing technologies. However, when passing from academia to real-world conditions, the SHM adoption is still an open issue, mainly due to cost-related constraints, differences in geometries and material properties, influence of uncontrolled environmental and operational variables (EOVs). In this context, this research work provides different methodologies to address the main challenges behind the SHM of large-scale structures.

First, cointegration has been applied for the first time on a unique and complex structure, such as the steel roof of the G. Meazza stadium in Milan. The existence of a cointegrating relationship between the tiltmeter signals installed on the roof produces a stationary time series, where the effects due to EOVs are eliminated. This enhances the possibility of identifying potential damage conditions (Fig.1).

A second study proposes a new diagnostic tool for damage diagnosis when implemented as novelty detection. This combines cointegration analysis and robust outlier statistics to separate outliers due to EOVs from those due to damage (Fig. 2). The procedure has been validated considering as damage-sensitive features the main natural frequencies of the KW51 bridge. In response to the need to have reliable estimates of crowd-induced loading on civil structures, the present work proposes a vision-based method that uses Digital Image Correlation (DIC) able to directly measure the crowd loads. The accuracy and the applicability of the technique has been experimentally validated on real-life stadium grandstands.

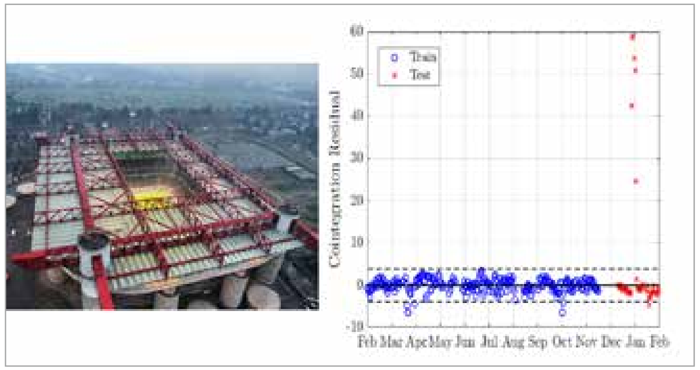

Fig. 1 - The roof of the G. Meazza stadium: thanks to cointegration, the linear combination of the tilting signals generates a stationary residual, in which all the EOVs-induced trends are compensated. This enhances the possibility to identify real structural modifications (red outliers in the graph).

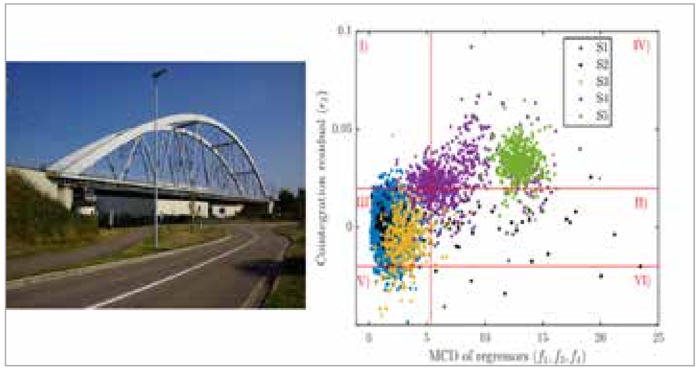

Fig. 2 - The residual-outlier map plots the cointegration residual as a function of the MCD of the regression inputs, using the natural frequencies of the KW51 bridge as input features. Based on the obtained values for these two parameters, it has been possible to separate outliers to cold temperatures (black dots) from those due to retrofitting (green dots)

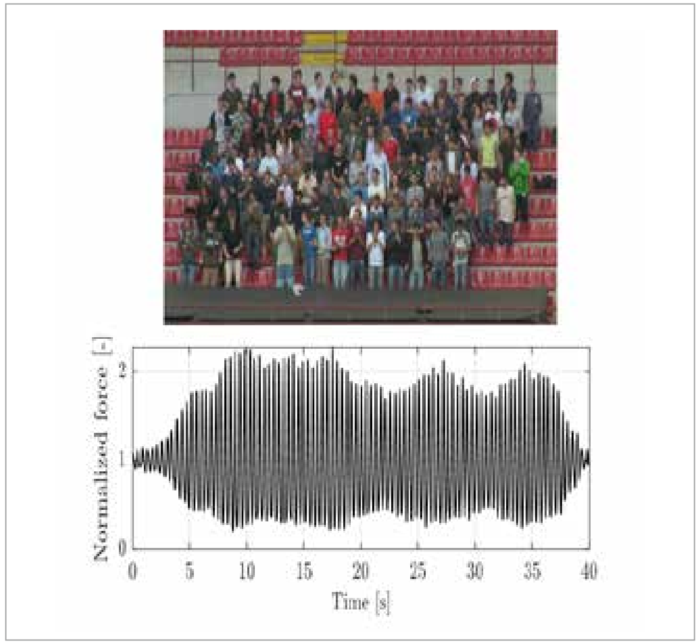

Fig. 3 - Example of a force signal estimated with DIC starting from an image sequence. In this case, a crowd made of 108 volunteers jumping on a real grandstand is considered.

FULL SCALE SMART MONITORING OF HIGH VOLTAGE TRANSMISSION LINES

Federico Zanelli - Supervisor: Prof. Giorgio Diana

High Voltage Transmission Lines (HVTL) are the structures built with the purpose of transferring electrical energy from the point where it is generated to the point where it is employed in different ways. Many existing HVTL are approaching their service life both from a technical and economical perspective, and for this reason companies managing these structures need to develop maintenance strategies with the goal of extending the operational life of a line on the basis of its condition. From a structural point of view, wind flowing on a HVTL represents the most important action for the design of towers and fittings. However, the static load acting on the towers is not the only problem to be solved in the design of HVTL. Conductors, in fact, are stranded cables endowed of low structural damping and this makes them very susceptible to wind induced oscillations generated by the fluid-structure interaction. The wind action on conductors produces three main wind induced phenomena in different conditions that are aeolian vibrations, subspan oscillations and galloping. While subspan oscillations and galloping are rarer but can lead to severe structural damages due to clashing of conductors, clamps loosening, breakage of insulator strings and even total collapses of towers and conductors, aeolian vibrations lead to fatigue issues to both fittings and conductors due to their frequent repeatability in time. In this context, vibration monitoring represents a key tool to assess the strain level present on the conductors caused by the aforementioned wind induced vibrations. Nowadays a real time monitoring system to be used to detect the wind induced phenomena acting on the conductors of a transmission line and measure the subsequent level of strains is not available on the market. Vibration recorders are usually employed for a limited amount of time just after the construction of a new line in order to check the effectiveness of the designed and installed damping system. In addition, these devices present several limitations in their usage and cannot be adopted for the intended purposes in long term monitoring campaigns. The idea proposed in this thesis work is to develop an innovative and smart wireless monitoring system able to measure in real time a fatigue indicator already exploited in laboratory fatigue test with the goal of detecting possible fatigue issues on the monitored line.
This parameter is represented by fy_{max}, where f is the frequency of vibration and y_{max} is the antinode amplitude of vibration, which can be obtained by means of acceleration measurements. To measure fy_{max} in real time from a line, a suitable monitoring system composed by a gateway and wireless sensor nodes has been developed.
A specific acquisition logic of the high-level algorithm, ruled by the wind speed acting on the line, has been designed. The firmware to be implemented on the microcontroller of the sensor nodes has been written in order to perform acceleration measurements and to carry out on-board computations to obtain the synthetic index representative of the level of vibration. The smart sensor nodes have been moreover developed with the aim of realizing energy autonomous and wireless devices, which are essential features to perform effectively continuous monitoring of HVTL. In addition to the knowledge of the data acquired through the ad-hoc developed sensor nodes, it is of the utmost importance the knowledge of the system dynamic behaviour for correlating the collected vibration data to the stress level. An algorithm able to employ the data acquired by sensor nodes as input for numerical simulations to obtain the real strain level in the section of interest of the span was developed.
This algorithm represents the link between experimental data and numerical simulations and makes it possible to take advantage of both these tools in the proposed method. The complete method was then adopted for the first time in a field test in Manitoba (Canada) on a triple bundle HVDC transmission line. A numerical-experimental comparison was carried out to check the consistency of the data acquired and the developed algorithm was employed to compute the strain level acting on the span. The innovative method was moreover used to carry out an estimation of the conductor fatigue life on the basis of the stress level obtained through the use of the algorithm. The motivation for this activity can be found both in the industrial and academic field. As already pointed out, a major challenge for Transmission System Operators (TSO) is represented by the need of analyse transmission lines structural obsolescence and anticipate maintenance actions and therefore this new method and system is being industrialized at this aim. Regarding the scientific point of view, there is still a limited knowledge on the physical mechanisms of some phenomena, such as subspan oscillation and galloping. Moreover, the amount of experimental data available is in these cases very scarce and this makes troublesome the validation of numerical models developed in the years to predict the conductor's dynamic behaviour. By means of a continuous monitoring in time, it is then possible to cumulate the stresses detected and compute the residual fatigue life of both the fittings and the conductor. This innovative method can be used in case of new lines to check the efficiency of the installed damping system in the most critical spans and on existing lines to understand the structural obsolescence of the various components and to verify that the line is in safe condition with respect to vibration. Moreover, a Condition Based Maintenance approach, which is already a standard way to carry out maintenance in other fields, could be adopted by TSO using this method.

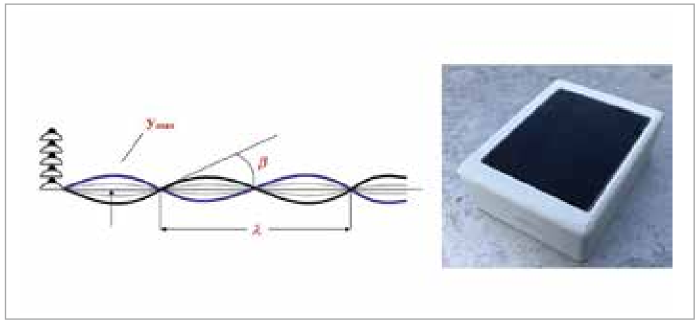

Fig. 1 - Main parameters used for aeolian vibration studies and external view of a wireless sensor node prototype

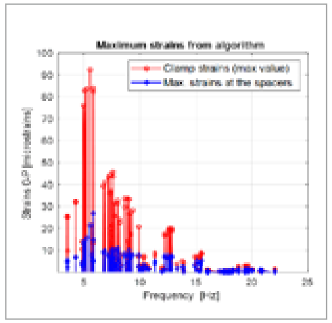

Fig. 2 - Maximum strains obtained from the Manitoba field test with the innovative method