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PhD Yearbook | 2020

DOCTORAL PROGRAM IN MECHANICAL ENGINEERING

Chair:
Prof. Daniele Rocchi

The PhD Programme in Mechanical Engineering of Politecnico di Milano offers top-level knowledge in one of the most profitable sectors in Italy and Worldwide; it is a key instrument to access leading enterprises and to achieve prominent positions in large international companies devoted to research and development, innovation and design. The primary employment market is composed of leading companies and organizations dedicated to innovation, research and technical development, high-tech SMEs and governmental departments. Our Programme currently ranks 9th in the world according to QS World University Rankings (Mechanical, Aeronautical & Manufacturing Engineering 2020).

As for career perspectives, a recent survey (run by Politecnico in 2019) showed that our PhD Candidates are 100% employed after one year, in national and international companies and academic and non-academic research institutions. On average, the survey showed that people earning our PhD title are paid 35% more than the corresponding employees with a master title.

Within our Programme all Doctoral Candidates follow a minimum path of three-years, which includes specific courses and lectures, held by Faculty members and foreign professors and experts: in particular, our candidates have access to a series of research seminars delivered monthly by international top level faculty (Mecc PhD Lectures) and to full courses provided by European and non-European academic experts leading to the obtainment of at least 20 ECTS. They also experience in-depth research, lab activities and active cooperation with international industries, institutions and research groups. With this background, our Doctorates are able to blend the exactness of scientific knowledge with the ability to deal with management and industrial issues. These skills are well appreciated in the industrial field and make their scientific profiles suitable for prestigious positions at national and international level.
In the following pages 20 abstracts belonging to PhDs of the 30th (1), 31st (8) and 32nd (11) doctoral cycles (defended in 2019 and 2020) are proposed. They represent a good overview of the international vocation of our PhD Programme, with half of them having been developed by international fellows. Female presence accounts for 15%.
Nearly 100% of the PhDs were supported by fellowships provided by the Italian Government, Industries, and European and National projects.

RESEARCH AREAS

The PhD Programme in Mechanical Engineering covers a number of different disciplines, being devoted, in particular, to innovation and experimental activities in six major research areas. All doctoral thesis displayed in the following pages belong to one of these areas:

***Dynamics and vibration of mechanical systems and vehicles**:* this research line is organized into five research areas, namely Mechatronics and Robotics, Rotordynamics, Wind Engineering, Road Vehicle Dynamics, Railway Dynamics. It features modelling of linear and non-linear dynamic systems, stability and self-excited vibrations, active control of mechanical systems, condition monitoring and diagnostics.

Measurements and experimental Techniques: the Mechanical and Thermal Measurements (MTM) group has its common background in the development and qualification of new measurements techniques, as well as in the customisation and application of well-known measurement principles in innovative fields.
MTM major research focus is oriented towards the design, development and metrological characterisation of measurement systems and procedures, the implementation of innovative techniques in sound/vibrations, structural health monitoring, vision, space and rehabilitation measurements.

Machine and vehicle design: this research area is involved in advanced design methods and fitness for purpose of mechanical components. Advanced design methods refer to the definition of multiaxial low and high cycle fatigue life prediction criteria, and the assessment of structural integrity of cracked elements, the prediction of fatigue life criteria of advanced materials as polymer matrix composite materials (short and long fibres), the definition of approaches to predict the influence of shot peening on fatigue strength of mechanical components. Gears, pressure vessels and helicopter components are dealt with. Optimal design and testing of vehicle systems create a synergism between the theoretical and the experimental researches on ground vehicles.

***Manufacturing and production systems**:* this research field gives relevance to the problem of optimal transformation of raw materials into final products, addressing all issues related with the introduction, usage, and evolution of technologies and production systems during the entire product life-cycle. PhD activities, in particular, are developed within the following research fields: Manufacturing Processes (MPR), Manufacturing Systems and Quality (MSQ).

***Materials*:** this area is focused on the study of production process and characterization of materials, for structural and functional applications. Excellent research products were obtained both on fundamental research topics (e.g. nanostructured materials, foamed alloys, chemical phenomena in liquid melts, microstructural design ecc.) and on applied research (e.g. failure and damage analysis, texture analysis, high temperature behaviour, coatings for advanced applications, etc.). The research projects carried out in recent years addressed specifically the following research topics: Steelmaking and Metallurgical Processes, Advanced Materials and Applied Metallurgy.

***Methods and tools for product design*:** two main research topics are addressed in this field: PLM-Product Lifecycle Management, which includes process

modelling, engineering knowledge management, product innovation methods, systematic innovation principles and methods, topology optimization systems, and data/process interoperability, and Virtual Prototyping, which includes virtual prototyping for functional and ergonomics product validation, haptic interfaces and interaction, reverse engineering and physics-based modelling and simulation, emotional engineering.

LABORATORIES

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

INTERNATIONALIZATION

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

We have ongoing agreements with MIT (Progetto Rocca), Technion – Israel Institute of Technology (Double PhD), Shanghai Jiao Tong University (Double PhD), École Centrale Paris (Cotutelle), Delft University of Technology (Double PhD and Cotutelle), RWTH Aachen (Double PhD), X'ian Jiao Tong University (Double PhD), University of Antwerp (Double PhD), Northwestern Polytechnical University (Double PhD), TUM (Cotutelle), ETH Zurich (Cotutelle), University of Illinois at Urbana Champaign (Cotutelle), Laval University (Double PhD), EAFIT (Cotutelle), Qatar University (Double PhD), AGH - Akademia Górniczo-Hutnicza (Cotutelle), NTNU (Cotutelle).

We also have ongoing collaborations within a wider international network, that includes some of the highest-level and best-known universities all over the world, such as the University of California at Berkeley (US), Imperial College London (UK), Tsinghua University (CN), University of Michigan (US), École Polytechnique Fédérale de Lausanne (CH), Norwegian University of Science and Technology (N), University of Southampton (UK), Technical University of Denmark (DK), Pennsylvania State University (US), Chalmers University of Technology (SE), Virginia Tech (US), Technische Universität Darmstadt (DE), University of Bristol (UK), The University of Sheffield (UK), Politécnica de Madrid (ES).

In 2019 21% of our candidates spent a total of 97 months abroad in European and international universities and research centres. Incoming Visiting PhDs were overall 17, mostly from China.

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DESIGN OF SEMI AND FULLY ACTIVE ACTUATORS TO REDUCE ROTOR INDUCED VIBRATIONS ON A HELICOPTER FUSELAGE

Lorenzo Aquilante - Supervisor: Prof. Francesco Braghin

Helicopters are subjected to intensive vibration phenomena that are due to their mechanical complexity and high demanding performance. Considerable efforts have been expended by industry to reduce vibrations at levels that are comparable to those registered on the other aircrafts. The potential benefits are straightforward: reduced crew fatigue, improved electronic equipment reliability, increased fatigue life, an extended flight envelope, increased passenger comfort and enhanced reliability. The most prominent source of vibrations is represented by the main rotor: the interaction between the airflow and rotor blades generates cyclic aerodynamic loads on the rotor hub that are transmitted to the gearbox and then to the fuselage, with a risk of amplification. The mechanical linkage between fuselage and gearbox has always been object of study and improvement as it provides the structural sustain of the fuselage during flight, and hence, represents the principal transmission path of both static and dynamic loads from rotor to the airframe. Therefore, the fuselage suspension system has been referred to as an important benchmark for the development of the most advanced vibration control devices, that nowadays become integral parts of the suspension itself. This doctoral thesis proposes two different innovative actuators that work as both structural linkage elements and anti-rotor induced vibration devices, obtaining two fully embedded solutions which satisfy the ultimate target of compactness. The first solution is a semi-active actuator which applies a collocated vibration control at the attachment points between the fuselage and the suspension system, while the second one is a fully-active actuator which is designed to implements both AGVR (Active Gyrox Vibration Control) and ACSR (Active Control of Structural Response) logics, that respectively represent a collocated and a non-collocated vibration control strategies. The detailed design of both solutions is discussed, describing features and performance at different operating conditions that have been extracted by experimental flight tests. The work presented in this doctoral thesis has been developed in collaboration with Leonardo Helicopters® and represents one of the research activities involved into the Comfort Project (http://www.leonardocompany.com/en/-/futuro-elicotter-future-helicopter) whose reference aircraft is the AW139 helicopter (see figure 1).

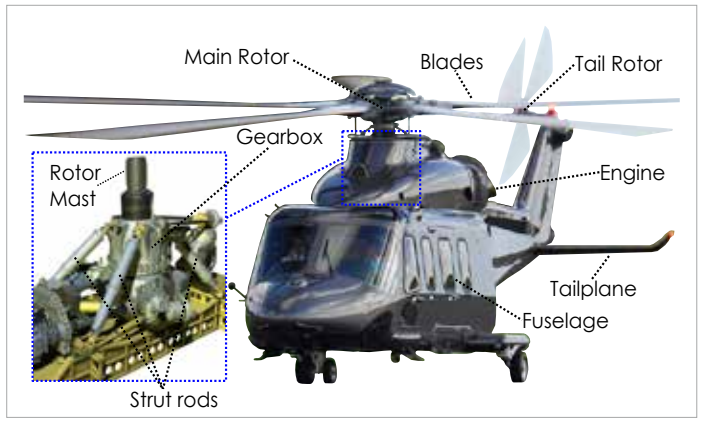

Fig. 1 - AW139 Leonardo Helicopter and its fuselage suspension system.

COGNITIVE AND MOTOR REHABILITATION SYSTEM FOR HOME-THERAPY

DEVELOPMENT OF AN ACTIVE HAND EXOSKELETON AND AN AI-BASED VIRTUAL ASSISTANT

Beatrice Aruanno - Supervisor: Mario Covarrubias Rodriguez

Nowadays, we are experiencing a social transformation: the world population is ageing. According to the United Nations, in 2019 one in eleven people in the world will be over 65-year-old. A longer life brings new opportunities but it can cause an increased incidence of diseases such as stroke. Worldwide, stroke is the third leading cause of disability. A stroke can be defined as a neurological deficit due to a central nervous system infarction or haemorrhage. Among its numerous consequences, there is the contralateral paralysis of the hand. This symptom hinders many activities of daily living. Many stroke survivors are involved in rehabilitation therapy with medical experts for years after the disease. It has a high social and economic impact both on patients and society. Literature review shows that moving towards a home-therapy with mechatronic devices seems promising. However, there are still numerous open challenges in literature such as the comfort, the portability/packability, the cost, and the usability for non-expert users.

One aim of this thesis is to move a step further developing a portable hand exoskeleton for hand rehabilitation that could be used at patients' home with the help of their family. The design process involved possible users of the device: medical professionals and bioengineers employed at the Villa Beretta rehabilitation centre plus some post-stroke patients. I think that having feedback from the medical perspective is a fundamental advantage for the development of an effective device. The outcome is the hand exoskeleton named HANDY. The 'glove' is designed to extend the user's fingers without harming the skin, and following their natural movement. It is a blend of different flexible and rigid parts obtained using additive manufacturing. The remote actuation unit includes linear actuators, electronic components (including a PCB realized on purpose, a LiPo battery, and a dedicate router for wireless communication), plus some security elements. All are mounted inside a padded backpack to obtain a highly portable device (Figure 1).

A further issue with traditional rehabilitative therapy, related with the social and economic impact on patients and families, is the therapy abandon rate. Some patients experience difficulties in interacting with these innovative devices, others feel loneliness feeling. This leads me to the second aim of this thesis: the development of a virtual assistant that could be the linking element between patients and therapists. Starting from users' needs, a combination of 3D modelling and Natural Language Processing techniques resulted in MAIA (Figure 2). Starting from the appearance decided with preliminary focus groups with therapists and patients, I created the final 3D rigged and animated character. MAIA interacts with users using natural language. It combines some AI-based features to capture the user's need, convert it into a machine-readable input, classify the context and the main concepts (intents/entities) of the request, chose and perform the appropriate actions, generate a textual response for the user, and synthesize it with a neural voice.

Another primary cause of the therapy abandon is the monotony of the therapeutic exercises. Especially in view of an home-therapy setting, it would be necessary an application that includes different types of customised exercises depending on the patient's conditions. For this reason, I developed a desktop application for both therapists and patients. It includes predefined passive repetitive movements, active exercises where the patient drives HANDY with her/his healthy hand thanks to an optical sensor (a Leap Motion controller) and a more engaging serious game based on an activity of daily living that combines motor and cognitive aspects of the disease (Figure 3). It allows me to combine HANDY and MAIA with therapeutic exercises, offering patients a different, and possibly more engaging, approach to their rehabilitation. Furthermore, therapists can not only use the application to customize the therapy but also monitor and record patients' signs of progress throughout the execution of exercises instead of only in the assessment phases, as it happens commonly.

The system has been designed to assist post-stroke patients during their rehabilitative therapy towards regaining their autonomy. Users (therapists and patients) have been actively consulted during the whole development. This led to several advantages. HANDY is lightweight (only 190g) on the hand, permitting repetitive rehabilitative exercises without fatigue. The glove material minimizes skin abrasion and its shape prevents misalignments and finger hyperextension. Portability is ensured by the small backpack and wireless dedicated connection. MAIA enables natural language interaction with the system such as asking assistantship and instructions. It also provides a more hearty and non-invasive feedbacks compared to traditional ones. The application offers users customizable passive, active and cognitive exercises based on the patient's condition. During the preliminary tests with post-stroke patients, these aspects led to promising results in terms of usability and willingness to use of the system.

Fig. 1 - Global setup of the hand exoskeleton HANDY

Fig. 2 - Final 3D rigged model of the virtual assistant MAIA

Fig. 3 - Example of cognitive and motor rehabilitative exercise based on activities of daily living with the Leap Motion controller

MODELLING AND TESTING OF TRIM PANELS FOR ROTORCRAFT INTERIOR NOISE PREDICTION

Simone Baro - Supervisor: Prof. Roberto Corradi

Tutor: Prof. Andrea Bernasconi

Interior noise comfort is becoming more and more of crucial importance in the automotive, railway, aircraft and rotorcrat industry. One of the most difficult challenges, due to the vicinity of multiple noise sources contributing through multiple transfer paths, is that of improving the passengers comfort in rotorcrafts. Trim panels are the very last attenuation stage for vibrations and noise before reaching the cabin and are therefore critical components to be carefully designed, together with the vibration isolators connecting them to the fuselage, for reaching the target interior noise comfort level.

In the present dissertation mathematical models for predicting the vibro-acoustic performance of trim panel-isolators system are presented, accounting for both airborne and structure-borne paths.
The trim panel modelling is approached through a Discrete Laminate Model (DLM) accounting for panel asymmetric motion solely and an arbitrary stacking sequence. With reference to the airborne transfer path, models for predicting the Transmission Loss under diffuse acoustic field excitation, integrated with the DLM, are presented and experimentally validated on typical aeronautical sandwich panels (Figure 1). With reference to structure-borne path an extensive characterization of different vibration isolators is performed and their vibration isolation performance when coupled to a beam receiving structure assessed, both numerically and experimentally. Assuming a vibration source on the fuselage side, the space-averaged mean quadratic velocity of trim panels is investigated through a dedicated hybrid deterministic/SEA model of the trim panel coupled to vibration isolators (Figure 2). The model developed accounts for the isolator dynamics, trim panel uncertainties associated to uncertain boundary conditions or manufacturing process imperfections, as well as for the actual panel stacking sequence. Capabilities of the hybrid model in predicting the plate vibrational level for variations of the vibration isolator and trim panel properties is finally assessed.

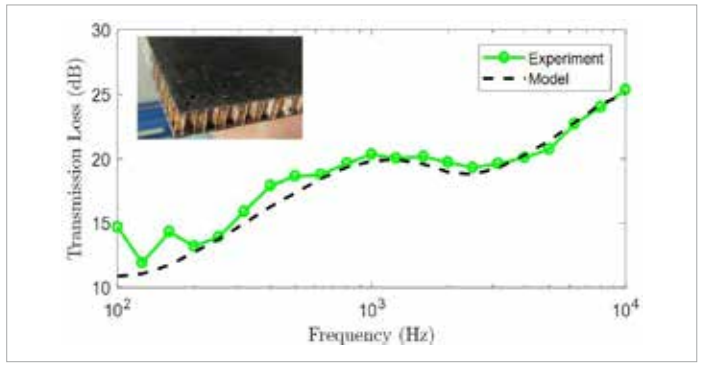

Fig. 1 - Airborne path: Transmission Loss model validation

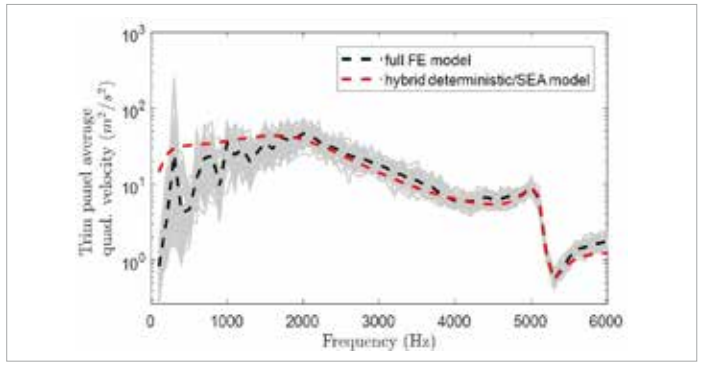

Fig. 2 - Structure-borne path: assessment of the trim panel-isolator system response through the hybrid deterministic/SEA model

AN IMPACT MONITORING SYSTEM FOR AEROSPACE STRUCTURES

Alessio Beligni - Supervisor: Marco Giglio

Co-supervisor: Claudio Sbarufatti

Impact Monitoring is attracting the interest of the international academic community and companies, as an effective system able to deal with the problem of impact events on aerospace structures. The problem is actual and intensifies with composite materials adoption, that is the current companies' trend for building lightweight and performing aerospace structures; in fact, unexpected impacts by foreign object could produce Barely Visible Impact Damages (BVID). The dangerousness of this kind of damage lie in the fact that it could remain hidden in the structure, causing its continuous deterioration with performances reduction and increasing the risk for the common safety.

Moreover, the Impact Monitoring system could be integrated with other on-board/monitoring systems, allowing the Condition Based Maintenance (CBM) implementation and bringing positive effects, in terms of costs and vehicle availability.

The work presented in this research is about an Impact Monitoring system implementation, considered composed of two main parts: (i) a Passive Impact Monitoring part and (ii) an Active Damage Monitoring part. Algorithms for each part of the complete system are developed in the MatLab environment, following a unique flow (Fig. 1).

The Passive Impact Monitoring part has the aim to identify the impact event, meaning detection of the impact occurrence, localization of the impact position and impact force time history reconstruction. These information are recorded by sensors installed on the structure; they completely characterize the impact event and are used to activate the second part of the system, giving an alarm to the pilot, on-board Artificial Intelligence or management system. The proposed solution for the Passive Impact Monitoring part is a combination of signal processing techniques and optimization tools, especially designed for the impact identification problem:

1) Threshold method for impact detection.
2) Genetic Algorithm (GA) for impact localization.
3) Deconvolution technique for impact force reconstruction.

If the force is high enough to produce a damage, the Active Damage Monitoring part of the system is activated, with the aim to identify the impact damage, meaning detection of the damage presence and its localization. These information completely characterize the impact damage present in the structure and complete the Impact Monitoring system operation. Moreover, they can be used to ease the maintenance and fleet management. The proposed solution relies on the generation of ultrasonic Guided Waves (GW), using PZT elements, for inspecting the structure. The GW are acquired by sensors and the damage identification is performed calculating a Damage Index (DI), that gives indications about the health state of the structure.

The designed methodologies were tested on Carbon Fiber Reinforce Polymer (CFRP) panels and Glass Fiber Reinforced Polymer (GFRP) panels representative of the real structure (Fig. 2), considering both damaging and non-damaging Low-Velocity Impacts (LVI) and High-Velocity Impacts (HVI). The algorithms training and validation demonstrated the effectiveness of the monitoring system, investigating multiple aspects and highlighting difficulties that could hamper the complete system operation. Among them, the temperature, the load conditions and multiple impacts could hamper the system performances, because of their influence on the dynamic behavior of the structure.

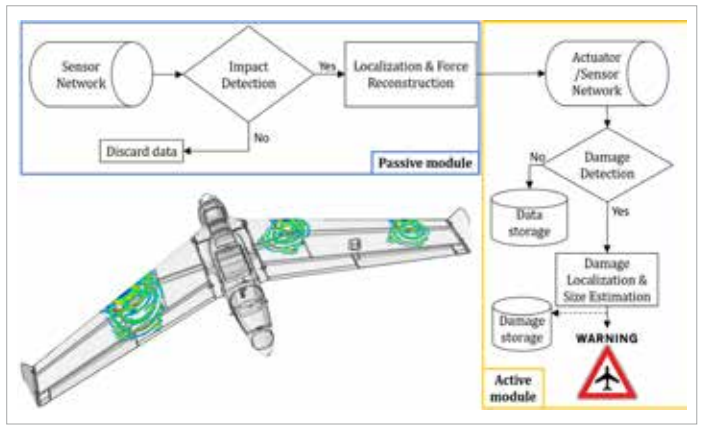

Fig. 1 - Impact Monitoring system flowchart.

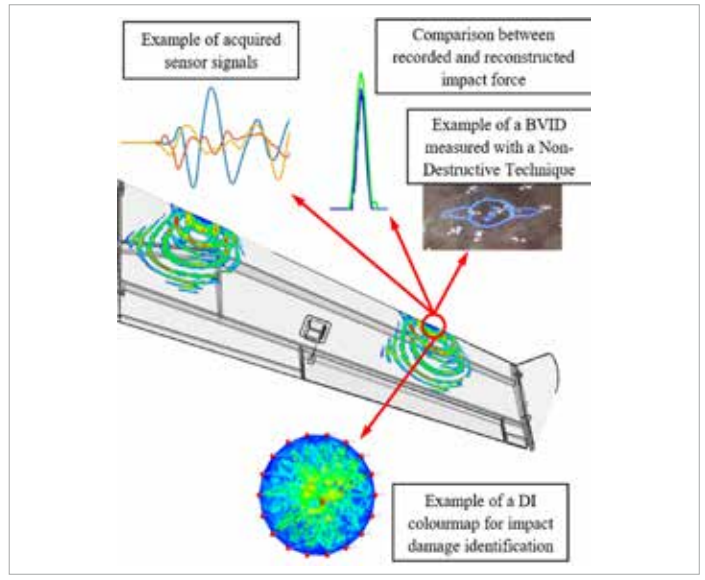

Fig. 2 - Conceptual operation and main outputs of the complete Impact Monitoring system.

INVESTIGATION ON THE FATIGUE-STRENGTH OF SLM PRINTED MICRO-LATTICE MATERIALS BY EXPERIMENTAL TESTS AND μCT-BASED FINITE ELEMENT ANALYSES

Laura Boniotti - Supervisors: Prof. Stefano Foletti, Prof. Stefano Beretta

AM technologies offer nowadays new and unusual possibilities to produce lightweight and promising SLM-printed micro-lattice materials, with a new range of properties. The use of these-lattice materials is still restricted, due to the lack of knowledge about their fatigue strength and fatigue behaviour.

Specimen design

The first aim of this research has been to choose a specimen design that allows to well predict the mechanical properties of the corresponding lattice material. Two different unit cells topologies have been considered and the number of unit cells in the height and in the cross-section of the specimens have been analysed. In addition, a particular specimen design has been developed for the mechanical testing in tension, in which unit cells with graded densities have been interposed between the solid grips and the micro-lattice gage section, to avoid the common failure at the interface between them.

Experimental tests

These specimens have been used to perform several experimental fatigue tests. High cycle fatigue tests have been performed in compression-compression, in tension-tension and in tension-compression. A methodological approach for the analysis of metal foam and cellular solids has been applied to analyse the experimental results, based on the study of the damage in the material: the number of cycles at which the damage initiation in one of few struts occurs and the number of cycles at which the failure of the specimen follows the propagation of the damage can be identified. The fatigue strength in compression has been found out as around three times the fatigue strength in tension. The damage propagation in tension is much faster than in compression and it is possible to see that a damage is permitted in the run-out compression-compression tests, while, no damage is permitted in the run-out condition in tension. To validate this approach, a failure analysis has been performed, by means of SEM and optical microscope images and by means of CT scans.

Failure analysis

This failure analysis allowed also to study the cracks in the micro-lattice and the microstructure of the struts. In particular, it has been highlighted how struts with different printing angle result in different microstructure: coarse microstructure with significant porosity and a worst surface quality characterises the downward face and a finer microstructure can be found in the upward side of struts with small printing angle; a more uniform microstructure characterises struts with higher printing angle. In addition, it has been demonstrated that the fatigue failure occurs due to the surface irregularities that acts as stress raisers: cracks and passing-through cracks seem to start from these irregularities and lead to the failure of the struts, regardless the internal porosity and the microstructure that have only a secondary role in the fatigue crack nucleation (Fig.1a).

Surface irregularities

To analyse the effect of these surface irregularities, the DIC technique has been applied to obtain the strain field in a micro-lattice specimen (Fig.1b). This technique shows how the heterogeneity of the struts results in several strain localisations that have been measured. These experimental results have been used to validate a FE model based on the as-manufactured geometry of the specimen, obtained by means of the CT-scan.

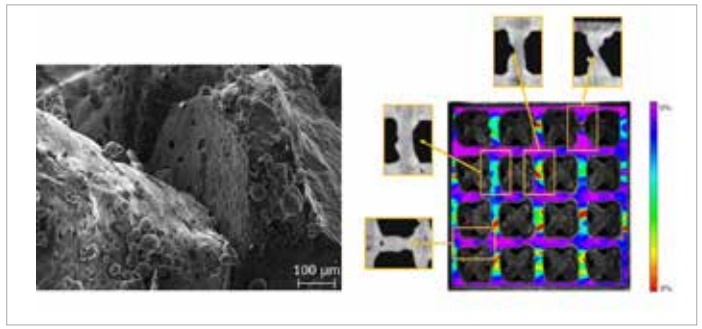

Fig. 1 - a) Failure analysis: fatigue cracks and failures start from surface irregularities, regardless the internal porosity and the microstructure. b) DIC results: measure of strain concentrations in a micro-lattice material under a static load.

FE models have been consequently used to develop a numerical model for the evaluation of the effect of surface irregularities. FE results have been processed to evaluate and compare the quality of as-printed lattice materials obtained with different process parameters or with different parental materials. In order to study the failure mode and the strain concentrations in the micro-lattices, experimental fatigue tests has been performed in the CT scan and the DVC technique has been performed: strain localisations have been highlighted adjacent to the surface irregularities (Fig.2) of the struts and the damage initiation predicted by means of the methodological approach has been validated.

Fatigue strength prediction

A numerical model for the fatigue strength prediction has been developed on FE models based on the as-manufactured geometry and validated by means of the DVC and the experimental results.

The numerical model for the fatigue strength prediction is based on the multiaxial fatigue criterion by Sines, to address the multiaxiality of the stresses in the micro-lattice materials. Starting from the main hypothesis that failures occur due to surface irregularities, an equivalent stress amplitude is calculated in each node of the surface of the FE models (Fig.3), by interpolating the values of the stresses in an area identified by means of the critical distance. The stress amplitude is compared to the fatigue limit of the parent material, predicting the failure of the struts when it exceeds this limit value. The fatigue strength under uniaxial cyclic loads has been studied. The load has been applied in different loading directions and a relation has been found between the fatigue strength in different loading directions and the printing angle of the struts.

The numerical model has been used to predict the fatigue strength of the micro-lattice materials under multiaxial cyclic loads: in-phase and out-of-phase loads has been applied. The multiaxial load conditions are more detrimental than the uniaxial ones and out-of-phase load conditions are the most critical ones.

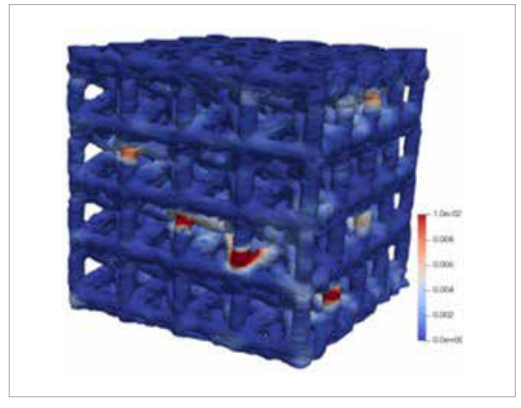

Fig. 2 - DVC results: measure of longitudinal strain in a SC-BCC micro-lattice material during a HCF test.

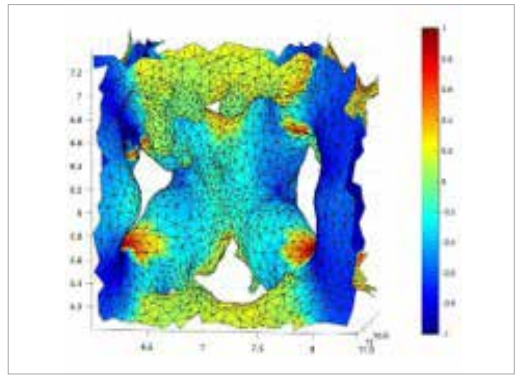

Fig. 3 - Numerical fatigue strength prediction: local values of equivalent stress amplitude in a SC-BCC cell under a uniaxial load in compression.

ADVANCED METHODS FOR CONDITION MONITORING OF RAILWAY INFRASTRUCTURE USING IN-SERVICE VEHICLE ACCELERATION MEASUREMENTS

Anna De Rosa - Supervisors: Prof. Stefano Bruni, Prof. Alan Facchinetti

Rail transportation is one of the safest forms of transport, although reducing the probability of fatalities, injuries and damages is always demanded. The improvement of infrastructures standards in terms of Reliability, Availability, Maintainability and Safety (RAMS) is one of the most important topics for the railway infrastructure managers, together with reducing the costs. Monitoring and maintaining the track geometry is crucial to guarantee the safety and the comfort for the passengers, but it also represents one of the major costs related to the railway system.

The track geometry irregularity has a relevant influence on the dynamic response of the vehicle. The abnormal vibrating response of the vehicle may affect the ride comfort for the passengers and, in the worst case scenario, their safety. Therefore, analyse and optimize the track condition monitoring procedure is an essential topic. Track irregularity is usually monitored by means of dedicated track recording vehicles (TRVs), provided with sophisticated laser optical and inertial measurement systems, which periodically acquire the track geometry deviations from the ideal position. Since, only few diagnostic vehicles are available for each railway operating company, due to the high cost required to be built, to run and to be maintained, although optical measurements are very accurate, they cannot be continuously acquired on the entire railway network. So, the time interval between two consecutive acquisitions may be not optimal to optimally schedule the maintenance interventions. For these reasons, this thesis is focused on developing new methodologies for track condition monitoring using measurements of the vehicle's running dynamics that can be acquired daily onboard the in-service trains with robust and relatively inexpensive transducers, during normal line service. To evaluate the track irregularity status from the vehicle acceleration measurements, analysing their relationship is crucial. This relation is investigated with both model-based and signal-based approaches.
The thesis is mainly focused in the estimation and the monitoring of the irregularity in the lateral direction, which represents the most complex problem. Since the lateral dynamics is strongly influence by the relative motion that may take place between the wheel and the rail, due to the peculiar geometry of the wheel rail contact.

The first part of the thesis is focused on model-based methods to estimate the irregularity in the lateral direction (lateral alignment and cross-level). Model-based condition monitoring techniques rely on the in-depth knowledge of the system. They can provide very good results if the mathematical formulation of the problem is sufficiently accurate. The purpose of the research is to develop some methods aimed to estimate the track irregularity from running dynamics measurements performed on-board a vehicle negotiating the line at service speed. The problem is formulated as inputs estimation and can be dealt with in both the frequency and time domains. The methodologies developed in the literature provide good results concerning the analyses in the vertical direction. On the contrary, the literature is scarce regarding the estimation of the lateral track irregularity, which represents a more complex problem. The lateral dynamics is strongly influence by the relative motion that may take place between the wheel and the rail due to the peculiar geometry of the wheel rail contact. For these reasons, the methodologies presented in this chapter are focused on the lateral plane.
The first method is formulated in the frequency domain (FD) and consists in a pseudo-inversion of the vehicle FRF matrix. The second is defined in the time domain and it is based on a Kalman Filter (KF) observer. The two methodologies are firstly compared by means of virtual measurements produced by a fully non-linear three-dimensional multibody model of the rail vehicle in excess of 100 states. With the numerical experiments, both the methodologies are able to provides very accurate reconstruction of the lateral and the cross-level track irregularities in a range of wavelength from 3 to 180 m. Then, the FD and the KF methods are tested using field measurements to investigate the potential and the robustness of the methodologies when a limited set of measurements is available and when the model parameters are affected by uncertainties. The lateral track irregularity is identified quite well using the FD method, while the KF significantly overestimates it in the medium wavelength range from 25 to 80 m. However, the estimation in the most critical wavelength range D1 (3 – 25 m) shown satisfactory accuracy. Based on the results achieved, it can be concluded that both the FD and the KF methods provides very accurate results in the numerical experiments when all the model parameters are known, and a complete set of measurements are available. Moreover, in the application considering field measurements, good results are obtained in the estimation of the lateral irregularity using the FD method in a wider range of wavelength. The KF method performed well at shorter wavelengths.

The second part of the thesis is dedicated to the signal-based approaches. The linear correlation is evaluated using the Pearson's correlation coefficient and the regression lines. This approach provides very good results in the vertical direction where a high correlation has been observed between the accelerations and the vertical track irregularity. This result allows to transfer the track geometry threshold limits set by the standard on the acceleration measurements. Defining the threshold limits on the accelerations, the monitoring of the track condition can be performed continuously, allowing the detection of the defects in their early stage and therefore to optimally schedule the maintenance.
In the lateral plane, the vehicle dynamics depends on the position of the wheelsets on the track and consequently on the interaction forces and moments that occur in the wheel-rail contact area. Moreover, the lateral acceleration is influenced not only by lateral irregularity but also by the cross-level. Due to the non-linearities introduced by the wheel-rail contact, the correlation in the lateral plane is much more challenging. For these reasons, the signal-based approach used a machine learning (ML) based fault classifiers to monitor the lateral and the cross-level track irregularities in the wavelength range D1. The configuration chosen is a binary classification: the Class1 is related to small track irregularities, in terms of cross-level and alignment, that corresponds to track conditions not being in need of maintenance intervention; the Class2 includes cases in which one or both the above mentioned irregularities are higher than a set threshold level and requires scheduling of maintenance interventions. The ML model receives as input the SD of the lateral and roll bogie frame accelerations and gives as output the classification of the SD of the lateral and cross-level track irregularities. The ML-based classifiers are developed using MATLAB and three independent classifiers based on Decision Tree, Linear and Gaussian Support Vector Machine and Gaussian are trained on training dataset with 5-fold Stratified Cross Validation method. The performances of the classifiers are evaluated and compared with each other. Analysing straight track sections, the algorithm that provides better performance is the linear SVM with 92.9 % of accuracy and 70.3 % of precision.

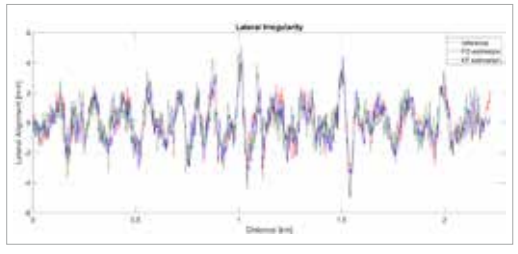

Fig. 1

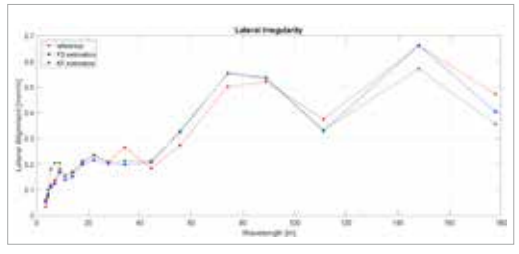

Fig. 2

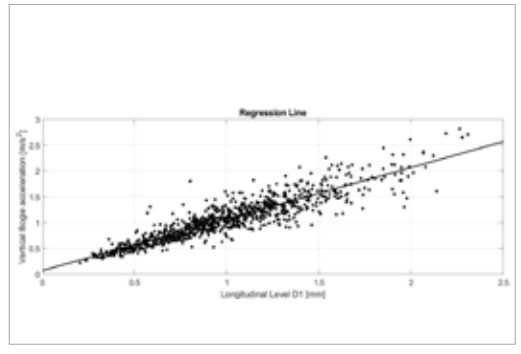

Fig. 3

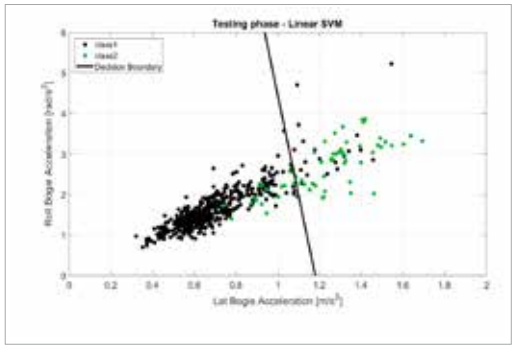

Fig. 4

STRUCTURAL OPTIMIZATION OF MEMS GYROSCOPES AND MECHANICAL COMPENSATION OF QUADRATURE ERROR

Daniele Giannini - Supervisor: Prof. Francesco Braghin

In this research work structural optimization is introduced as an innovative design method for MEMS gyroscopes. The approach is then finalized to the reduction of the gyroscope quadrature error, by exploring passive mechanical solutions as alternatives to typical active compensation ones.
The importance of Micro Electro-Mechanical Systems (MEMS) has grown continuously in the last few years: their small dimensions, low cost and high reliability allow to integrate MEMS into widespread devices.
In particular, **MEMS gyroscopes** are microsensors that employ complex internal microstructures to measure the angular velocity and that are utilized in a wide range of applications. The design procedure of MEMS gyroscope structures is a crucial matter: the typical approach is trial and error, involving manual and iterative adjustments of the geometric features to match the desired requirements. This results in a long and laborious procedure, that is highly dependent on the designer's experience as well as time consuming and costly. A significant progress in the MEMS industry is therefore expected by the introduction of **structural optimization** algorithms: in this work the benefits of both size and topology optimization techniques are investigated.
The purpose of **structural size optimization** is to tune a set of parameters that describe the dimensions of the structural elements, in order to satisfy the design requirements and optimize the desired performance. The approach is here used to develop an automatic design environment for MEMS structures (*feMEMS*), addressing the design of triaxial beating-heart MEMS gyroscopes. The tool allows the parametric generation of the structural geometry, the FE analysis of its dynamic behaviour, and the layout optimization with respect to the design objectives (cf. Figure 1).
A valid aid to the MEMS industry is expected from the developed tool, in terms of design process speed up and performance maximization.
On the other hand, **structural topology optimization** does not require any parametrization of the layout by the designer, but directly searches for the best distribution of material within the available design space, generating non-intuitive structural shapes and fostering innovation (cf. Figure 2). The method is here assessed for the design of 2D single mass in-plane MEMS gyroscopes: the convergence properties of the algorithm are studied when different formulations of the optimization problem are employed and different requirements are specified.
One of the most important performance parameters of MEMS gyroscopes is **quadrature error**, that occurs as an undesired mechanical coupling between the drive and the sense axes, increasing the sensor offset. Quadrature error is mostly due to fabrication imperfections, namely to anisoelasticity effects in the flexural beams originated from non-uniformities in the etching process.
Typical solutions to quadrature error follow two main approaches: improvements in the fabrication process and adoption of active control logics or electronic filters. In this work, **passive mechanical solutions to quadrature** are investigated as an alternative to active compensation: focusing on out of plane quadrature, the aim is to develop innovative mechanical layouts that are intrinsically less sensitive to fabrication imperfections and thus to mechanical quadrature.
Simple modelization strategies for the effects of fabrication imperfections on the gyroscope dynamics are first developed, in order to allow the identification of suitable conceptual solutions to quadrature reduction. The identified solutions are implemented into full gyroscope layouts, that are optimized using the proposed automatic techniques: a progressive quadrature reduction is expected from the developed layouts, reaching also more than 90% (cf. Table 1).
Finally, focus has been given to the effect of local etching perturbations along the structure, that have shown experimental evidence on one of the prototyped layouts (GkPoliMecc).
In order to better investigate the problem, a set of simple test structures has been designed and then industrially manufactured. They will allow to identify the optimal shielding geometries around the elastic elements, that minimize local etching perturbations and maximize the robustness of the proposed quadrature reduction solutions.

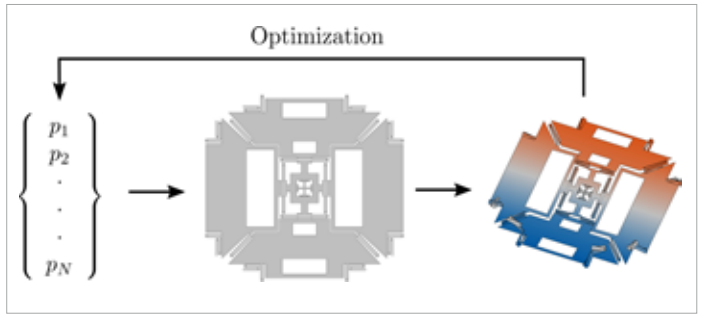

Fig. 1

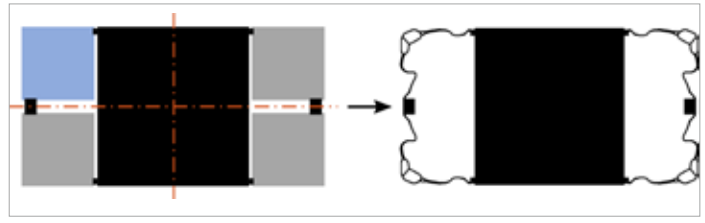

Fig. 2

NUMERICAL QUADRATURE ERROR VS. BASELINE

	Pitch axis	Roll axis
GkPoliMecc	42.30%	41.70%
GkPar	15.20%	23.40%
GkFrog	- (monoaxial)	7.30%

Tab. 1

SURFACE FEATURES AND THEIR EFFECTS PRODUCED BY LASER POWDER BED FUSION (LPBF)

Milad Hamidi Nasab - Supervisor: Prof. Maurizio Vedani

In the recent years, the application of Laser Powder Bed Fusion (LPBF) process has received a special attention due to its ability to produce geometrically complex and lightweight parts. Despite the disrupt benefits of LPBF, the full potential of the technology has a long journey to go. However, the field is rapidly evolving and an exhaustive understanding of the process is of paramount importance. LPBF suffers from a low surface quality which affects the stand-alone philosophy of this manufacturing process due to its need for several post manufacturing processes to improve the mechanical behaviour of such parts compared to their counter parts processed by conventional manufacturing processes.

Moreover, the quality of LPBF surface and near surface regions, the governing physical phenomena and their effects on the mechanical behavior are not yet fully understood. In this regard, the current work starts with a particular attention to surface and sub-surface regions of parts produced by LPBF in term of their morphology, microstructure, chemistry and mechanical behaviour to improve the general understanding of defect genesis. Ballings, spatter particles and partially melted metal powders are distinguished by their morphology, size and microstructure. It is shown that these differences arise from different cooling rates during their generation. Ballings share the same microstructure with the bulk material, both experiencing cooling ruled by conduction with already consolidated substrate. Spatters and partially melted powders show coarser microstructure driven by solidification mainly governed by convection and radiation during their flight in the inert atmosphere of the process chamber.

Spatters are identified as the most critical feature on LPBF surfaces and a study concentrated on the chemical, physical, microstructural and mechanical properties of the spatter particles is carried out. The study shed light on the criticality of these particles and their deteriorating effects on the generation of surface, sub-surface and bulk lack of fusion defects.

Consequently, different surface finishing post manufacturing treatments are employed to improve these surfaces by removal of the typical as-built surface features and sub-surface defects, i.e. sandblasting, vibro-finishing, and machining followed by polishing. Through fatigue results it was demonstrated that the residual surface and sub-surface pores are the principal responsible for the pre-mature fatigue failure of LPBF parts. A significant improvement was achieved by machining followed by polishing due to the adequate material removal from surface regions.

Last but not least, a comprehensive coupled investigation of metrological methods and cross-sectional analysis were performed to evaluate the effects of surface features and volumetric defects typical of additively manufactured materials. Fatigue tests and fractographic analyses were conducted to support the finite element simulations and a proposed fracture mechanics model. The results demonstrate that the standard metrological methods alone cannot provide all of the data needed to model the fatigue behaviour of additively manufactured materials robustly. Moreover, a statistical model describing the competition between volumetric defects and surface irregularities was developed and validated.

MICRO EXTRUSION OF FEEDSTOCK FOR MANUFACTURING STAINLESS STEEL MICRO BI-LUMEN NEEDLES

Sandeep Kuriakose - Supervisor: Prof. Massimiliano Annoni

The miniaturization of the components for advanced properties highly necessitates the production of high length to thickness aspect ratio micro parts in recent decades. Fabrication of high aspect ratio stainless steel micro multi-lumen tubes for biomedical and multi-fluidic application is such a case where current processing methodologies are constrained. The processing methodology used for manufacturing of multi-lumen or multi-channel tubes are constrained in case of stainless steels due to the difference in behaviour of metals and alloys at micro scales due to size effects, and difficulties as well as defects in forming at very high forming temperature required for the steels. The recent research advancements suggest feedstock extrusion as a highly promising method for manufacturing metallic micro multi-lumen tubes of high aspect ratio. The bi-lumen tubes can be extruded using metallic feedstock in green-state and then can be further processed by debinding and sintering operations. Extrusion of feedstock multi-lumen tubes aims to the application of bi-lumen needles and requires developing a process chain by incorporating appropriate manufacturing processes to achieve the final geometrical, surface and structural properties required for the tube's application. Maintaining the geometrical accuracy, dimensional tolerances and surface finish for bi-lumen tubes during extrusion and along the process chain is crucial for the properties of the final tube.

In this Ph.D. research work, a process chain for micro extrusion of feedstock for manufacturing high aspect ratio stainless steel micro tubes was developed. The study of a process chain consisting of feedstock selection, micro extrusion, debinding, sintering, grinding and plasma polishing (see Fig.1) was carried out for manufacturing bi-lumen needles for assisted fertilization by feedstock extrusion.

The studies on effect of feedstock types on extrusion of high aspect ratio tubes showed that feedstock properties are critical in achieving a continuous extrusion of high aspect ratio parts. The extrusion study also showed that feedstocks and their binder contents influence the surface and structural properties of the extruded tubes very much. This study showed that the feedstock ageing could affect the extrusion behaviour by affecting the part surface properties with an increase in the surface roughness while retaining a similar homogeneity, porosity and structure in the cross-sections. Extrusion studies with 17-4PH feedstock gave an average roughness value (Sa = 1.73 µm) which is a good value and much less than the average metal particle size of the feedstock. The tube surfaces after sintering maintained the surface irregularities produced during the extrusion in the green-state with a slight reduction. This suggested that the important step to control the geometrical and surface properties in feedstock extrusion process chain is at green-state extrusion.

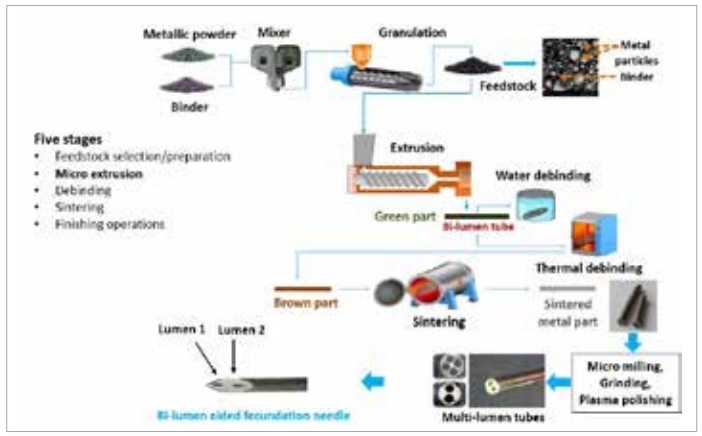

Fig. 1 - Process chain for micro extrusion of bi-lumen tubes for fabricating bi-lumen needles (figure adapted from wikiwand.com)

The feedstock micro extrusion studies carried out by extruding high aspect ratio bi-lumen tubes at green-state by varying the extrusion parameters showed that micro extrusion parameters, extrusion temperature and extrusion velocity and their interaction are very influential for the geometrical features and surface finish of the extruded bi-lumen tubes. This tendency is continued for water debound and pre-sintered states too. The deviations of bi-lumen tube features were observed to be more distinct in the high extrusion temperature levels. Multi-objective optimization on the basis of ratio analysis (MOORA) found out that low extrusion temperature and screw speed produced an average good surface and optimum quality. 'Fingerprint' analysis was carried out to identify the most influential product features in extrusion of feedstock to be monitored in-line. Fingerprint analysis and the analysis at sintered state showed that tube diameter and roundness of the tube are the product fingerprints to be monitored at optimum process conditions for assuring the overall quality of the bi-lumen tubes in-line. The study revealed that monitoring and controlling the bi-lumen tube's identified product fingerprint features and by maintaining right process parameters, whole features and quality of the extruded tubes can be maintained.

The bi-lumen tubes produced in the sintered state by feedstock extrusion processing required additional processing to improve the surface roughness. To be used as bi-lumen needles, the bi-lumen tubes had to be sharpened to the lancet shape in addition to the tube surface polishing. The grinding study was carried out to understand the feasibility of the needle tip on the extruded tubes. Results showed that selecting the proper grinding parametric levels is important and the optimum parameter selection can achieve the least Ra value of 0.01 µm on 17-4PH stainless steel. The plasma electro polishing study showed that process parameters, voltage and polishing time have a significant influence on the generated surface finish of the sintered extruded bi-lumen tubes. Plasma polishing demonstrated the capability to polish the tube surface to Ra = 0.40 µm and those are competing values to commercially used bi-lumen needles in assisted fertilization. Feedstock extrusion processing proved to be a promising methodology for fabrication of bi-lumen needles (see Fig. 2) for assisted fertilization.

Fig. 2 - The feedstock used for extrusion and bi-lumen needles fabricated by feedstock extrusion processing

STOCHASTIC APPROXIMATE ANALYTICAL METHODS INTEGRATING CONTROL MECHANISMS FOR EVALUATING THE PERFORMANCE OF ASYNCHRONOUS MANUFACTURING SYSTEMS

Maria Chiara Magnanini - Supervisor: Prof. Tullio Tolio

Introduction

Asynchronous systems with deterministic processing times are the backbone of production of discrete parts especially in high wage countries. Indeed, when volumes are high, as it happens in most of the products for the final user, automation becomes profitable in comparison with repetitive manual operations. Automated machines bring to almost deterministic processing times and since a perfect balancing among the machines is normally not possible, frequently machines start their operations at different instants in an asynchronous way. Despite their diffusion, these systems are rarely analyzed by means of analytical tools since the most commonly used hypothesis in the available analytical approaches normally entail a significant departure from their real behaviour. Therefore, the improvement in the accuracy of performance evaluation models is directly linked to the capability of modeling a wide range of manufacturing systems, having continuous and discrete production, as well as being asynchronous.

Research objectives

The overall goal of this work is to provide a stochastic approximate analytical method integrating control mechanisms for evaluating the performance of asynchronous manufacturing systems producing discrete parts.

Analytical method means that the model presented here consists in a set of mathematical statements and relations that, relying on some system dynamics, represent a simplification of the real system, and are (approximately) analytically solved in order to get the system evaluation in terms of performance measures. In particular, a state-based model is used, based on continuous-time mixed continuous- and discrete-state Markov Chains.

Control mechanisms mean that the model includes control features, in form of controlled state-based transitions and the introduction of controlled states. Current analytical methods can deal only partially with the integration of control mechanisms, and novel model equations for the evaluation of long lines (*decomposition equations* have accordingly been developed to deal with the full integration of control mechanisms.

Asynchronous manufacturing systems mean that the goal of the proposed method is to be capable of dealing with manufacturing systems producing discrete parts and where production rates differ among machines, as it happens in most of existing manufacturing systems.

This is achieved by using the *control mechanisms* to model the joint relation among resources in the system.

In conclusion, the proposed work should provide a set of methodologies and tools based on hypotheses that are extremely close to the real industrial context and that can be used to solve problems involving the design and operation of manufacturing systems.

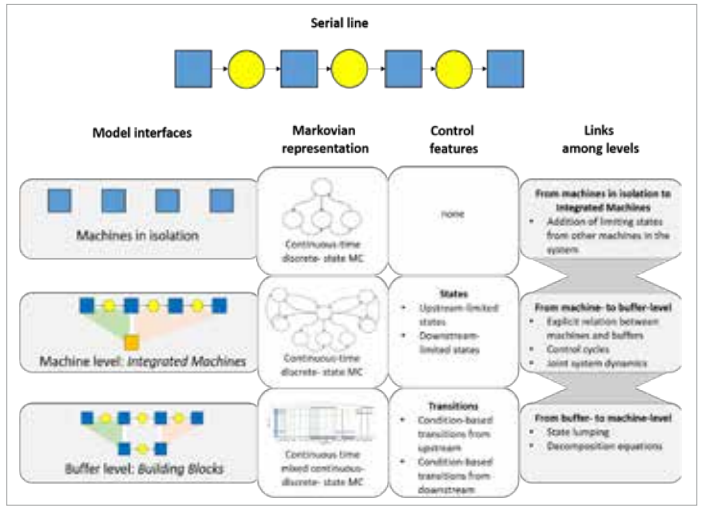

Fig. 1

Methodology

The goal of the approach herein presented is to provide a method to accurately evaluate the steady-state performance of manufacturing systems characterized by explicit controlled dynamics. The main performance measures are represented by system throughput, average inventories and steady-state probabilities of the machines. The overall model structure is depicted in Figure 1.

The model proposed is based on approximate analytical methods, in particular on a two-level decomposition approach. In the two-level decomposition approach, the manufacturing system is decomposed according to two different viewpoints:

- At machine level, the manufacturing line is decomposed in Integrated Machines. Each Integrated Machine represents the original machine as inserted in the system. Indeed, its state-based representation includes limiting states from the upstream and downstream part of the line with respect to the considered machine. Therefore, the Integrated Machine models the dynamics of the overall system centered in the considered machine.
- At buffer level, the manufacturing line is decomposed in Building Blocks. Each Building Block is composed by an upstream pseudo-machine and a downstream pseudo-machine decoupled by a buffer, where the upstream pseudo-machine represents the upstream part of the line with respect to the buffer concerned, and the downstream pseudo-machine represents the downstream part of the line in relation to the buffer concerned. Therefore, the Building Block represents the inflow and outflow of the overall system centered in the buffer concerned, which is regulated by the dynamics of the upstream and downstream pseudo-machines.

Results

Numerical validation shows good results for the model compared to discrete-event simulation. The applicability in an industrial context is demonstrated through the analysis of two real cases. The first case includes the evaluation of an Opportunistic Maintenance policy in a manufacturing line producing components for ready-to-assemble furniture, compared with Preventive and Corrective Maintenance. Results show that the benefits of the opportunistic maintenance (policy 1) are particularly evident in high-throughput manufacturing systems, where significant pressure on maintaining the system operational is found (Figure 2). The second case analyzes different restart policies in a food production system characterized by mixed continuous-discrete production, with the goal of improving production quality. By using the proposed method, the two policies can be compared with respect to the throughput of good parts and the percentage of scrap. In particular, it is possible to use the proposed methodology as a decision support tool for the production line control. Indeed, according to the context, different goals might be set: one possible goal when demand is very high could be to maximize the throughput of good parts, another goal when demand is stable could be to minimize scrap for a specified throughput rate.

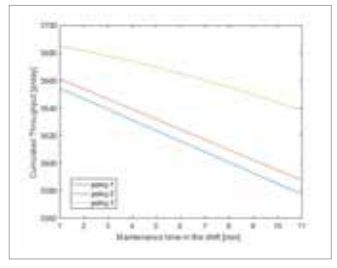

Fig. 2

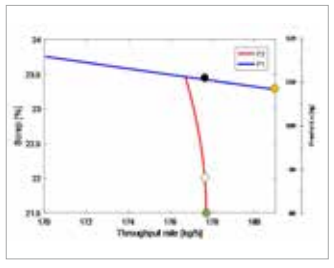

Fig. 3

Conclusion

This work opens the path for more integrated analytical models for performance evaluation. In fact, the proposed model can be used as a performance evaluation function in wide optimization frameworks. Moreover, the easy implementation of control policies allows the evaluation of different use-cases on the same model, that provide an accurate representation of the reference system. The proposed method has been developed with the goal to be furthermore enlarged in terms of system topology, machines and products characterization, control policies analysis.

DEVELOPMENT OF TOOLS AND SYSTEMS FOR THE PROTECTION OF WORKERS FROM FOOT-TRANSMITTED WHOLE-BODY VIBRATION

Pietro Marzaroli – Supervisor: Prof. Marco Tarabini

Several workers are exposed to mechanical vibration and the harmful effect of the exposure is well documented in literature. The induced vibrations to the extremities of the limbs may cause neurovascular problems, namely, Raynaud syndrome, even resulting in disabilities. These problems have been linked to higher frequencies than the ones affecting the human body as a whole. Therefore, the first part of this dissertation describes the mechanical design and development of the actuators system able to generate the triaxial vibration needed to characterize the response of the standing human subject from 1 to 80 Hz. The machine is based on the architecture of the linear delta robot with vertical actuators. The dimensions of the machine were selected to optimize the kinematic performances. The index selected for the optimization process was the inverse of the conditioning number. Since it is not possible to obtain a direct equation which links the inverse of the conditioning number of a linear delta robot with vertical actuation axes to the independent variables, it was decided to follow a numerical process. The generalization of the selection method lead to the formulation of a generalized mathematic method to directly link the design parameters of a linear delta robot with its kinematic performances. After the size optimization, it was possible to estimate the forces required for the movement of the platform. To do so, a simplified model of the linear delta robot was created in the multibody dynamic simulation software Adams. Such values were used as reference values for the dimensioning of the motor and reduction of the robot. With the constraints deriving from the selection of sizes, motors and ball screws, it was possible to design the components of the linear delta robot. The moving parts were designed to ensure the transmission of motion with a high stiffness and no backlash; however, their mass must be minimized, to not decrease the dynamic performance of the robot. All the parts were then produced and mounted; the result is shown in Figure 1.

After the production of the machine, its performances were estimated both in terms of frequency response function, tested through the modal analysis, and in terms of characterization of the signal provided by the movement of the platform. The modal analysis of the shaker is carried out through the creation of a model of the machine according to the Finite Elements Method (FEM) and its validation through the Experimental Modal Analysis (EMA). Given the results obtained, it is possible to say that the EMA procedure validates the FEM model. The performances of the shaker have been evaluated by imposing pseudo-random and sinusoidal stimuli. The pseudo-random stimulus tests aimed at evaluating whether the shaker could produce the design acceleration simultaneously along the three directions, suitable for evaluating the human response to vibrations. The harmonics tests were aimed at evaluating the quality of the signal generated, in terms of noise affecting the signal, uniformity across the surface of the platform and undesired rotation associated to the translation of the platform. The tests done on the machine using pseudo-random noise confirm that it can generate pseudo-random noise up to 80 Hz across the three mutually perpendicular spatial axes simultaneously. The average root-mean squared error between the modulus of the spectrum of generated signal and the signal measured directly on the platform is 6,9 mm/s^2 across the three axes, and it is 5,5 mm/s^2 when a person is standing on the platform, i.e. lower than 1% of the imposed acceleration, as it is shown in Figure 2.

The results of the tests done using sinusoidal signals highlight harmonic distortion and undesired partial rotation of the moving platform, thus limiting its employment in generating three-directional noise with a desired spectrum.

In addition to the machine required to characterize the response of the foot to vibration, it was also necessary to create the mathematical models to understand phenomena at the base of the different foot pathologies that can be linked to the vibration. For this reason, a 2D lumped parameter model of the foot-ankle system was proposed. Such model is shown in Figure 3.

The numerical values of the viscous and elastic elements of the model were optimized with the objective of reproducing the transmissibility from the ground to five different positions on the foot and the apparent mass of a standing person subjected to vertical whole-body vibrations. The results show that the modelled curves are contained in the uncertainty bands of the experimental data. In fact, the mean quadratic error between average measured curves and modelled curves, (expressed as mean ± standard deviation) is equal to 0.3 ± 0.1 for the modulus and 0.3 ± 0.3 rad for the phase. Moreover, a sensitivity analysis based on the Monte Carlo method was implemented to evaluate the effect of uncertainty on the optimized stiffness and damping parameters of the model on the resulting functions. Each parameter was extracted from a normal distribution with mean equal to the optimized value of the parameter and standard deviation equal to 20% of that same value. The results show that the variability in the modelled curves resulting from such perturbation is lower than the experimental intersubject variability. The model, therefore, can be used to estimate the effect of different corrective measures proposed to attenuate the vibration transmissibility at the extremities of the lower limbs.

Fig. 1 - Picture of the Linear Delta Shaker inside the MetroSpace Lab, at Lecco campus of Politecnico di Milano

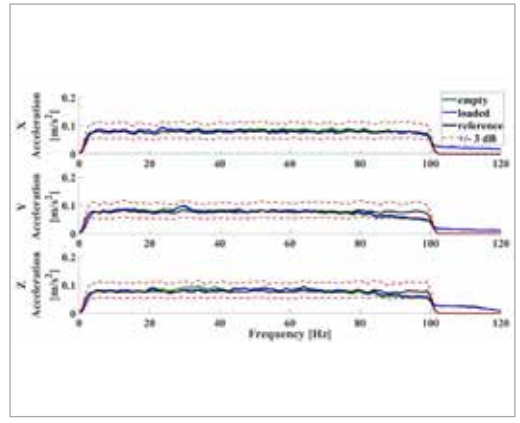

Fig. 2 -Comparison between the imposed acceleration signal and the acceleration of the moving platform, free and loaded with a person standing on it, along the three directions

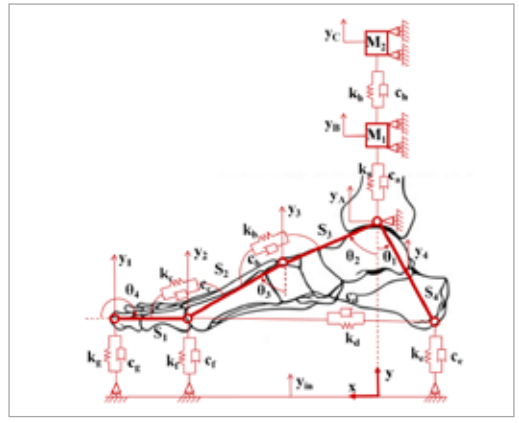

Fig. 3 - lumped parameters model proposed to represent the foot-ankle system and to reproduce the apparent mass of a standing person.

NUMERICAL-EXPERIMENTAL APPROACH FOR THE INVESTIGATION OF THE DYNAMICS OF A SURFACE MINER

Alessandro Medolago – Supervisor: Prof. Stefano Melzi

Mechanical rock excavation, that is the removal of rock material by means of heavycutting or digging equipment, has had a great relevance to the evolution of society because of its application to the mining and construction sectors. In particular, coal extraction and underground mining boosted the development of this technology. Nowadays, mechanical excavation is applied in a variety of industries and faces the challenges of the contemporary world: economic competitiveness and environmental sustainability. To deliver on these expectations, a constant evolution in the excavation process understanding and in the equipment technology is fundamental, and this has pushed the scientific community to develop a new discipline called “rock-cutting mechanics”.The authors made an important effort to improve the comprehension of the mechanics of rock cutting, in particular of the chip creation phase. This is fundamental to guide the development of tools and systems, and to address the major challenges as the improvement of penetration efficiency, and the minimization of the wear. At the same time, several models were developed for the calculation of excavation forces and this was done with numerical, theorical and experimental approaches. However, the prediction of the loads acting on the equipment’s structure and on the tools, due to the dynamics of the cutting processis still an open issue. During the excavation, the machine’s structure is excited by the cutting actions, generated by the picks-rock interaction, and its vibration can, in turn, influence the cutting process. These vibrations, if not properly addressed, can lead to failures which have heavy economical drawbacks and also endanger the safety of the operators.The present work focuses, then, on the development of a model to simulate the machine’s dynamics during the excavation, intended as a tool to support the design of safer and more reliable machines. This goal was pursued with the study of a 1150XHD RH rock milling machine produced by the company Tesmec S.p.A.. Experimental evidence of the machine’s behaviour, in an actual operative situation, was gathered and a model to simulate its dynamics was developed and validated.

PROJECTOR-BASED SPATIAL AUGMENTED REALITY FOR COLLABORATIVE DESIGN ACTIVITIES: APPLICATION AND INTERACTION

Federico Morosi - Supervisor: Prof. Gaetano Cascini

Introduction

Modern technologies have improved the capability of design activities to develop and select optimal solutions by digitally replicating some product features. Their integration inside a design process relies on the knowledge of the users to extract from the simulations the required information. The data used in creative industries are mostly images and 3D models that are abstracted so as to make the result impossible to distinguish from a real product. This approach suffers when the design session deals with inexperienced users for the interpretation of the outputs' physical properties; furthermore, current design supporting software tools are not friendly enough and offer low support to collaboration. As a result, a large number of design iterations and high development costs affect the design process in the initial development stages. The use of early prototypes can partially mitigate these risks by providing, at the expense of higher resource consumption, tangible interactions to multiple users. On the other hand, the immutable nature of the prototypes implies to manufacture a new variant for each modification, and it prevents to have real-time visualization of the results. A more effective and rapid prototyping method is to simultaneously transfer in a single environment the useful properties that are owned by the digital and real worlds. Projection-based Spatial Augmented Reality (P-SAR) provides the technical means for this goal by using the projector's coloured light beam to change the external object appearance. The latter, belonging to the physical world, can be freely manipulated thanks to tracking sensors that adjust the augmented contents according to the placement.

Objectives

Since the applicability of P-SAR is still limited to modify superficial details of objects, this thesis aims at investigating which are the technical features necessary to promote the technology integration in the design process of real operational environments. The research, thanks to the use of a working SAR platform, intends to identify a proper interaction modality with the augmented contents that enable fast and intuitive modifications on the product layout. This task is accomplished by considering the requirements of collaborative sessions where all the participants need to efficiently communicate and visualize the ideas as mixed prototypes. In addition, thanks to test campaign involving professional designers and their clients, the activity points to recognize those design fields where the technology can benefit the most, as well as to measure its impact on the efficiency of a complete design project.

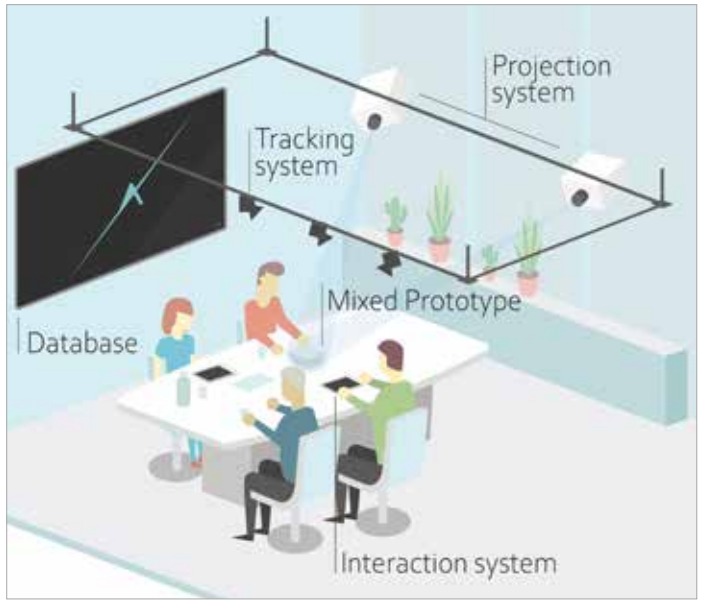

Fig. 1 - Schematic representation of the developed projection-based SAR platform with the definition of its main components.

Results

The major outcome of the research is the development of a customizable and scalable platform based on P-SAR technology. The system is made up of front-end elements, i.e. mixed prototypes and interaction device, that can be manipulated by all the actors of the co-creativity session and back-end technologies, i.e. desktop computer, standard projectors, infra-red camera sensors and web database application, that support the functionality of the system. These components are arranged in three modules (figure 1 i.e. interaction, visualization and tracking) that allow having a white tracked prototype, without shape constraints, digitally augmented with the external finishing thanks to a multi-projection system. Several interfaces and devices have been integrated with the platform in order to explore different interaction modalities (figure 2): (i) a standard desktop setup and (ii) a handheld touch device for precise and personal interactions, (ii) a wide touch display for increasing the shared and interactive environment and (ii) a tabletop tangible user interface for improving the user's engagement and the system immersivity.

Conclusions

Thanks to this research, an interaction paradigm based on touch and tangible interfaces has been successfully integrated with real design activities in the field of packaging, interface designs, ergonomics and product look (figure 3), where mixed prototypes are proven to be effective working tools. Testing activities, in fact, revealed the accuracy and usability achieved by non-expert users in manipulating the projected contents is comparable with more professional software. This simplicity to use the HCI, jointed with the capability of a P-SAR system to render in real-time interactive features of a real-like product, facilitates the idea sharing and the early evaluation of design requirements that are usually considered in the final stages with a huge risk of large impact on the project finances. An early analysis, where a packaging project developed with the use of the SAR in a single collaborative session after the initial brief is compared with a traditional design workflow, demonstrated a considerable reduction of the total lead time (-70%), the number of iterations (-50%), the men hours (-33%), the direct costs incurred by the agency (-20%) and a faster identification of the final selected design solution.

Fig. 2 - Representation of the 4 different types of interfaces (desktop, tablet, touch screen and tangible interface) developed to support the use of the SAR platform according with the design scenario.

Fig. 3 - 4 Different types of design fields (product look, fashion accessories, packaging and ergonomic/interface development) that have been successfully tested with the SAR platform.

LASER CUTTING MONITORING AND CONTROL FOR REAL-TIME DROSS ATTACHMENT REGULATION

Matteo Pacher - Supervisors: Barbara Previtali, Mara Tanelli, Sergio Matteo Savaresi

Introduction

For many applications and particularly for cutting metal sheets and thin tubes, laser cutting has become the reference technology thanks to its flexibility and the gain of productivity if compared with other competitive technologies such as abrasive water jet cutting and electrical discharge machining. The quality of the laser cutting process is traditionally determined considering different quantities, namely, dross attachment, kerf width, surface roughness, heat affected zone and presence of burns on the cut edge. However, these features do not have the same relevance, and it has been found that dross attachment is the most influential output parameter. Accordingly, this study focuses on dross attachment only and proposes a continuous and quantitative measurement variable that is to be estimated via monitored quantities. The amount of dross attachment produced during the process is eventually regulated to a desired level thanks to the development of a closed-loop control system.

Objectives

The main objectives of the thesis according to the scheme of the process include:

- the definition of a quantitative and continuous output parameter, y, related to the dross attachment formation;
- selection of the source of information to be used for the online estimation of the system output;
- investigation of the source of information to be used for estimating the output, and development of the estimator yielding an accurate estimate of the defined process output;
- identification of the system dynamics and design of the closed-loop controller structure.

Results

A custom monitoring architecture was designed to collect the process emission through a coaxial industrial camera. This solution permitted to enhance the time resolution of two order of magnitudes with respect to relevant scientific and industrial literature.

The presented method for dross attachment estimation relies on process emission images. Image information is processed at different levels to produce significant geometrical features of the laser irradiated zone. These features are then mapped via an artificial neural network to produce an online estimation of dross attachment.

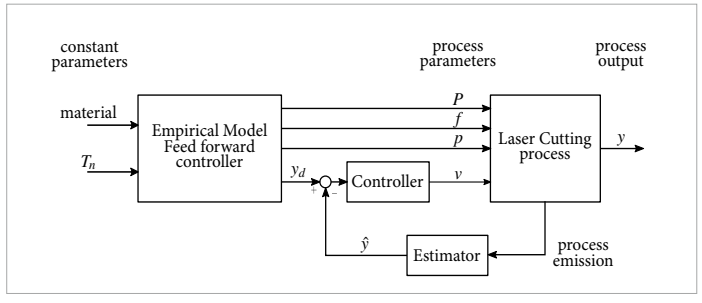

Fig. 1 -.Block diagram of the presented control scheme

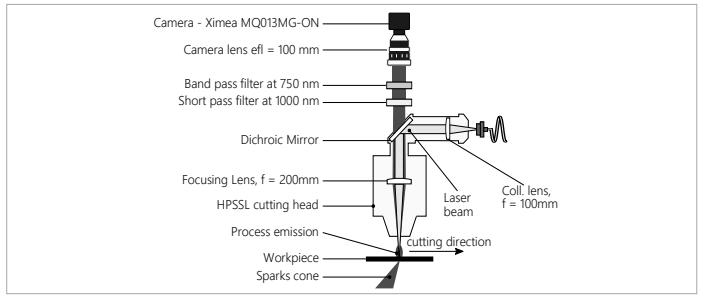

Fig. 2 -.View of the implemented monitoring architecture.

The resulting dynamical system has been identified and a controller is finally built up to either minimize or set dross attachment to a desired level. The performance of the proposed control system has been experimentally validated. As a final remark, the costs of the implemented solution are limited possibly favoring its introduction in the industrial field.

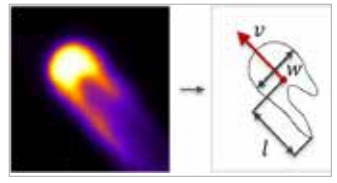

Fig. 3 - Example of a process emission image proposed in pseudo colors and results of the image analysis algorithm.

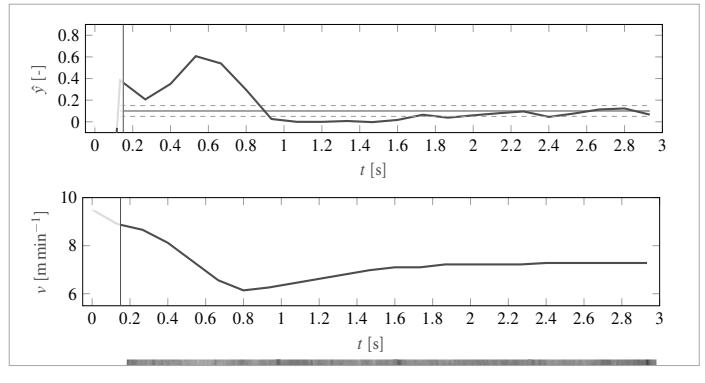

Fig. 3 - Closed-loop experiment where the dross attachment has been regulated to a low setpoint value thanks to the developed estimation and control system.

Conclusions

The presented results definitely open the possibility of designing a new generation of intelligent machines that can adapt the processing conditions to the specific manufacturing needs. An ad hoc trade-off between quality and productivity can be found for the specific production job and quality assurance can be provided. These features well integrate with the concepts of Industry 4.0 and Zero Defect Manufacturing and constitutes a considerable contribution for shaping the Industry of the future.

Acknowledgements

The presented PhD project has been founded by the BLM GROUP and has been realized in strict cooperation with Adige SPA. The authors are particularly grateful to the colleagues of Adige SPA for the professional support received during the study and the precious advices about the laser cutting technology.

MODELLING AND EXPERIMENTAL TESTS OF A VEHICLE DRIVELINE AIMED AT IDENTIFYING KEY PARAMETERS AFFECTING IDLE RATTLE

Gianluca Quattromani - Supervisors: Edoardo Sabbioni, Federico Cheli

From a historical point of view, the automotive industry has always faced vibration and noise problems concerning the powertrain system of cars. NVH (Noise, Vibration, Harshness) concerns are treated with attention, because they have a great impact not only on vehicle comfort but also on the reliability and the pleasantness of the car. Indeed, a vehicle's NVH characteristics are closely related to how it is perceived in terms of quality.
The presented thesis is focused on the realization of a set of dynamic software tools to analyse the dynamic behavior of the powertrain. The powertrain taken in consideration is a large front engine car with a rear transaxle gearbox, that has been made available from OEM.
The aim of this work was to obtain, through simulation, the key parameters that could principally affect NVH behaviour. In particular, great attention was put on the identification and analysis of mechanical component that can greatly affect *idle rattle* and *gear rattle*.
To approach the problem, the author decided to divide the study in five main areas of research:

1) Creation of a multibody DMF (Dual Mass Flywheel) model.
2) Creation of a Powertrain Multibody model and analysis of idle rattle at bell-housing level.
3) Proposing a new bearing layout to mitigate the harshness of bell-housing idle rattle.
4) Creation of 1D torsional simulation model and analysis of idle rattle and gear rattle at gearbox level.
5) Proposing hardware and software solutions to mitigate idle rattle and gear rattle at gearbox level.

DMF is the starting point to realize an accurate dynamic model. This component is the main decoupler for torsional vibration of the vehicle driveline, but it also provides some decoupling of axial vibration coming from the engine.
A Multibody model has been presented and extensively validated concerning the torsional behavior, both for low rpm - low frequency zone but also at high rpm speed with high frequency and high hysteresis.
This model has the innovation of being a complete 3D model that can deal not only with torsional torque but also with all the forces exchanged by the component in a 3D space. It has also been shown that radial forces can be generated inside the DMF during some specific working conditions due to its peculiar geometry.
The DMF model was then included into the complete Powertrain Multibody model. The Powertrain model has been assembled with a multibody approach, including flexible elements modelled with lumped parameter approach.
The author evaluated at first powertrain mode purity, to ensure that torsional resonances were quite separated, in terms of natural frequency, with respect to the powertrain 3D vibration modes.
The model has then been validated as concerns torsional dynamics (comparing experimental torsional vibration on the gearbox with respect to the simulated ones) and for 3D dynamics.
In the presented work, the author did reproduce on simulation the bell-shaft orbitals and radial movements that were experimentally acquired. Since idle rattle on the bell-housing side, has been proved experimentally to correlate with radial impacts of bell-shaft on its supports, a new layout of support bearings was proposed. The new layout has been simulated giving extremely positive results, which have been confirmed experimentally with the measurements of radial vibration of the bell-shaft. Further, a test driver confirmed the proposed solution to be beneficial for idle rattle NVH performance.

The MB model was then used to synthesize a 1D torsional model of the powertrain, which on its turn allowed to simulate both idle maneuver and full load ramps.
The model has been validated with experimental torsional vibration measurements. In particular, it was proved that the model can replicate torsional dynamics during idle as well as the multibody model. Concerning the full load ramps, a positive correlation was found on main engine order for COT (Computed Order Tracking) analysis of torsional vibration at gearbox clutch.
The author developed a metric called IM (impulse metric) to evaluate how critical the impulses are along all the driveline backlashes. The proposed Metric is an innovative index to quantify the harshness of idle rattle. The IM index showed that, on the gearbox side, some critical rattle should be expected for some specific idle maneuvers. The test driver confirmed that during the same maneuvers idle rattle is present on the gearbox side.

On the same powertrain, the test driver complained a gear rattle noise in full and partial load maneuver. With the same 1D simulation model, a full-load ramp has been simulated, showing great torsional amplification at very low rpm speed due to a gearbox resonance. In order to correlate the torsional resonance with gear rattle, a feature has been extracted from experimental accelerometer signal on the gearbox. The extracted feature is called MGR (Metric of Gear Rattle) and it combines the variance and crest factor of the signal. The metric proved the connection between torsional resonance and gear rattle, showing very high values at the same engine speed of torsional resonance.
Also, the MGR metric is a novelty rattle detection index, developed by the author together with the OEM team to quantify severity of gear rattle.

Finally, some hardware and software solutions to the reported NVH issues on gearbox side, has been proposed. To specifically deal with idle rattle issues, a software strategy able to change drag torque on the gearbox clutch has been developed. This strategy changes the mean load on the driveline during idle, changing accordingly the preload on driveline backlashes.
This condition has been simulated showing great results in terms of reduction of the IM metric related on idle rattle. The same maneuvers were tested on vehicle, giving positive results in terms of mitigation of the idle rattle phenomenon.

Concerning gear rattle, the main purpose to mitigate NVH relates issues was to decrease torsional vibration on the gearbox clutch, since the torsional amplification have been proved to be related with gear rattle. In order to do so, a CPVA (Centrifugal Pendulum Vibration Absorber) has been designed and simulated it on the 1D torsional model. The model has shown a great reduction of torsional vibration at medium-high rpm but very low effectiveness at low rpm (where the resonance is present). For this reason, the proposed solution has not been implemented on the vehicle.
To mitigate gear rattle, the author then evaluated a software strategy based on clutch-slip. The proposed software strategy controls the clutch slip on a certain positive value. The analytical model shows that, taking advantage of the torque characteristic of a wet clutch, it is possible to achieve good isolation increasing rpm slip. The strategy has been simulated on the 1D simulation model obtaining a very good reduction of torsional vibration.
The software strategy has been then tested on the vehicle, receiving a positive feedback from the test driver's subjective evaluation. During the maneuver the accelerometer signal on gearbox was acquired and processed to obtain the respective MGR metric. The MGR index confirmed the effectiveness of the proposed strategy from an experimental point of view.

In conclusion this thesis work explored meaningful simulation models (Multibody model and 1D torsional model) that helped the author to interpret idle rattle on bellhousing, idle rattle on gearbox side and gear rattle. With the following models a diagnosis of the different phenomena has been made and consequently some hardware and software solutions have been proposed to mitigate the listed NVH issues. The solutions were tested and confirmed the positive results obtained in simulation.

INNOVATION IN THE PRODUCTION PROCESS OF CUSTOM-MADE SCOLIOSIS BRACES WITH ADDITIVE MANUFACTURING

Davide Felice Redaelli - Supervisor: Emanuele Zappa

The work presents a new manufacturing process for the production of patient-specific scoliosis races by using the 3D printing technology. The scoliosis is the most common spine disorder and the treatment consists on a combination of physical therapy and use of back braces, which are used to support and help realigning the spine. The current manufacturing processes are based on thermoforming a plastic plate, requiring the production of a positive mold to be wrapped, which is then discarded as a waste. Moreover, the production is still very dependent on the technicians manual operations reducing the repeatability of the process. This thesis proposes the use of 3D printing for manufacturing the brace, which could improve the repeatability of its characteristics.
The production process should be changed also for the sculpting phase, which can be performed in a virtual environment by means of CAD tools. In order to reach a stable process, the work was organized in different steps: acquisition of patient's 3D skin, creation of brace and skeleton models, numerical simulations, analysis of additive manufacturing technologies and evaluation of materials.
First of all, to acquire the patient's 3D skin model, different 3D scanners were compared using both standard reference objects (i.e. flat plane and spheres) required by the common guidelines and also manikin parts, representative of the orthopedic application. The investigation included also the test of different motion approaches around the chest of a manikin for the handheld scanners.
As a general result, the fixed scanners performed better in terms of reconstruction
quality, but the model has to be acquired over a long time period. However, the orthopedic application requires to have a fast scan of about 30 seconds, making them impractical. The handheld scanners, on the other hand, can compute a fast reconstruction by moving around the patient in few seconds. Results showed that Artec Leo and Structure Sensor are the most appropriate for the orthopedic centers. The Artec Leo resulted in higher accuracy (about 0.2 mm), which could be required for very detailed parts, while the Structure Sensor can be stably used for the back brace design, with an accuracy of about 0.6 mm.
Next, analyzing the current CAD tools for sculpting the tessellated models, I identified issues in the different software packages, which would require a future integration. The most relevant gap is the absence of a 3D skeleton model that could be used as a visual reference in the 3D virtual environment. The technicians are currently limited to using bi-planar X-ray images to assume how the brace would interact with the patient's body. For this reason, I developed a pseudo-parametric skeleton model that could be morphed according to these two projections to obtain an approximated patient-specific skeleton model, which can be used as a reference when sculpting the brace, in its low poly formulation.
Moreover, a NURBS-surface formulation of the model was imported in the numerical simulation tool to compute the interaction between the brace and the patient's body. A set of simplified simulations was performed to verify the usability of the developed model and the possibility to obtain a relatively fast numerical simulation to validate the sculpted brace before 3D printing it during the design phase. The simulations converged showing the possible interaction analysis, but they required more than an hour due to the non-linearity of the contact problem. Complementary simulations where performed on the simpler case of a wrist orthosis without considering the interaction with the patient's anatomy. The orthosis was constrained as a cantilever beam supported with a roller and loaded with a force in the hand palm. This simulation assessed the feasibility of using the Topology Optimization tool for reducing the weight of an orthotic device, obtaining an optimized material distribution in contrast to purely aesthetic patterns. The mass was reduced of about 25% in 6 minutes, which was more than 10 times the static structural simulation time. This means that applying the Topology Optimization to the more complex case of the chest brace with the contact interaction could be exponentially larger.
Regarding the Additive Manufacturing, the FFF technology was selected for the best compromise in terms of costs, speed and printing volume. Different materials were initially considered, but only PLA and PETG were deeply analyzed and compared to the thermoformed material (PP). The best results were obtained with the PETG, both for the mechanical properties and for the inter-layer adhesion, verified with a SEM analysis. This material was thus used for 3D printing a full brace that was successfully tested with a volunteering patient. The positive feedback regarded not only the patient but also the orthopedic physician and technicians involved in the experiment.
The overall conclusion of the thesis is that the process is currently feasible in all the different steps, even though these have to be performed separately by using different software packages. Thus, a further integration of the various tools is required in order to allow a simpler implementation of the process in the orthopedic centers.

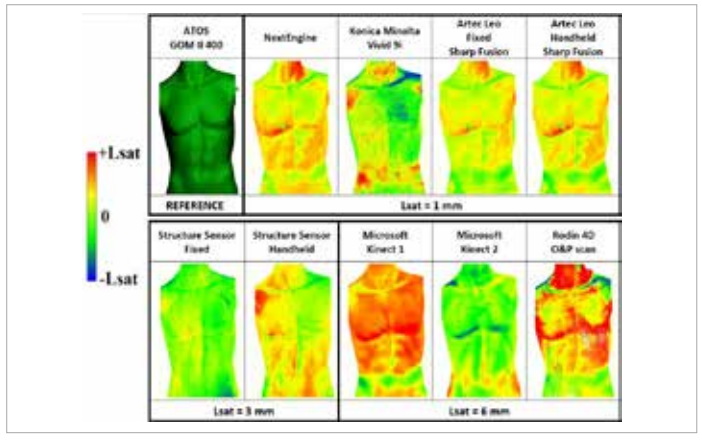

Fig. 1 -.3D scanner comparison on mannequin chest.

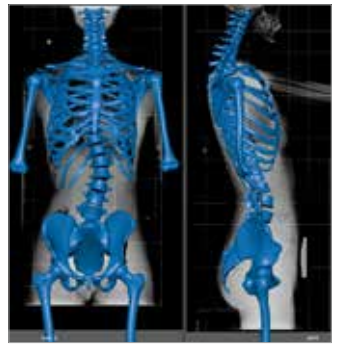

Fig. 2 -. Pseudo-parametric 3D skeleton model, morphed according to bi-planar X-ray images

Fig. 3 -. 3D printed scoliosis brace worn by volunteering patient.

MIXED-INTEGER OPTIMAL CONTROL METHODS FOR THE ENERGY MANAGEMENT OF HYBRID ELECTRIC VEHICLES

Nicolò Robuschi - Supervisor: Prof. Francesco Braghin, Prof. Federico Cheli

Over the past twenty years, automotive manufacturers and research centers have been increasingly investing resources and efforts into the development of alternative propulsive technologies to lower fuel consumption and pollutant emissions in passenger and commercial vehicles. Hybrid electric powertrains represent a concrete answer to address these problems, providing reduction of greenhouse gas emissions and fuel consumption whilst guaranteeing drive pleasure. Notwithstanding this, the growing complexity and degrees of freedom of current hybrid powertrain architectures impose a tailored supervisory energy management strategy to unleash the full potential of the hybrid vehicle, both in terms of fuel economy and driveability.
In this thesis we study models and optimization algorithms to address the problem of computing the minimum-fuel energy management strategy of a hybrid electric vehicle on a given driving cycle. Specifically, we derive a detailed quasi-static model of the hybrid powertrain accounting for the nonlinearities of each subsystem. Afterwards, we propose three new algorithmic frameworks to efficiently solve multi-state optimal control problems with mixed-integer control variables, arising when optimal power split, gearshift and engine on/off signals are sought.
We showcase the effectiveness of the algorithms in terms of solution quality and reasonable run time by analysing real case studies. Numerical results show that the proposed methodologies can assess fuel-optimal control strategies with a low computational burden, paving the way for extensive parameter studies and unbiased comparisons among different hybrid powertrain architectures to be performed rapidly.

ADDITIVE MANUFACTURING FOR SPARE PARTS PRODUCTION

Marco Rossoni - Supervisors: Prof. Giorgio Colombo, Prof. Mario Guagliano

Spare parts are components aim at replacing a broken or worn-out component. Oftentimes, the item being replaced is part of a system whose functionality, performances and appearance should be kept unchanged.
In several industrial context, Original Equipment Manufacturers (OEMs) report decreasing revenues from the direct sales of final product. Such reduction can be ascribed to the contraction of both the sales volume and the single unit selling price.
The growing ratio of the developing countries slowdown and the current global concurrency model are partially the reasons behind this scenario. Looking for other source of revenues, global firms are now betting on the improvement of after-sale services. Spare parts are critical items for both the companies and customers. From the company point of view, their management is often difficult. Depending on the characteristics of their demand pattern, companies try to determine the optimal number of stocked units and the best logistics to ensure a high customer satisfaction while keeping the cost of this service as low as possible. A meaningful example of the parts relevant for this thesis are the spares for vintage/ classic cars, whose replacements are oftentimes unavailable for whatever reason. The enthusiasts in this field are worth to buy expensive and rare components, taking back to functionality their collectibles.
In this scenario, two new actors, operating besides the traditional spare part supply chain, have included. The shape of the new service will be a digital platform exposing sub-services in order to successful printing the spare part, also by non-expert users (Figure 1).
The digitalization step should take into consideration reverse engineering methodology to allow a generic user to obtain the final 3D model of the part he/she needs to print. Two different non-contact technologies have been explored and tested: the laser scanning and the photogrammetric technology. Practical examples are presented in order to understand the potentiality and the criticalities of them, especially when they are introduced in the platform ecosystem.
Despite from a platform perspective the photogrammetric technology would be the most suitable, it does not provide 3D models accurate enough to undergo the next steps of the pipeline. Conversely, the laser scanners provide good results in terms of accuracy, robustness and user-friendliness of the process.
Since the spares were usually not designed for additive manufacturing, each part has to be re-designed to fulfill the process parameter of the AM technology selected in order for the building cycle to end successfully. The adopted methodology to the DFAM is relatively new in engineering and in additive manufacturing, especially for the design domain. The ontology has been chosen as methodology and tool to integrate design for additive manufacturing knowledge and rules in the proposed approach and pipeline.

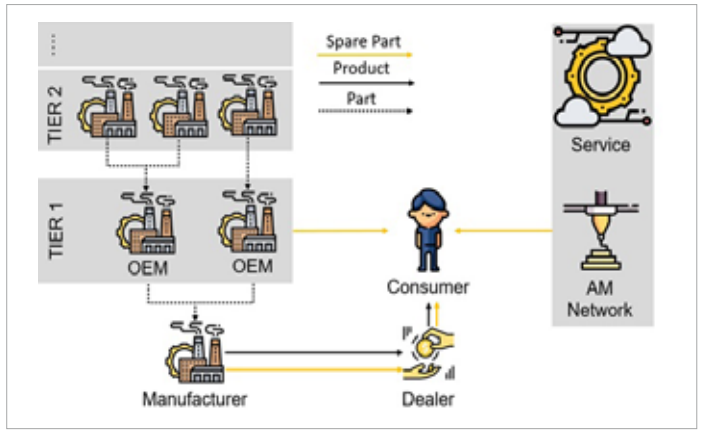

Fig. 1

Since the ontological research has a strong theoretical basis but, oftentimes, it struggles with the operative side, the ontology proposed has been presented through practical example. The formal model has been connected with off-the-shelf software tools used in the additive manufacturing domain to translate the CAD model to the final g-code for the machine. For each step, the role of the ontology is supporting the users in the selection of proper machine and process parameter as well as to check the consistency of the information asserted by the user itself. At the end of this stage, the manufacturer that will print the spare has to be selected from the ones available on the platform: it implements an auction-like system where, the platform send out request for quotations to the manufactures that, in turn, answer with a quotation to be sent to the final consumer. Once the he/she has selected the most suitable quotation, the part is printed and delivered.
In order to test the feasibility of the pipeline and highlight the limitation of the proposed approach, four case studies have been carried out. a car door handle, a fairing for a vintage motorbike, the windows switch of a car (Figure 3) and the bracket of the floating disk brake caliper. The current limitations of the pipeline are the following. For the digitalization phase, the photogrammetric process is strongly limited by the hardware available on the market. Despite the ontology-based DFAM approach is powerful, it requires knowledge to be described in a rigid and formal way and, at present, it is not always possible for AM knowledge. Other limitations regard the liabilities and warrantees that can be issued for the AM produced components: the validation through experimental sessions and simulation of the final mechanical properties of the printed parts should be conducted to ensure that the performance level matches with the original parts.
Expected benefits on spare part management can be seen from different perspectives. From the customer side, (cost) affordable parts will be available regardless of the lifecycle of the original good, extending the life of the product under consideration. From the company side, inventory cost will be (partially) avoided; no more need to forecast unpredictable demand patterns and increased customer satisfaction with lower costs. Furthermore, this study provides useful insights for future work to understand at which point of the product lifecycle the AM should replace the original manufacturing methods. From a technological perspective, the formalization of AM knowledge provides explicit evidence on (i) how the current workflow for printing is fragmented; (ii) how the use of tessellated surface from an early design stage is inconvenient and (iii) how the design for metal additive manufacturing is immature for such an application.

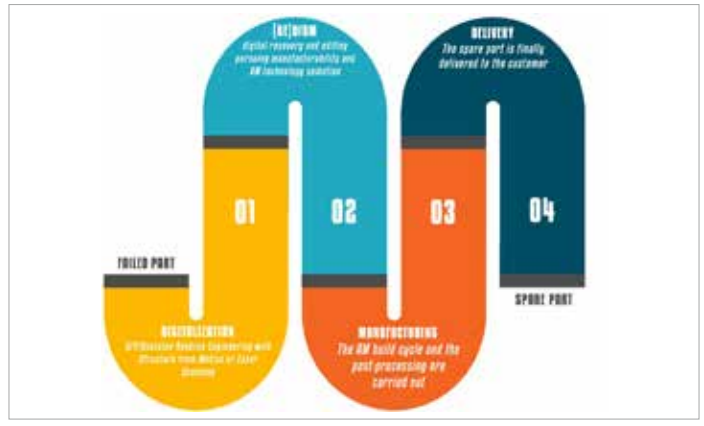

Fig. 2

Fig. 3

DUST MONITORING IN MARTIAN ENVIRONMENT

Arash Valiesfahani - Supervisors: Prof. Bortolino Saggin, Prof. Diego Scaccabarozzi

In this work, the flowrate measurement scheme for a particle analyzer project to do science in Martian atmosphere, was designed and developed. The instrument MicroMED is an optical particle analyzer with measurement target of the particle size distribution and density in terms of particles per unit of atmosphere volume. The latter target requires the instrument to have the aerosol volume flowrate measured. However, this measurement is not feasible in the Martian working conditions by using available sensors. Since the instrument's fluidic system looks like a Venturi-type one, a good correlation between the flowrate and the pressure difference between the atmosphere and the fluid at the contracted section can be expected. Therefore, by characterizing the instrument's fluidic circuit in the working conditions, one can derive the volume flowrate from the measurement of the pressure difference.

In order to approach this objective, at first a flowrate measurement system for low-pressure gases and laboratory use was designed and implemented. This reference measurement system after validation was applied in the experiments for the characterization of the instrument's pump performance and inlet-outlet circuit, in the expected working conditions. On the other hand, in order to measure the provided pressure difference in the instrument's optical system needed to derive the flowrate, suitable pressure transducers were specified, selected and characterized in Martian working conditions.

The simulator of instrument's fluidic circuit, including the inlet-outlet ducts and the optical head simulating volume, was characterized with CO_2 as working gas in Martian pressure conditions. The obtained data led to derivation of instrument's inlet-outlet fluidic resistances that allows deriving the volume flowrate of intake gas from one pressure measurement.

OPTIMAL DESIGN OF ROAD VEHICLES SUBSYSTEMS

Liunan Yang - Supervisor: Prof. Massimiliano Gobbi

The higher demands for vehicle performance and the trends in driveline electrification make the chassis of modern vehicles more complicated than ever before. Automotive manufactures tend to increase the market share by reducing the product life cycle and increasing the number of models offered on the market. Therefore, vehicle development engineers are given a limited amount of time to design complex systems with multiple objectives in several disciplines.

The primary objective of the research work is to seek efficient approaches to optimise vehicles performance, with particular attention paid to road vehicles subsystems. The suspension system and electric vehicle powertrain are optimised by using multi-objective optimisation (MOO) techniques and multi-disciplinary optimisation (MDO) methods.

The suspension system performance is evaluated and optimised by considering simplified vehicle models and employing new suspension components. The main suspension performance indices, discomfort, road holding, and working space are derived analytically for the proposed quarter-car models with additional spring and inerter. The multi-objective optimisation is performed analytically for the suspension models with additional spring. The optimal values of the additional spring stiffness should always be at least twice the tyre vertical stiffness. Invariant points and sub-invariant points are derived by analysing the frequency response function (FRF). The differences in the frequency domain also support the requirement of a detailed model of the suspension. Compared to the conventional quarter-car model, the proposed models have better accuracy and can provide more information while tuning the suspension components. Multi-objective optimisation is carried out to obtain the Pareto-optimal sets numerically for the suspension architectures with inerter. The results confirm that specific architectures provide advantages when all the design variables are varied. The inerter benefits are more evident in all the considered architectures, when the suspension spring stiffness is kept constant.

Decomposition-based MDO methods, analytical target cascading (ATC) and collaborative optimisation (CO) are applied to two chassis optimisation problems. ATC and CO are compared with the conventional single-level all-in-one (AiO) formulation regarding simplicity, transparency, accuracy, and efficiency.

In the passive suspension optimisation problem shown in Figure 1, ATC and CO methods are considered. Instead of directly optimising the spring stiffness and damping coefficient, multiple parameters of the spring and of the damper are selected as design variables. Discomfort and road holding, as well as the total mass of the spring-damper system, are considered as three objective functions. The Pareto-optimal sets obtained by the three methods are compared in Figure 2.

In the electric vehicle powertrain optimisation problem shown in Figure 3, the energy consumption and gradeability are optimised considering the selection of the electric motor and the battery pack. Since the problem includes integer design variables, a branch and bound algorithm (BnB) as well as a genetic algorithm (GA) are considered for each method to solve the optimisation problems. The Pareto-optimal sets from the proposed methods are provided in Figure 4.

It turns out that AiO is the simplest formulation, with moderate accuracy and efficiency. ATC is the best choice for both problems, since it can provide solutions with good accuracy efficiently.

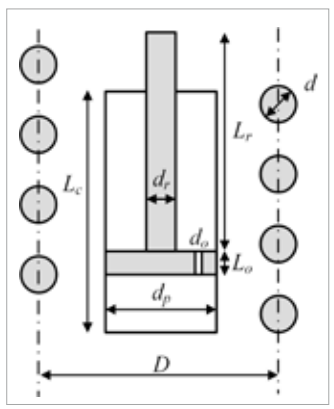

Fig. 1 - Suspension model

However, the cost to understand the formulation and to implement the procedure needs to be evaluated in advance. Similar with ATC, CO also needs to take effort in the learning and programming process. But its accuracy and efficiency are not as good as ATC. It also needs to be noticed that the convergence of ATC has been proved by the other researchers, but the CO might have convergence problem.

Both the suspension problem and electric vehicle powertrain problem are typical multi-objective optimisation problems with many design variables, while they do cover different level of complexity. Therefore, the obtained results can be considered quite general. Except for the choice of MDO methods, the optimisation algorithms and corresponding settings need to be selected properly for each system model and subsystem model based on the properties of the specific optimisation problems. The knowledge could help the designer to apply MDO methods when optimising complex systems during the vehicle chassis development process.

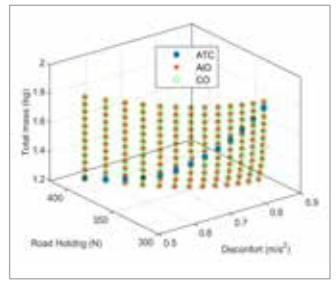

Fig. 2 - Comparison of Pareto-optimal sets of suspension optimisation problem obtained by different MDO methods

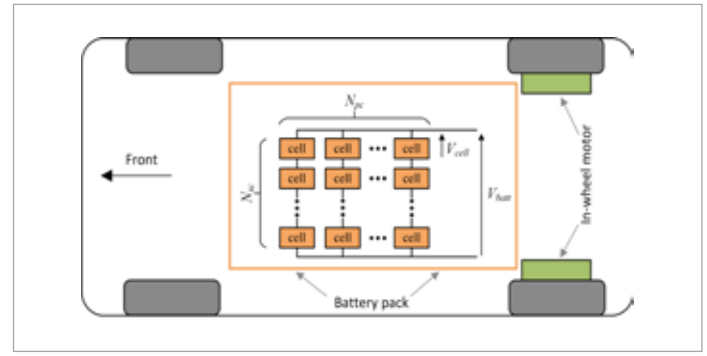

Fig. 3 - Electric vehicle powertrain model

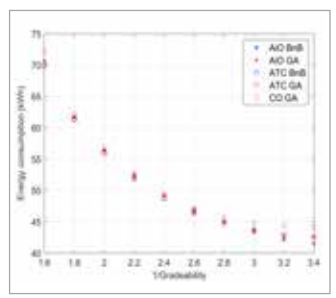

Fig. 4 - Comparison of Pareto-optimal sets of EV powertrain optimisation problem obtained by different MDO methods