# DOCTORAL PROGRAM
# IN MECHANICAL ENGINEERING

Chair:
**Prof. Bianca M. Colosimo**

Within the current global economic scenario, striving to recover from general slowdown and uncertainty, Mechanical Engineering still stands out as one of the leading and driving sectors of industrial manufacturing in Italy. In terms of per-capita manufacturing production, our country ranks 2nd in Europe and 4th on a worldwide scale (Confindustria, Scenari Industriali n.4, June 2013).
In this competitive panorama, and in order to respond to the requests of a challenging sector, the PhD Programme in Mechanical Engineering provides doctoral candidates with a strong scientific training, fostering and refining research and problem-solving abilities with respect to the academic and non-academic milieu. Our Programme, organized within the Department of Mechanical Engineering, relies on the development of an interdisciplinary and integrated high-level educational offer, by focusing on a comprehensive scientific proposal, from conception to realization.

All Doctoral Candidates follow a minimum path of three-years, which includes specific courses and lectures, held by Faculty members and foreign professors and experts, in-depth research, laboratories and active cooperation with international industries, institutions and research groups. With this background, our Doctorates are able to blend the exactness of scientific knowledge with the ability to deal with management and industrial issues. In this view, their scientific profiles are suitable for prestigious positions at national and international level within universities and research institutions, large industrial and consulting companies, SMEs.

**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, Dynamic Vehicle, Gear and Power Transmission, Geometrical Metrology, High-Temperature Behaviour of Materials, La.S.T., Manufacturing System, Material Testing, Mechatronics, MI_crolab Micro Machining, Microstructural Investigations and Failure Analysis, Outdoor Testing, Physico-Chemical Bulk and Surface Analyses, Power Electronics and Electrical Drives, Process Metallurgy, Reverse Engineering, Robotics, SIP (Structural Integrity and Prognostics), SITEC Laser, Test rig for the Evaluation of Contact Strip Performances, VAL (Vibroacoustics Lab), VB (Vision Bricks Lab), Virtual Prototyping, Water Jet, Wind Tunnel.

## INTERNATIONALIZATION

We foster internationalization by strongly recommending and supporting PhD candidates' mobility abroad, for short-term study and research periods up to 18 months. We promote, draft and activate European and extra-European Joint Degrees, Double PhD Programmes and Joint Doctoral Thesis; our Department is actively involved in EU-based and governmental third-level education agreements such as Erasmus Mundus, Cina Scholarship Council and Brazilian Science Without Borders.

60% of PhD Candidates enrolled in 2013 are foreigners; overall female presence (Italian and non-Italian) accounts for 15%.

Our international network includes some of the highest-level and best-known universities all over the world, such as MIT-Massachusetts Institute of Technology (US), University of California at Berkeley (US), Imperial College London (UK), Tsinghua University (CN), University of Illinois at Urbana-Champaign (US), Delft University of Technology (NL), University of Michigan (US), École Polytechnique Fédérale de Lausanne (CH), Technische Universität München (DE), University of Southampton (UK), Technical University of Denmark (DK), Pennsylvania State University (US), Chalmers University of Technology (SE), Technion-Israel Institute of Technology (IL), Virginia Tech (US), Technische Universität Darmstadt (DE), University of Bristol (UK), The University of Sheffield (UK), École Centrale de Paris (FR), Politécnica de Madrid (ES), Université Laval (CA).

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# INVESTIGATION OF GEOMETRY TRANSFERABILITY OF LEMAITRE'S CONTINUUM DAMAGE MECHANICS MODEL

**Nima Allahverdizadeh-** Supervisor: **Prof. Marco Giglio, Prof. Andrea Manes**

Problem of the failure is as old as human made structures. By progression of the technology and complexity of the structures, this problem has become more serious. There are different frame works dealing with failure and aimed to predict it in the structures. Damage mechanics is one of these frameworks. Inside damage mechanics there are also different categories of damage models with different physical background. Continuum damage mechanics (CDM) is one of these categories and Lemaitre's model is the first and most commonly used CDM model. In order to apply a damage model first it is necessary to calibrate the model for the each material. It is supposed that once a model is calibrated for a material it is possible to apply it for all loading conditions. However, it has been shown that in fact damage models predictions' is not always good and in some cases they may fail to have promising results. It is necessary though to have a comprehensive understanding about the advantages and drawbacks of each damage model. Lemaitre's continuum damage mechanics model has been investigated in this research under different loading conditions. Test material is Ti-6Al-4V titanium alloy which is a commonly used material in the different applications



**1.Some of the specimens and experimental test set ups.**

especially aerospace industry. Lemaitre's continuum damage mechanics model and plasticity constitutive law with five parameters, has been calibrated for Ti-6Al-4V titanium alloy using inverse engineering and try and error method. A large experimental test program including 15 different loading cases and specimen geometries has been performed including multiaxial torsion and uni-axial tensile tests on the smooth and notched round and flat specimens. Figure 1 shows some of the specimens and experiment set ups has been performed.
Finite element model of all experiments has been reproduced using Ls-Dyna and Abaqus commercial softwares. Load-displacement data obtained from the finite element models has been compared with the experimental results in the

all cases. Figure 2 demonstrates finite element model of the specimens. Comparison of the failure displacement in numerical models and experiments showed that Lemaitre's continuum damage mechanics model's accuracy changes by changing the geometry and loading conditions and the same accuracy of the calibration which has been done on the uniaxial test of round smooth specimen cannot be achieved for the other experiments. However, Lemaitre's model was still able to predict the failure displacement in most of the cases with quite good accuracy and less than 20% error. By changing the stress state which can be represented by variation of the stress triaxiality and lode angle, accuracy of the predictions of model for the failure displacement changes. In the two region, model's predictions for the failure displacement has errors bigger than 20%. First region is the triaxiality region around 0.15-0.35 and lode angle around 0.3-0.5. Transition from the shear dominant to the tensile failure can be potential reason for the big error of the model in this region. Second region which model's predictions has big errors is related to the experiments with high value of triaxiality and lode angle (bigger than 1). Very different stress state in this region in compare

with calibration condition can be the possible reason for big error of the model. Lemaitre's model was also able to predict the critical points in all experiments properly and in all cases damage initiation location in finite element models matches with the experimental data. Analyzing of the stress state in the experiments by calculating the average stress triaxiality and lode angle demonstrated that different loading conditions which leads to different failure mechanism has been created in the experiments. SEM images of the failure surface of the experiments also shows different failure phenomena in the experiments due to the variation of the triaxiality and lode angle. In the notched flat specimens, a lot of dimples can be seen in the failure surface. Dimples have various sizes and secondary cracks are also visible in the failure surface. Failure is mostly ductile in the flat notched specimens. However, in some cases partially brittle ruptures are detectable in the failure surface. Among the notched flat specimens, specimen which has smaller triaxiality value, has more ductile failure surface and number of the micro cracks in the failure surface are less with smaller sizes. In the multiaxial torsion tests, failure is truly ductile with a lot of dimples in the failure surface. No micro
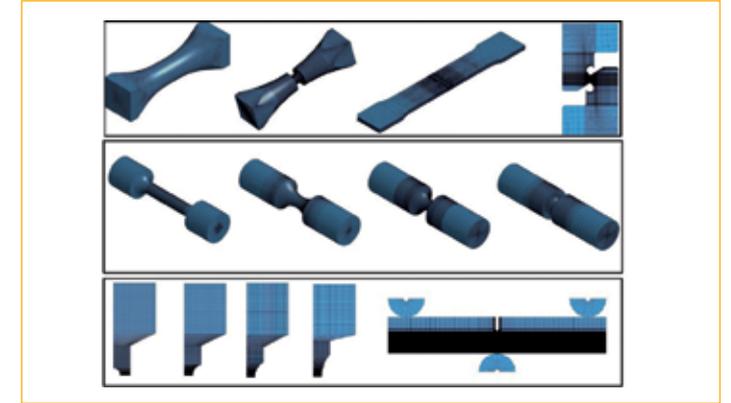


**2. Finite element models of the experiments.**

cracks exists in the surface and dimples are relatively uniform in size with none being large. Size of dimples are smaller in compare with the flat notched specimens. Sliding effects of the surfaces due to the existence of shear is also obvious in the failure surface of the multiaxial torsion tests. In the round notched specimens failure is ductile with typical dimple rupture which indicates tensile stress was dominant. There are a lot of small dimples that surrounded by larger ones. It has been shown by comparison of the numerical and experimental load-displacement data that changing the triaxiality and lode angle clearly affect the plasticity constitutive law which normally supposed to be independent

from the geometry and loading conditions. This effect has to be taken into consideration in the practical applications.
Finally as a further application, the model has been applied in the three point bending test and it has been shown that calibrated model was not able to achieve a reasonable accuracy in the prediction of the failure displacement with original calibration obtained from the smooth specimen. However, new parameters for the model can improve the accuracy of the model. Very high mesh sensitivity of the results also has been observed for the three point bending test.

# DEVELOPMENT OF AN ASSISTIVE REHABILITATIVE ROBOTIC SYSTEM

**Masoud Amiri -** Supervisors: **Prof. Federico Casolo**

The objective of present work is to make an assistive rehabilitation robot by minimizing complexity of the system in order to increase reliability and to decrease final cost and make the robot suitable for home-use and wheelchair based mounting.

The project started with focus on type of actuator, since the robot is used for low speed application, use of an efficient transmission system was necessary to obtain desire speed at joints of robot while to keep high torque at the output. A hydraulic actuator based on hydrostatic transmission was a suitable choice to obtain good power to weight ratio while to minimize size of the actuator. In this system because primary part and secondary part are connected through hydraulic hoses, it is possible to mount primary part on the base of the robot and secondary part on the joint to decrease weight of the actuator and consequently total weight of the robot. While simulation results shows correct work of this type of actuator and transmission, the only problem with this system was to find a miniature hydraulic pump and motors and the other components with desired characteristics which make it very difficult to find on market, noting that designing and building of these components

were time consuming and out of scope of this thesis the final decision was selection of flat dc motors plus commercial harmonic drives in order to have an actuator and transmission system as compact as possible, while production and experimental test of this system has been postponed to future. Being light weight and simplicity plus to have workspace near to workspace of human arm were key factors to design the robot. The final prototype of the robot uses profile of aluminum to reduce weight while it keeps complexity minimum. Low weight of the robot allows mounting it on wheelchair and portability of the system is key point to use it at home. For reduction of actuator weight and also reduce cost of the system two set of spring-cablepulley systems have been used which compensated total weight of the robot and a portion of weight of human arm, also spring configuration is adjustable to be set according to different patients.
Development of the mathematical model of the system has been the preliminary and essential phase for the development of the new robotic device to be connected to the forearm in order to contribute to the movement of the hand. The model was built using Matlab/ simulink and in addition to the

robotic device it also includes a simplified scheme of the human arm. In order to limit the computational load of the first prototype, the glenohumeral joint is constrained to the wheelchair frame because the patient arm is not expected to exceed 90¡ degrees for flexion or adduction angles. The control system of the equipment has been modeled by means of Matlab code but was implemented to the hardware in C code. The model is not only used to analyze the virtual movement of the arm in order to contribute the system design including brushless motors, transmissions and springs – but is also part of the control system. The device is an end-effector type robot, it can be mounted on a wheelchair slightly behind patient's shoulder and is connected to the forearm .The robot can cooperate for the movement of hand within its physiological space except for extreme abduction and extension angles of the shoulder. It has five degrees of freedom, three active and two passive. The passive degrees of freedom prevent to overstress the gleno-humeral joint due to inaccurate positioning of the forearm on the device.
The control system is based on impedance control, use of this control strategy will allow us to understand desire of the patient

to do the required task while the control parameters can be selected according to different patient category, basically this technique allows a variable deviation from a predefined trajectory rather than imposing a rigid movement that can be obtained by normal position controllers.
For the simulation not only the robot but also the human arm has been modeled to make sure that robot is able to apply force or torques as much as subject needs, simulation results prove that by changing the level of disability of the subject the control is in a way that subject must actively participate during desired task and in fact in this way robot training will increase therapeutic outcome with respect to traditional training. All the software required for programming and governing the system motion have been implemented on three identical little electronic boards, these electronic boards have been designed and built specifically for this robot and it is possible to program different control logics on them, these boards occupy smaller spaces and have much lower dimension and weights with respect to similar commercial boards.
The robot has different operating modes. When the arm of the subject is completely passive, the device (in the first

operating mode) must provide the patient of the full help -energy and control -required for a per-settled movement. As the subject's condition improves it is possible to use another operative mode with which the machine help can be modulated to the patient ability, this approach allows to monitor and certify the improvements. When a patient is enough strong the robot can also work against the subject action in order to strengthen the muscles. With another operating mode the subject can be partially or totally released by the gravity forces, so that a weak arm can recover the active ability to move the limb. The last working mode of the system, the more complex and still under development, will provide the patient with the help to perform a generic, not previously known task. This function will probably be the most effective for the ADL. The challenging part of this development is the decoding of the patient will of motion.
The preliminary tests of the prototype of the new device mounted on a power wheelchair are encouraging: it is light, not noisy, and easy to move by the subject. Experimental tests have been done for two different cases, the first one with full gravity compensation as well as the mode which the subject is helped to repeat a stereotype exercise for auto-physiotherapy.

For these initial tasks the system is user-friendly and the control system must be calibrated on patient characteristics. Experimental results verify simulation results on capability of system to apply only required help while it can keep the error minimum.

# AIR-ASSISTED WATER JET CUTTING TECHNOLOGY

**Francesco Arleo -** Supervisor: **Prof. Massimiliano Annoni**

The core of the present work is the water jet orifice which is considered the heart of the technology and for sure one of the most important component whose behavior directly influences the process performances and reliability. First of all, CFD-aided studies on the orifice outflowing regimes and jet stability are carried out aiming at a deeper insight of the complex fluid dynamic phenomena taking place inside the orifice and outlining the main causes of perturbation and process instability.

Briefly, the loss of coherence happens when the source of perturbation reaches the orifice capillary causing a loss of the hydraulic flip condition. Afterwards, a solution is studied in order to reduce and control the previously mentioned instabilities.

This solution consists in a controlled air flux blown inside the orifice tube thanks to a small hole linked to the outside ambient through a modified cutting head retaining nut. At the beginning, the proposed solution is tested again by means of numerical simulations showing promising results: supplying pressure enough, the forced air flux is able to coherently modify the inner velocity field, preventing any disturbances to reach the capillary region thus ensuring
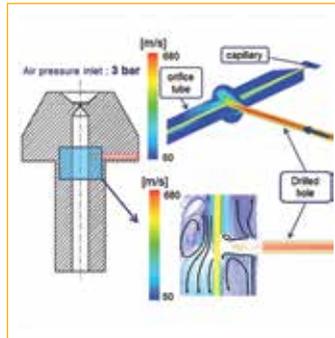


**1.Numerical results of the proposed solution.**



**2. Comparison between radial and tangential configuration in terms of downstream jet spreading diameter.**

the jet stability over any working condition (Figure 1); moreover, by increasing the air intake pressure it is also possible to modify the jet spreading in a controlled way, making it able to adapt the jet structure to any specific application.

This gives the birth to the Air-Assisted Water Jet cutting technology.

The air-assisted orifice concept is then tested practically by designing an Air-Assisted Pure Water jet cutting system prototype whose performances are characterized both fluid dynamically and technologically. The experimental characterization of the system is carried out on two different orifice capillary diameters Ø 0.08 mm and Ø 0.1 mm and two different air intake configurations, namely radial and tangential.

By means of an ad hoc developed visual analysis method it is possible to measure the air intake effects in terms of jet spreading and coherence length.

The two air intake configurations, radial and tangential, turned out to produce sensibly different effects on the jet structure: on one hand, by directly impacting on the jet the radial air intake is more aggressive on the jet structure; on the other hand, the tangential air intake has a peripherally "swirl effect" around the jet making the interaction more gentle thus preserving the jet coherence (Figure 2).

Nevertheless, the control of the jet coherence can have effects on the cutting quality since it varies the jet structure interaction with the target

material.

Whereas an experimental campaign tested the enhanced system performances in terms of cutting capability and kerf quality on a real industrial case study concerning closed-cell foams cutting.

Providing cutting energy enough by using the optimal orifice diameter, the radial air intake supplied by high pressure is statistically proved to be the best configuration to be used in cutting applications of soft materials showing an actual improvement of the cut kerf quality by smoothing the striations.

Furthermore, such a system can also be used passively by connecting a pressure transducer and monitoring the process by acquiring the pressure signal coming from the inside of the orifice while working. Experimental tests showed that the system is able to detect reliably orifice failure rather than the onset of instabilities. Finally, the air-assisted technology is transferred to high precision abrasive water jet machining integrating it in the design of a μ AWJ cutting prototype.

In this case, experimental trials based again on visual analysis demonstrate that a vacuum-assisted orifice with a tangential configuration is the best choice since it still guarantees the jet
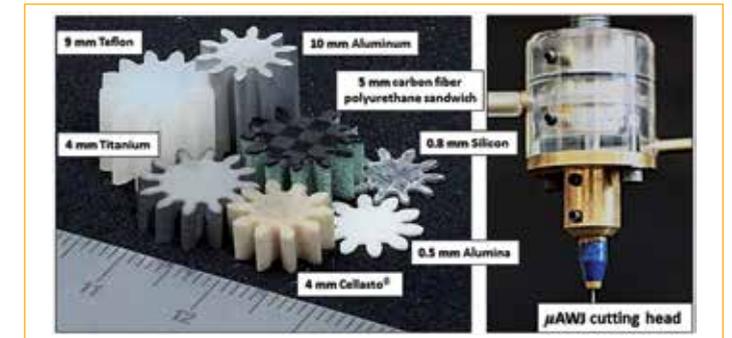


**3. Sample gears of different materials and thicknesses cut by the developed μ AWJ system.**

stability with a further increase of the jet coherence.

This is crucial when dealing with abrasive micro machining where a perfect control on the process parameters and a reduction of the sources of instability is fundamental.

The vacuum assistance makes the process stable and produces a highly coherent jet, thus allowing the downsizing of the cutting head preserving it from abrasive clogging.

Again, the μ AWJ cutting system is characterized technologically and tested as well on some case studies in order to prove the effectiveness of the solutions (Figure 3). In particular, concerning kerf quality, the tests prove how very good performances are achievable making this technology to compete, on equal footing, with other micro-machining

processes.

Water jet could be able to cut considerable thicknesses faster, ensuring high productivity and moreover it is a completely independent material process. The main purpose for the future is to challenge with other non-conventional technologies such as laser and EDM, in all those industrial areas concerning the machining of metal and nonmetal, heat-sensitive and non-conductive materials, composites and considerably thick workpieces.

Concluding, the Air-Assisted Water Jet technology is a viable way to enhance the process capabilities aiming at an holistic improvement of the Water Jet technology as a whole, opening the way to new applications in the field of high precision and micro machining.

# DEVELOPMENT OF A DYNAMOMETRIC WHEELSET FOR THE ESTIMATION OF WHEEL-RAIL INTERACTION FORCES

**Stefano Bionda -** Supervisor: **Prof. Marco Bocciolone**

The understanding of the contact mechanics is a relevant issue in railway engineering. The possibility of measuring the forces that arise at the contact interface has an important implication in several fields of railway engineering such as components wear, riding dynamics, but, more important, are essential to assess the safety of the vehicle against derailment.

In case of homologation, the European standard EN 14363 for the acceptance of running characteristics of railway vehicles, prescribes to assess the running safety, the track loading and the vibrational behaviour. The standard requires to performing in-line tests and, in many cases, it requires the measure of the contact forces. Considering the relevance of contact force measurements in terms of riding safety, one of the main goals is to increase precision and accuracy of the instrumentation. The second issue is related to the fact that the measurements have to be performed in a harsh environment and, in case of homologation campaign, the instrumentation has to last for years thus a high level of reliability must be guaranteed. In the present work, the method developed by Politecnico di Milano is presented, which relies on the usage of dynamometric
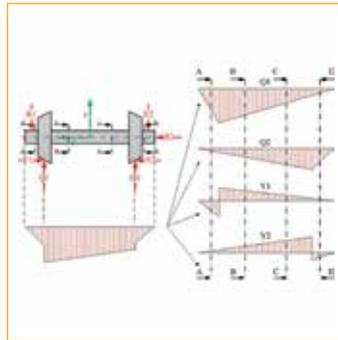


**1.bending moments and position of the measurement sections on the axle**

wheelset for the measure of the forces. This method consists in the combined measure of the bending moments on the axle and the measure of the deformation on the wheel-web in order to reconstruct the vertical and lateral forces. The longitudinal forces, instead, are inferred by the measurement of the torsion along the axle. Figure 1 shows the typical bending moments and the positioning of the bending bridges along the axle.

By means of the critical analysis of the method, the minimal set of measurement needed and the issues related with each typology of measurement section were investigated. The practical realisation of the bending bridges has been considered, focusing on the understanding and the elimination of the ripple effects that signal offsets

or mounting misalignments cause. A similar analysis has been performed for the wheel-web sensors, pointing out their relevance for measurement and the fact that are the most delicate sensors mounted and thus, could introduce reliability problems.

The second point of the present work is the analysis of the calibration process, which is an essential step for the characterization and the definition of the measurement uncertainty of every measurement device. It is easy to understand that the calibration must be performed considering all the factors that may affect the response of the dynamometric wheelset. Nevertheless, it is important to maintain the number of tests not excessively large. These goals have been achieved introducing the D-optimal design of experiment and characterising the test-rig used to calibrate the dynamometric wheelsets. The former allowed the definition of an optimal test plan, whist, by means of the critical analysis of the test-rig, the systematic errors that affects the force measurements have been individuated and corrected, allowing the understanding of the propagation of the measurement uncertainty up to the final measurements of the dynamometric wheelset. Figure



**2. Test-rig layout**



**3. Fuzzy logic algorithm scheme**

2 shows the layout of the test-rig realised and calibrated by the Department Of Mechanical Engineering at Politecnico di Milano.

All the points previously presented were aimed to increase the measurement precision of the dynamometric wheelset. In order to increase the robustness of the instrument, two possible ways can be followed. The first one is to obtain good measurements also in case of reduced measurement sets (i.e. degraded condition of the measurement system); the second is the possibility to introduce sensors that are more robust, allowing the possibility of using mixed nature measures.

The idea for increasing the precision of the reduced measurement sets comes from the consideration that a proper partitioning of the test plan leads to a series of calibration models (described by a calibration matrix) that provide good estimations within their calibration conditions (i.e. the lateral position of the wheelset). The problem then moved from the use of reduced measurement sets to the individuation of a

method for establishing which calibration model is the most suitable during the different conditions encountered during in-line tests. The first method introduced is based on the fuzzy logic. It allows recognising among various models, which one is the most suitable, switching or even combining their outputs, Figure 3 shows the scheme of the algorithm implemented.

The second method presented is based instead on the idea of the reformulation of the forces estimation problem as a Kalman Filter. This allow the introduction of the interactive multiple models algorithm. The outputs of a bank of concurrent Kalman Filters (each one characterised by a specific calibration matrix) are weighted and summed based on the model probabilities computed by a Bayesian estimator. Finally, the possibility to use mixed measurements has been investigated. In particular, the analysis considered the introduction of potentiometers for the measurement of the vertical deflections of the primary suspensions and the relative lateral displacement of the wheelset with respect to the

bogie frame. The main result emerged was the necessity of the introduction of a non-linear formulation to describe the relationship between vertical forces and measured deflection. This modification provided quite good results; nevertheless, the tests showed that in case of rapid movements in vertical direction the hysteresis of the suspensions has to be considered. In effect, the hysteretic effects cause a worsening of the estimation and a rheological model could be introduced to take into account also these frequency dependant effects.

# SURFACE RECONSTRUCTION AND MONITORING VIA GAUSSIAN PROCESSES

**Paolo Costantino Cicorella -** Supervisor: **Quirico Semeraro, Bianca Maria Colosimo**

Over the last years, there has been an increase in global competition, particularly within manufacturing. In this highly competitive scenario, shorter time and reduced costs for reaching the final client have become critical factors for any company involved in product development. The capability of achieving and maintaining a consistently high level of quality, both of the final manufactured good and in the entire design and manufacturing process, is fundamental in achieving such goal.

Modern manufacturing is characterized by low-volume high-variety production and close tolerance high-quality products are required, making quality control and inspection essential methods for measuring and controlling geometric variability.

Geometric tolerances have been gradually introduced alongside traditional dimensional tolerances, with the goal of providing a more comprehensive way for defining allowable variation for a given product geometry. Unfortunately, the time spent for inspection is an important factor that affects the final cost of a product. Hence, advanced measurement technologies, which provide the opportunity to collect thousands of data points in short time, have been developed.

Now, fundamental challenges are related to how to acquire and analyze geometric information more efficiently and effectively in order to cope with the increased requirements. The key ingredient here is an excellent surface reconstruction algorithm, which allows the reconstruction of a continuous surface given the scanned point samples of an unknown surface. This would be useful for many applications in industrial applications. Engineers can inspect the quality of their manufactured parts by scanning them and comparing with the original CAD model to assess if the feature variation is confined within acceptable boundaries (product quality inspection), or in statistical process monitoring, where it is necessary to capture the item-to-item variation to quickly detect any change in the manufacturing process from its in-control state.

The main purpose of this thesis is to model the "signature" (*i.e.,* systematic pattern) left by the process on the manufactured feature via Gaussian Process models (GPs) with a double goal: *i)* to present two methods for automatic reconstruction of accurate and smooth surface model of arbitrary topological type from unorganized sample points and, *ii)* to develop and analyze a novel statistical monitoring method which uses

the GP-predicted deviations of a surface from the in-control pattern.

The first part of the work regards the statistical reconstruction of shapes based on large datasets, which represents the geometry of a part measured by means of a non-contact device. These pose tremendous computational challenges for all statistical methods; for instance, spatial models based on GPs involve inversion of matrices that, for *n* observations, generally requires $O(n^3)$ operations and $O(n^2)$ computational memory, an amount of operations that remains out of reach with classical procedures, even for large clusters of processors. To overcome this issue, a new method called local GP has been proposed in the literature. It decomposes the entire domain into smaller parts and, to predict the value at a specific location, it uses only the points in the subdomain where the test site belongs to.

Our surface reconstruction is a generalization of the subdivision surface scheme introduced before. A principal contribution of our work is to show how it is possible to modify the classic subdivision rules to model adaptively more general shapes. In this framework, we proposed a new technique, based on a rotation of the surface followed by a nonparametric statistical

technique called CART, which provides fairly comprehensible predictors in situations where many variables interact in nonlinear ways. Besides, it allows to automatically find an adaptive mesh able to effectively adapt to local abrupt changes in the surface. Unfortunately, when the algorithm is applied to very complex shapes composed of multiple freeform surfaces, e.g. car bodies, the resulting partition of the space is characterized by many small regions. To overcome oversegmentation issues, we **adopt** another segmentation procedure, **able to produce results in accordance with cognitive science. E**xperimental results show that our proposed approach can be applied to real-world cases (Figure 1a – 1b), and a comparison with other methods shows that this is more accurate.

The last topic of the reconstruction part regards multisensor data fusion methods. They are used to go one step further by seeking original and different ways to analyze and combine multiple measurement datasets taken from the same measurand, in order to produce synergistic effects and ultimately obtain overall better measurement results.

In the second part of the work, a GP-based approach for surface monitoring is presented and
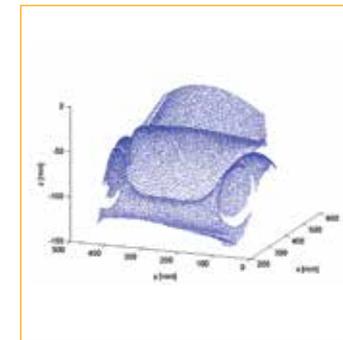


**1. Measured dataset**
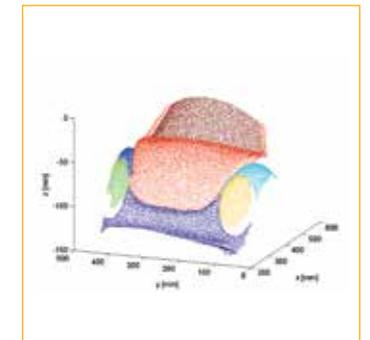


**2. Segmentation result**

analyzed through an extensive simulation study. Statistical surface monitoring is a new area of statistical process control (SPC), which has its origin in profile monitoring, where the quality of a process is best characterized by a functional relationship of a single variable. In this case, classical solutions cannot be adopted since it is well known that a sample with huge size usually degrades the detection performance of a multivariate control chart. For this reason, a novel statistical process control based on GPs is proposed, which collects all the point cloud information in few parameters and uses predictions in specific locations as a measure of deviance from the nominal behavior.

This approach is able to detect unwanted changes of the surface, provided that appropriate number and

sampling strategy of predicted points to be monitored is considered. In particular, it is proved that an optimal number of locations, where the surface has to be predicted exists, in order to maximize the probability to detect shifts of the process.

The innovative nature of the result is linked to the ability to break free from having to monitor the shape in a fixed number of points, which traditionally coincide with the measured ones, giving the possibility to flexibly choose their position and optimal number, to optimize performance of a quality control procedure.

# STRUCTURAL HEALTH MONITORING WITH ACOUSTIC EMISSION AND NEURAL NETWORKS

**Davide Crivelli -** Supervisor: **Mario Guagliano**

This Ph. D. thesis summarizes the work performed at Politecnico di Milano, Department of Mechanical Engineering, about the use of the Acoustic Emission (AE) technique for damage assessment in engineering materials and structures, mainly composites.

AE is a technique based on the observation that materials, when undergoing some type of damage, release energy in the form of short, transient elastic waves in the 100 kHz-1000 kHz band (Figure 1). These waves propagate in the structure through the material's bulk and surface, and eventually dissipate due to various phenomena. They can be recorded by means of appropriate sensors, usually of the piezoelectric type.

AE is generally considered a passive Non-Destructive Technique (NDT): it does not require to emit signals (i.e. to introduce energy in the structure) to detect damage; instead it waits for signals to be recorded by the system. This feature is of great interest: it is not required to continuously scan the structure in search of a potential damage. In other words, the source must be active to be detected; unstressed flaws will not generate AE.

There are several causes for AE. In metallic structures, AE can arise from crack propagation and plastic deformation, as well as from non-detrimental phenomena such as friction and bonding relative movement, together with spurious noise sources from parts that are acoustically connected. In composite structures, some AE causes are associated to the main composite failure modes, such as fibre breakage, matrix cracking, fibre pull-out, delaminations. An in-depth analysis of this activity can lead to source type identification based on waveform characteristics; this is the subject of current extensive research.

The research of efficient systems is pushing towards the adoption of lightweight structures, in order to save fuel, reduce transportation costs, and mitigate manufacturing and assembly issues. The advantages of composite materials, especially Fibre Reinforced Polymers (FRPs), are many: their very favourable stiffness-to-weight ratio allows to build a rigid and strong structure usually lighter than its metallic counterpart. However the damage behaviour of composites is not understood as precisely as in metals, especially regarding impact and high-cycle fatigue behaviour.

Structural Health Monitoring (SHM) systems are intended to fill this gap. These systems are networks of sensors and software processing algorithms conceived to be capable of detecting the presence of damage, localizing it, identifying its type and quantifying it. A SHM system will raise an alarm and give to the user some information regarding the health of the structure, and if maintenance is required.

The AE phenomenon has many attributes that make it desirable as a SHM or damage detection tool, including the capability to continuously monitor large structures using a sparse sensor array with no dependency on defect size. The calculation of source position can be achieved with good accuracy.

AE signals features can give information about the source type. However, the current state of the art includes techniques which require constant user input, tuning and expert evaluation. The thesis presents a novel unsupervised approach to the classification problem, based on Artificial Neural Networks (ANNs) and the k-means algorithm, where the optimal number of classes is chosen considering different quality parameters. The classification algorithm requires no input by the user other than AE data; it identifies the best number of natural signal classes and classifies the data accordingly. The AE technique has then been applied, together with the aforementioned classification algorithm, to a range of different materials, different loading conditions and different geometries. Glass fibre and carbon fibre reinforced polymers were considered, alongside with a test on a full-scale metallic railway axle. The geometries ranged from specimen-size to full panels, loaded in pure tension, compression, bending, fatigue; Acoustic Emission of impact-damaged materials was studied and compared to undamaged samples as well. Also, a full-scale crack propagation test of a railway axle monitored with AE was performed.

Among the tests performed, an experimental work was specifically intended for generating sources of different known damage modes that could be easily isolated from boundary effects (like edge reflections), while being in a known location and thus being easily distinguishable from other sources.

For this reason, a 500x500 mm carbon fiber laminate panel was manufactured (Figure 2). The panel was made of 8 unidirectional carbon fibre and epoxy resin composite layers. For the experiment purpose, in the innermost layers crack was obtained by cutting the fibres with a knife. After some fatigue testing, an artificial impact was performed in order to obtain
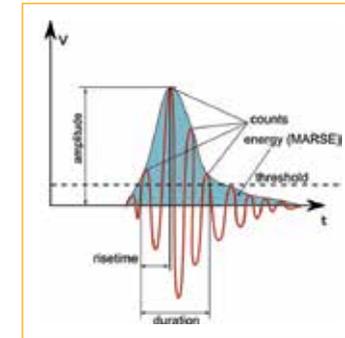


**1. Acoustic Emission signal and its typical parameters**
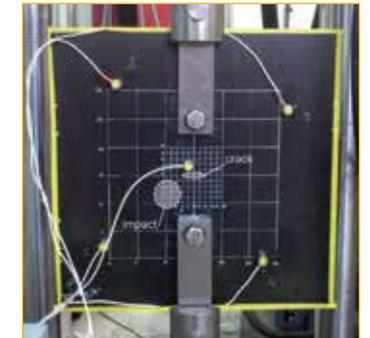


**2. The panel used for the artificial source characterization**
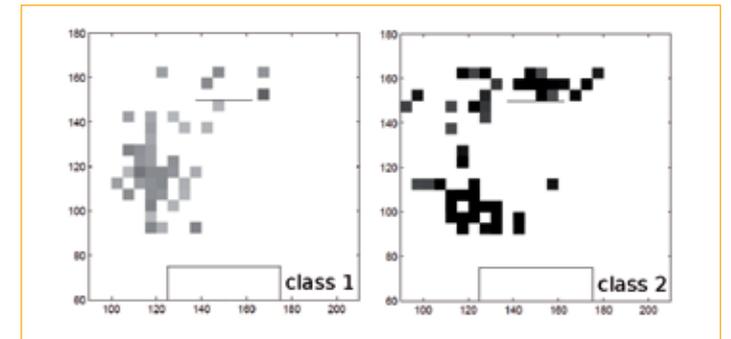


**3. Detail of the Acoustic Emission data, identifying two classes of signals**

delamination damage in another region of the panel. AE testing, together with the classification algorithm, allowed to identify two signal classes, a first one related to delamination and found only in the impacted area, and a second one related to matrix cracking and found in both areas (Figure 3).

The results presented in the thesis showed that the ANN based classification technique can aid in the interpretation of AE data, to the point that it could be used, in conjunction with other methods and algorithms, for the continuous on-line monitoring of structures minimizing the need of external inputs and user experience.

# DEVELOPMENT OF PROCESSING AND MONITORING STRATEGIES FOR LASER SURFACE TEXTURING OF TIN COATINGS

**Ali Gökhan Demir -** Supervisor: **Prof. Barbara Previtali**

Today, the attention on treating surfaces as functional aspect of a component grows, and the ideal of achieving designed or tailored surfaces becomes more relevant. Direct writing with the laser beam is the most flexible among possible manufacturing methods, since the same optical chain can be manipulated to work on different materials and patterns. Laser surface texturing (LST) is an ever growing application field that unites the micro geometries to large areas for functional surfaces. In particular, surface texturing in the form of shallow micro-dimples can improve the tribological behaviour of the component by containing lubricant inside the dimple, entrapping the wear debris, and contributing to the load bearing by generating hydrostatic pressure in the dimple. LST was developed for cold drawing dies with hard solid ceramic TiN coatings. These components undergo high friction forces, which can generate defects on the die itself or the component realized with it. In the present context, LST is destined to be applied to single or small batch components of high value. The applied TiN coating is 3-5 µm thick and laser machining should be limited in this extent. These components, due to their dimensions, are also difficult to measure or control

after process. Bearing in mind the texture dimensions, the control method would be based on high resolution microscopy applied on large surfaces. Such instruments adaptable to form of different dies are not commercially available. This means the process stability is crucial, which emphasizes the need of on machine, in-line measurement capabilities. This fact generates two important points that need to be addressed from research point of view:
1. As LST requires covering large areas with micro features, it is foremost important that the process should be applied with an industrial tool to render it economically viable to industrial production.
2. A method should be developed to monitor dimple depth, which is the most critical aspect of the laser machining process.
Laser micromachining with industrial fibre lasers and laser self-mixing interferometry were chosen as processing and monitoring methods (see Figure 1).
The present thesis work is mainly based on physical models used to explain the different machining regimes with different laser systems. Three different fibre laser sources installed in Politecnico di Milano and University of Cambridge were employed. Three different TiN
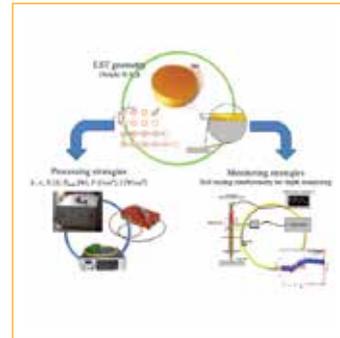


**1. The PhD project scheme depicting the two main parts of the work.**

coated substrates, representing industrial state of the art in die materials were used. The studied pulse duration range was 1-250 ns, with 1 µm and 0.5 µm wavelengths. Therefore, for each laser source a processing strategy was presented to control dimple diameter and depth, an experimental plan using the chosen strategy was proposed, and the efficacy of the processing strategy was evaluated.
Ablation depth measurement was studied in the scenario of percussion drilling of TiN coating on 39NiCrMo3 substrate with the MOPA, short ns, 0.5 µm fibre laser. The chosen scenario represented the best choice in micromachining quality with high productivity. The aim of the study was to prove the concept and demonstrate the limitation regarding future industrial
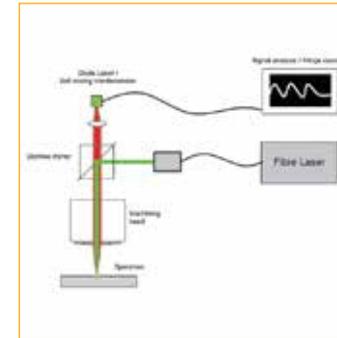


**2. The scheme of laser self-mixing interferometry for ablation depth monitoring**

applications. The measurement scheme used a 785 nm self-mixing interferometer beam launched into the same optical path with the processing beam (see Figure 2). The measurement was based on counting of interference fringes. Each fringe occurs at a displacement of $\lambda/2$, which also determines the resolution of the measurement device. The design requirements of the monitoring system and then the solutions incorporated on the realized opto-mechanical system were described. The system was then characterized for operational capabilities, especially in terms of interaction with the process emission and generated plume. The measurement performance was evaluated in comparison to a conventional depth measurement instrument. The results regarding the laser micromachining performance of ns pulsed fibre lasers have confirmed the feasibility of obtaining high quality dimples on ceramic coatings with accurate control of processing depth. Dimples with diameters between 20-60 µm were achieved without damaging the coating material with the
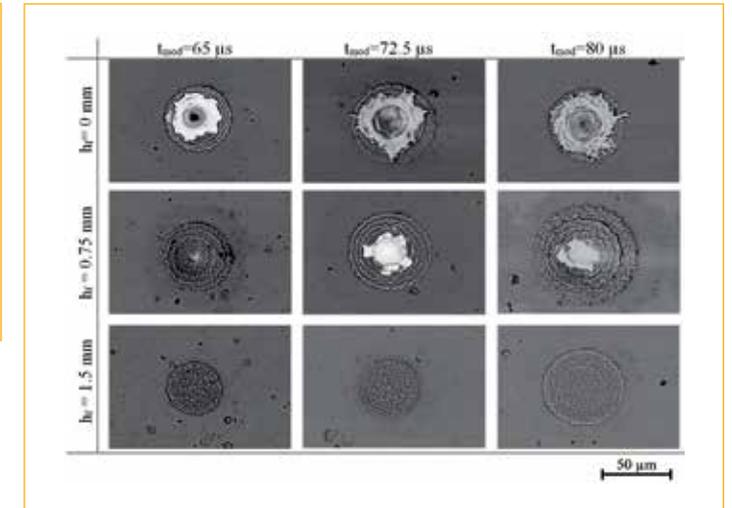


**3. SEM images of the dimples on TiN coating obtained with the Q-switched fibre laser with 250 ns pulses.**

substrate contamination. When machining beyond the coating thickness, high quality dimples without dross generation was achieved with 1-12 ns pulses. It has been confirmed that the developed processing strategy depends highly on the automation possibilities and the used beam manipulation system. The highly energetic Q-switched system that generated 250 ns pulses was used in a non-conventional manner to obtain pseudo single pulses. Although this approach enabled the feasibility of accurate depth control with the laser, the productivity was reduced compared to less energetic pulse duration variable and long ns MOPA systems. It has been observed that pulse durations around 1-12 ns seem to avoid melt generation, whereas longer pulses improve throughput. Pulse tunability therefore appears as an important feature for the next generation laser sources.

The self-mixing interferometry system with 0.4 µm depth and 29 ns time resolution was designed and implemented for ablation depth monitoring. The use of the system for measuring the displacement of the ablation front was validated in fast ablation conditions with limited machining depth. The critical point in the measurement remains with the fact that the used coherence detection method is prone to disturbances caused by the turbid media around the ablation zone. The problem was resolved by the use of a side gas jet, which is expected to divert the ablation plume and allow the measurement beam to pass into the drilled microhole. The self-mixing measurement was found to be statistically same to the ones carried out with the conventional measurement system.

# INTEGRATED QUALITY AND PRODUCTION LOGISTIC PERFORMANCE MODELING FOR SELECTIVE AND ADAPTIVE ASSEMBLY SYSTEMS

## Dariush Ebrahimi Azarbayejan - Supervisor: **Prof. Marcello Colledani**

Managing quality in the current turbulent manufacturing environment becomes crucial as the customer's requirements increase while companies are under cost pressure. Quality becomes even more critical when manufacturing systems join components. Typically, reducing the components' production variability is considered as an approach to improve the quality of assembled products, although increasing manufacturing time and cost. This approach can be infeasible, since the possibility of processing the components with lower variation is limited due to inherent process capability constraints.

Selective and Adaptive Assembly Systems are considered as a functional built method to improve the quality of the assembled product. The selective part of Selective and Adaptive Assembly Systems is characterized by the assembly of components based on matching predetermined classification groups. The adaptive part of Selective and Adaptive Assembly Systems is characterized by the control of process parameters in the upstream component manufacturing processes to produce components for a specific quality class. Parts are treated as individuals rather than statistically identical members of an ensemble. This is usually

expensive but it is used when the alternative, namely making the parts accurately enough for interchangeability, is even more expensive.

Selective and Adaptive Assembly Systems is applied in traditional industries such as mechanical component assembly.. In fact, due to the increasing pressure on high precision manufacturing and to the development of advanced and fast measurement technologies supporting on-line applications, selective assembly systems have attracted increasing interest in the last five years. Recently, selective assembly is applied in fast growing sectors such as micro-production, in renewable energy equipment production, and in the automotive body assembly. Several studies investigate the performance evaluation of Selective and Adaptive Assembly Systems from quality point of view. They typically consider the problem only from a quality perspective and neglect important production logistics features of the system, such as finite capacity buffers and unreliable machines. However, the complexity of logistics system in Selective and Adaptive Assembly Systems deteriorates the system productivity. The most important innovation of this thesis is the development of **an Integrated Quality and Production Logistics Model**

**for the Design of Selective and Adaptive Assembly Systems**. It is often necessary to evaluate many alternative system configurations in a short time which is only possible to perform with analytical methods. Therefore, a completely new analytical method is developed to estimate the system performance of Selective and Adaptive Assembly Systems. In addition we have developed several **efficient deadlock avoidance policies** because the policies which are proposed in the literature results in high level of scrap as well as system logistic complexity. Although in the literature the process adaptation design is addressed profoundly, but **optimally designing the process adaptability** in Selective and Adaptive Assembly Systems is not considered. Therefore, additional contribution of this thesis is a method to derive the optimal parameters of process mean shifts to meet desired levels of components matching. An example of selective assembly system is represented in Figure 1. This system can be integrated into a longer process-chain. We specifically focused on the integrated quality and production logistics performance of the selective assembly cell. We considered a selective assembly system where
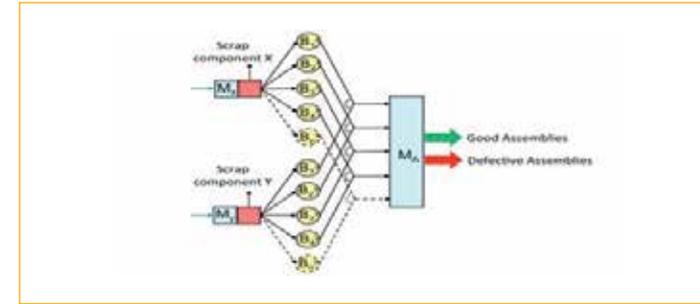


**1. Schematic representation of Selective Assembly Systems.**

two sub-assemblies, namely x and y, are assembled. The sub-assemblies are respectively processed by machines $M_x$ and $M_y$. After the process, each component is inspected and sorted into buffers, according to the measured key quality characteristic value.

Firstly, in order to achieve the performance of the system through above mentioned model, for each sorting machine as well as assembly machine a specific homogenous discrete time-discrete state Markov chain, has been characterized. In fact, for each machine the Markov chain separately includes all the machine states. (This is called Machine Level Decomposition). Then, a buffer level decomposition (BLD) for each buffer downstream of splitting machines is structured, i.e. a building block for each buffer that evaluates performance of that specific flow.

Therefore, an analytical iterative algorithm between machine level decomposition and buffer level decomposition is developed in order to compute Markovian states probabilities in steady state which is used to evaluate an approximate overall system performance. The analytical

performance evaluation model is developed and implemented in C++. The developed tool is tested in terms of accuracy and precision by discrete event simulation models.

The developed analytical method is applied to observe the system behavior of the selective assembly systems when the total buffer space is increased. The results show that although the selective assembly system provides a higher system yield with respect to the non-selective assembly system, but it affects negatively the total throughput of the system. It is shown that the total throughput of the system increased as the total buffer space increases, but due to the logistic complexity of the selective assembly system the total throughput of this system is reduced compared to the non-selective assembly system. It is important to notice that the negative effect of selective assembly system on the total throughput become less evident as the total buffer space increases. The combined result of increased yield and decreased total throughput is the remarkable increase of the effective throughput with respect to the traditional, non-selective, assembly system. In

addition, the positive effect of the selective assembly system on the effective throughput of the system is even more visible as the total buffer size increases. The behavior of the selective assembly system under more quality classes is explored and the results of the simulation show that although the total throughput is reduced, the system yield is increased as the number of quality classes increases. As a result of this competing effect, the effective throughput curve is concave. Thus, being concerned with the concave behavior of the effective throughput curve, it illustrates that there is an optimal point to select for the number of quality classes. Therefore, in order to make a proper decision for design of selective assembly systems in terms of number of quality classes, there is an absolute need to observe the trade-off between the total throughput and the system yield through the resulting effective throughput.

# SURFACE NANOCRYSTALLIZATION BY SEVERE SHOT PEENING: FROM CONCEPT TO APPLICATION

**Seyyed Mostafa Hassani Gangaraj -** Supervisor: **Prof. Mario Guagliano**

If one generates a material with high density of defects such that 50% or more of the atoms/molecules are situated in the cores of defect, then this new class of disordered solid would have number of peculiar and outstanding physical, thermal, mechanical and electrical properties. This was the essence of the visionary argument made in late 80s that eventually led to the advent of nanocrystalline (NC) materials.

Various kind of techniques have been developed to synthesize NC materials such as inert gas condensation, mechanical alloying, electro-deposition, crystallization from amorphous material equal channel angular pressing, high pressure torsion, accumulative roll bonding. Synthesizing ideal 3D NC material, however, comes with 2 major obstacles: It is challenging to produce porosity and contamination free NC material of sufficient size for characterization; Transferring into industrial scale is still an open issue in terms of process cost, sample size and material. Since most material failures including fatigue fracture, fretting fatigue, wear and corrosion are very sensitive to the structure and properties of materials surface, surface nanocrystallization was proposed to be a convenient alternative to bypass the difficulties of synthesizing buck NC component and yet harvesting the advantages of nanostructures in service. The basic idea used to disclose the concept of mechanically induced surface nanocrystallization is that repeated multidirectional plastic deformation caused by high velocity impacting balls generate defects, interfaces, increase dislocation densities and possibly develop new micro-structure like sub-grains and eventually new grain boundaries.

Surface mechanical attrition (sometimes called ultra-sonic shot peening) has been found to successfully generate surface nanocrystallization on different classes of materials. In spite of pieces of evidence, reported in literature, the knowledge cannot be used yet in order to engineer the surface and design for a given structure. The reason is mainly due to lack of a framework enabling to predict and simulate the process of grain refinement during severe peening. Complexities of the process involving many disciplines of mechanical engineering and material science such as contact mechanics, impact, plasticity, dislocation activation and grain refinement hinder the progress towards a comprehensive numerical framework. Moreover, systematic experimental studies on grain refinement during severe peening are still lacking in the field. The importance of such studies is that they could provide in-depth connection between parameters and the resultant structure.

To address the aforementioned call, a systematic study of surface nanocrystallization by severe shot peening was designed in the present work. Air blast shot peening was applied and adopted as it has more flexibility with respect to surface mechanical attrition to be applied on variety of components. It is also simpler and less expensive. Different coverage was adopted to span different classes of peening i.e. conventional and severe shot peening. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) observations were conducted to study the grain size refinement and surface nanocrystallization in all treated specimens, from conventional to severe (Figure 1). A numerical framework was also proposed in the present work to simulate all aspects of peening, i.e. surface roughness evolution, generation of compressive residual stress and simulation of grain refinement. The first two have been simulated using finite element method (Figure 2). Experimental measurements of surface roughness and residuals stress were used to
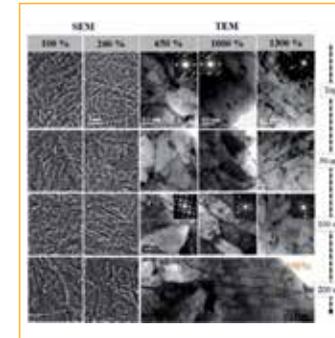


**1. Grain size refinement after severe shot peening.**
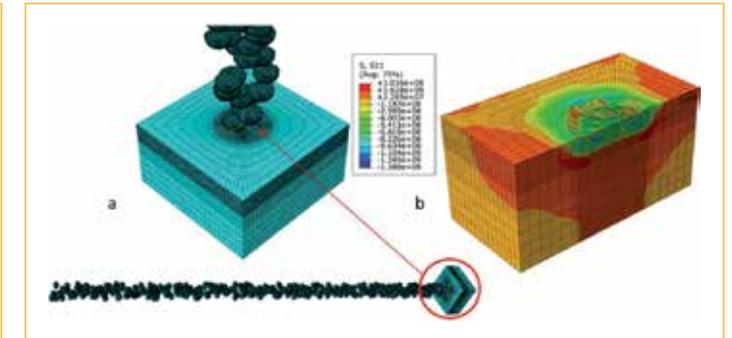


**1. Simulation of severe shot peening. a) Finite element model and b) Residual stress distribution.**

verify the strength of the finite element simulation. To simulate grain refinement, nonetheless, a dislocation density model was linked to finite element model. The model in fact uses the output of finite element to simulate different dislocation activities such as generation, migration, annihilation and eventually grain refinement. The comparison of dislocation cell size obtained by numerical framework and those measured by TEM observation shows a satisfactory and promising agreement. The numerical framework is indeed the first of its kind to simulate grain refinement by severe peening. The second line that is followed by the present research is to affirm and to exploit the benefits of nano-structured surface. It has been well known for a long time that kinetics of diffusion phenomena is highly dependent on time. Gas nitriding, as a well-known thermo-chemical surface treatment to increase surface hardness, is not an exception. A clear beneficial effect of nitriding duration on resultant mechanical characteristics has been reported in the literature. Therefore, prolonging nitriding may seem to be the first alternative to obtain a better functionality. It is accompanied, however, by the high energy cost of processing at high temperature. There is yet another alternative based on the fact that diffusion along nano-sized grains is much more enhanced in comparison with the diffusion through coarse grains. This justifies the idea of combination of severe peening and nitriding. Different combination of peening and nitriding were examined in the present work.

The treated specimens were characterized by SEM, residual stress measurement using X-ray diffraction (XRD), micro-hardness tests and surface roughness measurement. The specimens were subjected to rotating bending fatigue tests performed at room temperature in order to evaluate fatigue limit as an important design factor. SEM observations of the fractured surfaces were applied to illustrate the failure mechanism. Based on the results nitriding duration can be successfully reduced without losing improvements in mechanical characteristics and fatigue behavior if a suitable prior severe shot peening is performed.

# ASSESSMENT OF THE VCCT TECHNIQUE FOR MODELLING FATIGUE CRACK GROWTH IN ADHESIVELY BONDED COMPOSITE MATERIALS

**Azhar Jamil -** Supervisor: **Prof. Andrea Bernasconi**

Recent years have witnessed the emergence of adhesively bonded composites in heavy engineering industrial applications in the quest of continuous performance improvement and cost reduction, particularly due to their high rigidity and high load bearing capability in principal directions. Understanding the mechanical behaviour of such joints under fatigue is of considerable importance for fail-safe design which requires sophisticated numerical capability as most of the other techniques fail to provide any solutions.
The present Ph.D. thesis is dedicated towards the assessment and implementation of virtual crack closure technique *VCCT* in fracture mechanics based simulation of fatigue crack growth *FCG* in these adhesively bonded composites along with implementation in real industrial problems. *VCCT* is a state of art technique, based on the principles of linear elastic fracture mechanics *LEFM*, for the evaluation of strain energy release rates *SERR*. It has been recently implemented in most of the commercial finite element *FE* codes. As such the implementation of *VCCT* was undertaken in the codes of Abaqus® and Ansys® along with the understanding of available fracture criteria pertaining both to mode specific

and mixed mode conditions. Initially the static capabilities were investigated in these *FE* codes which paved the way for simulating the *FCG* particularly in Abaqus®.
Modelling *FCG* is generally based on simple numerical integration between the initial crack length $a_0$ and the final crack length $a_f$, of the Paris law or its modified expressions relating *SERR* with the crack propagation rate. This is implemented in Abaqus® by means of 'Direct Cyclic' analysis, which besides material definitions, requires certain parametric definitions along with the definitions of Paris parameters. Therefore, the Paris parameters of an adhesively bonded carbon fibre reinforced plastic *CFRP* specimen were determined from experimental data initially for Mode *I* double cantilever beam *DCB* specimen. A strong influence of transverse shear stiffness *TSS* was observed in the analytical correlations of the experimental data involving end openings with crack length and *SERR*. As such three point bending tests were conducted which lead to the determination of homogenised values of flexural modulus *E* and shear modulus $G_{xy}$ and the selection of Timoshenko beam on Winkler elastic foundation *TBWEF* as the Mode *I* compliance based data reduction scheme.
The 'Direct Cyclic' analysis was

utilised which depend on time integration points, number of terms in the Fourier series, number of iterations and the specified tolerance parameters. The study revealed that with higher time integration points along with a very small initial time increment preferably gave accurate results which however, increase the computational time drastically. A fixed number of Fourier terms are preferable as it avoids the repetition of the iterations in an increment corresponding to an increase in the number of Fourier terms. The 'Direct Cyclic' analysis was further utilised in modelling different joint geometries under Mode *I*, Mode *II* and mixed mode conditions in both two and three dimensions. The results obtained, as seen in Figure 1, were compared with equivalent cohesive zone method *CZM* results which showed good correspondence with each other as seen in Figure 2 and 3, however 'Direct Cyclic' reported huge computational costs.
Further an industrial component was modelled using the same 'Direct Cyclic' method in Abaqus® and the service life was estimated, however enormous computational times were involved in complicated industrial geometry. This problem of huge computational time was successfully overcome

by the use of an Ansys® based subroutine developed for Mode *I* geometry which significantly reduced the computational time from 501.40 to 20.36 seconds.
A summary of the conclusions of the main results are:
1. Modelling of adhesively bonded thick laminates requires careful examination of the effect of shear deformation, particularly in the case of *DCB* specimens, which behave like thick beams, and therefore appropriate models are required for data reduction of *DCB* tests on thick laminates
2. Three point bending tests with various span length proved to be an efficient method for determining the homogenised values of *E* and $G_{xy}$
3. With the increase of adherent thickness the foundation stiffness is dominated by the adherent and *TBWEF* appears to be a suitable data reduction scheme.
4. In comparison of modelling *VCCT* and *CZM* based *FCG* in different adhesively bonded joint geometries, the *VCCT* models agrees with the *CZM* models to within 4% except in the case of *SLJ,* where *VCCT* at present as implemented in 'Direct Cyclic' procedure in Abaqus®, do not allow the modification of the coefficient *B* and exponent *d* of Paris law according to the mixed-mode ratio *MM*, which is facilitated in *CZM* modelling.
5. Further the *FCG* is strongly dependent on *ΔG*, therefore even a limited difference causes a sensible difference in the elapsed number of cycles for a given crack growth.
6. Direct Cyclic based evaluation can be utilised

in the life estimation of real adhesively bonded industrial components; however it requires huge computational times lasting weeks.
7. Further investigations are required for modelling *FCG* of real joints involving Mode *II* and Mixed mode *MM* loading

conditions.
8. The use of user-defined subroutine in Ansys® for *VCCT* based simulation of *FCG* successfully overcomes the drawbacks of the 'Direct Cyclic' method in Abaqus® and significantly reduces the computational cost.

1. *3D VCCT* model showing distribution of Mode *I SERR* for the *DCB* specimen.
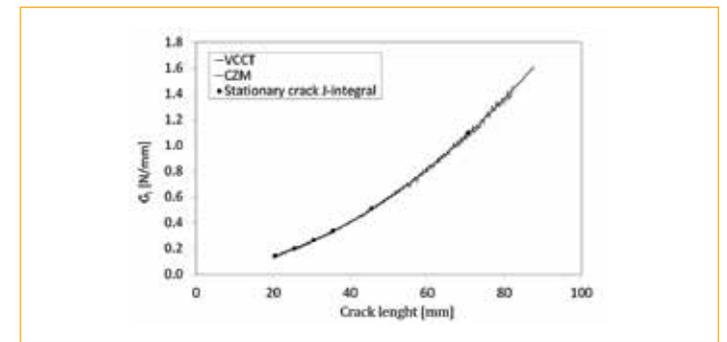


2. Comparison of SERR values obtained by VCCT with CZM and J-Integral methods for the DCB specimen.
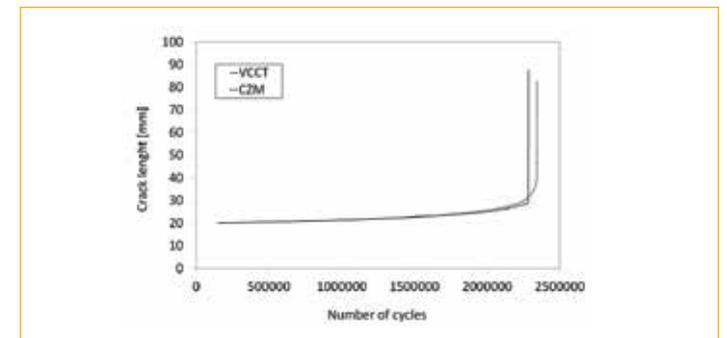


3. Comparison of *a-N* values obtained by *VCCT* and *CZM* for the *DCB* specimen

# STUDY ON INERTIZATION AND SAFE PRODUCTION OF EAF SLAG

**Davide Mombelli -** Supervisor: **Prof. Carlo Mapelli**

In every metallurgical process the production of a great amount of slag is implied. The industrial world struggled long in order to design a practical application for this waste, however this effort is often hindered by different applicative problems. Steel-making is certainly the human activity with the highest environmental impact, considering that, in addition to generating high fraction of solid waste (dust and slag), is associated to a high consumption of various forms of energy, mineral and carbon coke. In particular the safe disposition of steel slag represents one of the major costs that the steel-makers might to face. For these reasons, steel-makers started to design about an advantageous way to re-utilize these wastes in different application fields, not only strictly related to the steel industry.

Fortunately, today, the slag produced during the melting in the electric arc furnace are considered more than a compelling alternative to natural stone materials. Actual, the steel slag could be exploited in several application fields, such as land filling, road constructions and concrete production, since their physical properties are similar or even better to natural materials like gravel. However, these alternative raw

material must ensure absolute eco-compatibility to be used in civil applications. In particular their use limitation is due to the presence of polluting elements, including Cr, Ba, V, Mo, etc, that can be dangerous for human and environment. Such substances result by scrap use that contain painted, lubricated or polymeric compound scrap. Slag chemical composition has an important role in the immobilization or releasing the above mentioned toxic chemical species. Thus, the release extent of such polluting elements appears to behave as a function of the constituent phases, i.e., $CaO$, $SiO_2$, $Al_2O_3$, $MgO$, etc. characterizing the slag. For example, $MgO$ in the slag seems to be favorable for chromium immobilization but detrimental for the leaching of other polluting elements, i.e. barium and vanadium. The solution behavior of these elements have a parabolic law as a faction of $CaO$ and $MgO$ concentration, whereas their dependence on silica concentration is generally described by a linear law. The conditions, under which the leachates are produced, vary as a function of different physical parameters like particle size or liquid-on-volume ratio, influencing the resulting concentrations of metals in the leachates. Therefore, the interaction between slag and

water is a key-point to be understood in order to classify the slag as safe raw material. Besides the role of chemical composition, one of the most important issue to be solved is the unequivocally identification of which mineralogical phases are responsible to release the heavy and dangerous metals. Specifically microstructural phases, featured by high melting temperature, can crystallize during the solidification, avoiding amorphous structures formation and manifesting instability at room temperature. On the other hand, eutectic constituents or low-melting-point phases seem have a better behavior against leaching, since they assure high structure stability and low reactivity with water. Moreover, from a theoretical point of view, favoring the formation of low-melting-point phases should promote the slag vitrification. In this study different classes of EAF slag were investigated in order to correlate their leaching behavior with chemical and crystallographic features. Chemical composition and phase distributions were investigated and correlated with the results of standard leaching test (in according to EN 12457-2) performed both on massive and powdered slags on several EAF slag samples, coming from different steel productions:
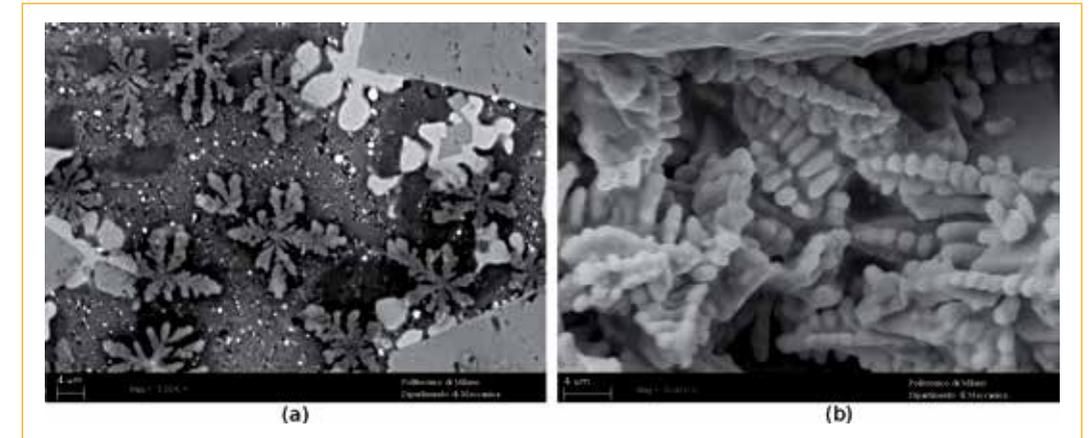


**1. Dendritic structures in EAF slag: (a) high chromium steel slag and (b) carbon steel slag.**

carbon steel, high alloyed steel and quality steel.

The current survey, that will be here discussed was aimed to achieve the following main goals:

characterize the diffusion, the dissolution and the releasing mechanisms of the polluting elements;

identify the correlation among the chemical composition, the phase morphology and the leaching behavior for the different slag groups;

identify the mineralogical phases involved in the heavy metal release and select which phases have to be promoted to improve the slag behavior against pollutants leaching;

set-up and install an inertization process able to transform the

slag microstructure to produce safe and eco-friendly slag; demonstrate the efficiency of the proposed stabilization process, applying it to several slag coming to different steel production.

To achieve these goals, several elution test on bulk and powder slag were performed on the different slag classes, varying the liquid-on-solid ratio and measuring the pollutants concentration in the leachate by means of ICP-OES. Morphological and microstructural characterizations were performed by means of SEM and XRD analysis in order to identify the main phases constituting the slag and recognize which of them

are responsible for pollutants leaching.

A stabilization process based on pure quartz addition into the slag stream during the deslagging operation was set-up. Efficiency of silica addition is presented and discussed, evaluating the effects induced by the process on slag microstructure. The modified slag were therefore compared with the as-received samples in term of leaching behavior at different liquid-on-solid ratio. The obtained results demonstrated the reliability of the proposed stabilization process that open the possibility to produce safe and environmental friendly by-product.

# DYNAMIC MODELING AND CONTROL OF FLEXIBLE MANIPULATORS

**Rajesh Kumar Moolam -** Supervisor: **Francesco Braghin**

Light weight and flexible manipulators have many advantages over heavy and rigid manipulators such as lower energy consumption, higher payload to manipulator weight ratio, small actuators to move manipulator arm, and safe to operate with human co-worker due to low inertia. These benefits come with flexibility in manipulator links or joints. The flexibility leads to vibrations on the manipulator endeffector.

The control of light weight manipulators is complex based on the nature of flexibility in the system, i.e. flexible joints, flexible links or flexible joints and links. Among them, the most difficult task is to control the flexible link manipulators because of link flexibility, under actuation and non-minimal phase nature. Under actuation is due to finite number of actuators to control infinite degrees of freedom that arise due to link flexibility. Non-minimum phase nature occurs because of non-collocation of actuators and sensors.

Despite of various advantages, the flexible link manipulators have less progress at the industrial level applications. There is a need to bring the advantages of flexible link manipulators to more general industrial applications by eliminating the difficulties

surrounded to it such as modeling link flexibility, under actuation and non-minimum phase nature in control design. The dynamic modeling that includes the link or joint flexibility is considered as an important step in model based control design to achieve better performance. In the past, many model based controllers were developed for flexible links manipulators but these studies are limited to planar models.

The goal of PhD thesis is to develop systematic approach for dynamic modeling and control of spatial flexible manipulators. The thesis on flexible manipulators is divided into two parts. The first part is focused on dynamic modelling of spatial flexible manipulators while the second part is focused on control design of spatial flexible manipulators for trajectory tracking.

A general purpose multi-body code has been developed to obtain a nonlinear dynamic model of spatial flexible manipulators for model based control design and simulation purposes. Both link and joint flexibilities can be included in the dynamic modeling. The flexible links are discretized using finite element method to get a finite dimensional nonlinear dynamic model.

In the dynamic modelling, deformation of each link is assumed to be due to both bending and torsion. The deformation of the joints is assumed to be due to pure torsion. The deformation of each link is assumed to be small relative to the rigid body motion. Thus, the configuration of each link is defined as the sum of rigid and elastic coordinates using a floating reference frame. The dynamic model is first derived using the principle of virtual work along with finite element method in generalized coordinates for general purpose implementation. Then, the system of equations in generalized coordinates is converted into independent coordinate form using a recursive kinematic formulation based on the topology of a manipulator.

The advantage of proposed general purpose multi-body code is that it uses minimum set of equations that define the dynamics of flexible manipulator, which is required in control design to reduce computation cost. In addition, it allows the dynamic modeling of any arbitrary manipulator configuration that consists of rigid links, flexible links and flexible joints.

To study the effect of flexibility

on robot manipulator dynamics, an open chain RRR spatial manipulator with flexible links and flexible joints was considered. The numerical simulations results showed that the link and joint flexibility can alter the motion of endeffector in workspace. Thus, Ignoring the link or joint flexibility can cause poor estimation of dynamic parameters and, eventually, poor performance of the control design.

Model based controllers were developed for trajectory tracking and vibration suppression of spatial flexible link manipulators. The following model based controllers were designed for an open chain RRR spatial flexible link manipulator:

1. PD Control
2. Stable Inversion Control
3. A Nonlinear Control
4. Adaptive Control

Among them, PD control and Stable inversion control were derived using feedback linearization technique. A nonlinear control and Adaptive control were derived using sliding mode technique.

The proposed model based controllers are implemented on open chain RRR spatial manipulator with flexible links. The simulation results are shown in Figure 1. The simulation results of PD controller showed good trajectory tracking at joint space. However, it is not very efficient to damp the endeffector vibrations. The stable inversion control showed better trajectory tracking compared to PD control, however this method
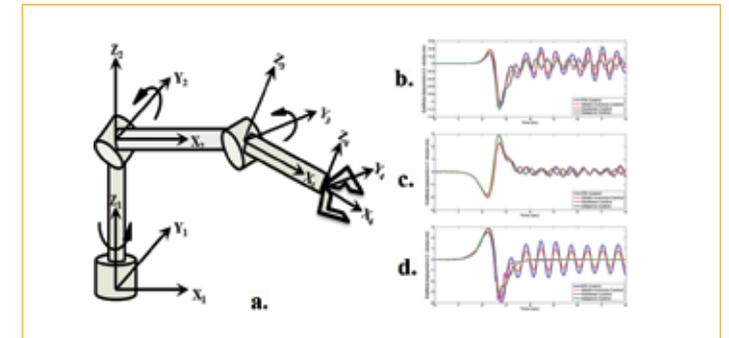


1. (a) Spatial RRR manipulator with flexible links (b) Endeffector X4Y4Z4 displacements on X-direction (c) Endeffector X4Y4Z4 displacements on Y-direction (d) Endeffector X4Y4Z4 displacements on Z-direction
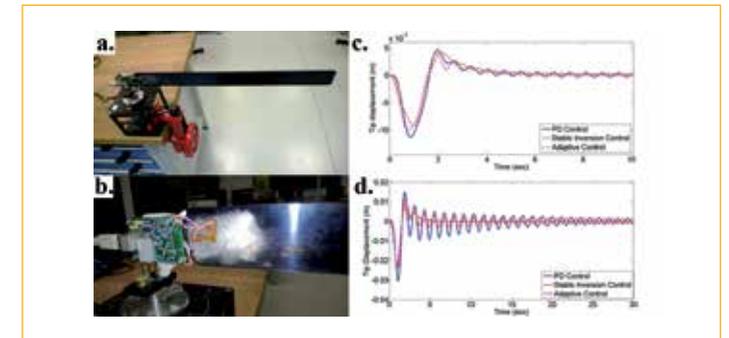


2. (a) Experimental setup of a single link flexible manipulator (b) Strain guage mounted at the flexible manipulator to measure tip displacements (c) Tip displacement with payload mass on endeffector (d) Tip displacement with payload mass on endeffector.

is incapable of damping the vibrations in case of unmodeled dynamics such as unknown payload mass. Moreover, stable inversion control can have good performance for planar flexible link manipulators compared to spatial flexible link manipulators.

Nonlinear controller and adaptive controller showed good trajectory tracking at the joint space and also efficient to damping the endeffector vibrations compared to PD controller and stable inversion controller.

To validate the model based controllers, the experiments

were performed on a single link flexible manipulator. The experimental results of single link flexible manipulator are shown in Figure 2. The experimental results showed that the adaptive controller has better trajectory tracking and vibration suppression compared to PD control and stable inversion control in the presence of additional unknown payload mass on the endeffector.

# VIBROACOUSTIC MODELLING OF SANDWICH PANEL WITH FOAM CORE

## Simona Moschini - Supervisors: **Alfredo Cigada**

MECHANICAL ENGINEERING

Energy efficiency has become one of the most challenging topics during last years. The global warming has been an issue for the international community since the beginning of the 90s. In 1992 the Rio de Janeiro Summit, to which 154 nations took part, drafted the United Nations Framework Convention on Climate Change (UNFCCC). The next target for the European Union (EU) is the 2020. European directives are oriented towards a nearly zero Green House Gases (GHG) emissions. The main strategic areas are transportation and housing that together cover more than 50% of GHG emissions in EU. Therefore, new light has been shed on the gathering of new strategies that reduce and limit GHG emission. Among them, emission reduction can be tackled reducing consumption. In transportation, for instance, GHG emission reduction can be achieved reducing the weight of the structural components. Lightweight structures became indeed widespread in several industrial frameworks, for instance in the aircraft industry. Being characterized by a pretty rich basket of design parameters lightweight structures can be tailored exactly to the specific requirement. As main drawback, this class of structures exhibits poor noise and vibrations

performances. They tend to vibrate easily inducing undesired noise. In fact, aiming to design of a structure effectively able to reduce sound transmission the historical rule of thumb "the heavier the better" is still valid. Increasing the mass of a structure leads to a better sound insulation. Anyway, in many application fields the lightweight became a strict design constraint due to energy efficiency requirements. Recent developments in material sciences along with the older concept of composite structures allow overcoming this difficulty. In particular, sandwich panels with foam core represent an appealing solution since they allow achieving better vibroacoustic performances. The metallic skins, usually in Aluminium, provide bending resistance while the core material and structure can be selected to obtain the desired performances. Sandwich structures offer a theoretical infinite number of possible skins - core combinations. Therefore, the availability of a reliable vibroacoustic numerical model plays a fundamental role in the structure design step. The numerical prediction of the structural performances, either in terms of vibration damping or sound transmission reduction, allows configuring the sandwich structure

according to the investigated practical problem. The aim of the current research is to develop an integrated numerical/experimental procedure to predict the vibroacoustic performances of a sandwich foam core panel. In literature, research works are typically focused either in accurate material characterization or in developing new strategies for efficient numerical modelling. Conversely, the current research work considers the whole workflow required for a reliable vibroacoustic prediction. The innovative feature of the proposed methodology is the integration among all the relevant aspects for vibroacoustic structural behavior evaluation: material parameter identification, vibroacoustic numerical modelling and experimental validation of the modelling strategy. Each of the abovementioned aspects has been studied and designed. A dedicated experimental activity has been designed and carried out to obtain the material parameters required for the numerical model implementation. The panel core is a viscoelastic material that requires a specific identification procedure. The characterization of material parameters has been done through a compression dynamo mechanical testing procedure. A sinusoidal strain

is imposed and measuring the resulting stress it is possible to identify the material Storage and Loss Modulus. The former quantifies the material elastic behaviour while the latter is related to the material viscous nature. Particular attention has been paid to the definition of the testing condition. The foam behaviour is frequency dependent and sensitive to the preload imposed during the test. A comparative analysis has been carried out to identify the preload value that mimics the confinement effect of the Aluminum skins on the foam core. The identification of the material parameters over the whole investigated frequency range represents the starting point for the numerical model development. The structural dynamic response has been evaluated through a Finite Element (FE) model while the coupled vibroacoustic problem has been tackled via a combined Finite Element - Boundary Element (BE) model. Typically, these kind of problems are addressed developing ad hoc numerical codes, especially whether they involve viscoelastic effects. Implementing a specific code requires a deep knowledge of the theory of the selected numerical method. The choice of using commercial codes in the current work, respectively Abaqus for the FE model and VirtualLab for the coupled model, increases the usability of the proposed modeling strategy. A layer-wise approach has been chosen for the dynamic model of the sandwich panel. The skins have been modeled using shell elements while solid elements have been selected for the core modeling. A perfect

tying has been imposed among skins and core. The modeling of the adhesive layer existing among skins and core has been neglected. This assumption derives from an experimental investigation that compares two Aluminum plates glued together and a single Aluminum plate of equivalent thickness. The additional glue layer does not influence significantly the damping vibration performances. Therefore, a dedicated modeling of the glue, a viscoelastic material, has been neglected in the FE model. The developed FE model allows to evaluate the structural vibrational response and to extract the sandwich panel modal parameters, in particular natural frequencies and mode shapes. The latter are the fundamental input for the coupled FE-BE model. Roughly speaking, the coupling between the two models is made projecting the structural mode shapes on a BE acoustic mesh of the investigated structure. A BE approach is then used to simulate the structural response to impinging sound waves taking in account also the structural modal behavior. The outcome of the coupled model is a prediction of the structure sound transmission capability. The FE and coupled FE-BE models prediction capability has been assessed in terms of either vibration damping or sound transmission reduction performance respectively. Dealing with lightweight structures makes the experimental activity more challenging, especially in terms of dynamic characterization. As a result few literature works present dynamic models of

lightweight structures together with experimental validation. In the current thesis instead the numerical/experimental comparison has been considered of fundamental importance for the assessment of the modelling strategy reliability. In particular, the vibration damping prediction capability has been checked comparing the experimental and predicted frequency response functions on two different test cases. The comparison shows good agreement in terms of natural frequencies and mode shapes while the predicted damping is higher than the experimental one. The vibroacoustic model has instead been validated evaluating the Sound Insertion Loss (IL) index, i.e. the change in the radiated power of a given source due to the positioning of an object between the source and the receiver, both numerically and experimentally. The comparison shows a nice matching between experimental and numerical IL in the investigated frequency range. To conclude, an overall procedure has been developed to evaluate the vibroacoustic performances of a sandwich structure taking in account all the relevant aspects and integrating numerical modelling and experimental tests. The developed model shows good reliability especially from the coupled vibroacoustic point of view.

# NUMERICAL AND EXPERIMENTAL ANALYSIS OF UNCERTAINTIES EFFECTS ON NONCONVENTIONAL FLUTTER INSTABILITY OF SUPER-LONG SUSPENDED BRIDGE

**Andrea Pagani -** Supervisor: **Prof. Alberto Zasso**

**1. Dendritic structures in EAF slag: (a) high chromium steel slag and (b) carbon steel slag.**

The continuous progress in knowledge and technology has let engineers design suspension bridges with increasingly longer spans. A major concern for such slender structures is that they suffer from aeroelastic instabilities caused by self-excited aerodynamic forces acting on the deck. While the risk of torsional divergence can be avoided by a careful aerodynamic design of the deck section, flutter instability still remains a critical aspect. Since the first aeroelastic studies of civil structures, the problem of stability has been studied from a deterministic point of view; nowadays, this approach is the starting point of probabilistic analyses that take into account two main different kinds of uncertainties.
The first kind of uncertainties concerns the structural

properties of the bridge. Even if the numerical modelling of civil engineering structures is more and more refined, uncertainties related to a lack of information on the as-built structure still remain (material properties, non-structural elements effects, boundary conditions or local constraints).
The modelling process is difficult to deal with at the design stage because new structures are often unique and without any closer terms of comparison. The second kind of uncertainties deals with fluid-structure interaction and with several aerodynamic issues. Wind tunnel tests are a core part in the bridge aerodynamic assessment of a long suspended bridge to define the coefficients that will be used in numerical simulation to predict the structure behaviour.

On one hand, the analytical models adopted to compute the aerodynamic forces acting on the bridge, approximate the aerodynamic phenomena. On the other hand, they rely on experimental coefficients that are measured in wind tunnel on scaled models that, apart from uncertainties related to the measurement process, contains a lot of possible elements of mismatching with the real structure (Reynolds number self-similarity, the residual turbulence of nominal smooth flow, the surface roughness of the model, the appropriate representation of the aerodynamic effects of sharp edges, ecc.). Realizing a model that behaves as the real structure by an aerodynamic point of view is one of the great challenging for a wind engineer. All these uncertainties have to be carefully taken into

account in the evaluation of the aeroelastic stability since they can have a great effect on the results. This is particularly important for very long span bridges, since the design of such a bridge relies on structural and aerodynamic optimizations. This work deals with the effect of structural and aerodynamic uncertainties on the aeroelastic performances of the Izmit Bay Bridge that is going to be a part of the 420 km Gebze-Orhangazi-Bursa-Izmir motorway under construction at the mouth of the Bay of Izmit (Turkey). With a north-south deck direction, it is characterized by a three-lane dual carriageway (no railway arrangement). The structure is a three-span suspension bridge with a main span of 1550 m, two side spans of 566 m and two H-shape towers 252 m high. The deck is a classical streamed line single box, 30.1 m wide and 4.75m thick, with 2.92m wide inspection walkways at both sides.
It will become the world's fourth longest suspension bridge.
Wind tunnel tests (Figure 1) highlight that two vertical-torsional instabilities arise at the same mean wind speed. The first one consists the coupling of the homologous mode with an anti-node at mid span. The second one involves the second order vertical and torsional modes (node at mid span), and, unconventionally, also a vertical side-span mode.
Further numerical analyses highlight that classical flutter mechanism is not able to reproduce the experimentally observed one because the effect of vertical higher modes need to be considered.
Dealing with the reliability
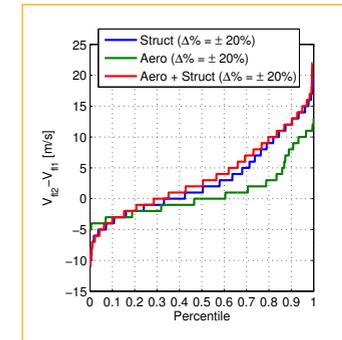
**2. Statistical analysis of the instability mechanism of the IBB with structural and/or aerodynamic uncertainties**

analysis, Monte Carlo method was applied to the aeroelastic problem assessment of the IBB that is very a-typical bridge by a wind engineering point of view. By a structural point of view, the greater uncertainties rely on the effectiveness of the FE modelling, that is quantified by a benchmark between the numerical and the experimental identified frequencies of 14 different bridges.
Facing with aerodynamic coefficients, they can be potentially modulated by a lot of parameters. In order to verify their sensitivity to possible changing in the deck fluid-structure interaction, two model with little modification despite the nominal one were tested. Aerodynamic coefficients show negligible modifications and as a consequence also the stability analysis show not relevant differences. The model is also robustness considering slightly variation in the angle of attack. Numerical simulations show that the epistemic variations of both structural and aerodynamic parameters produce not negligible effects on the flutter mechanism. Structural variations produce larger effects on the

**3. Uncertainties propagation on the residual damping of the 1st torsional mode**

flutter onset than the ones produced by the aerodynamic parameters even if of the same order of magnitude.
The synchronous flutter velocity of the two presented kind of flutter is a circumstance that is typical of the nominal case but, by a statistically point of view, it occurs only in the 20% of the simulations (Figure 2). The main mechanism of instability is the one caused by the coupling of the modes with an anti-node at mid-span.

Finally, this analysis highlight that, under specific conditions, the system shows instability at relative low mean wind speed due to a modification in the flutter mechanism that depends on the particular "*S-shape behaviour*" of the damping of the first torsional mode (due to both structural and aerodynamic uncertainties). This can also be noted by the analysis of the residual damping (Figure 3) that gives information about the stability of the structure at mean wind speeds typical of the in-service operative conditions of the bridge.

# MODEL-BASED MONITORING AND CONTROL OF MACHINE TOOLS DYNAMICAL BEHAVIOR TO ENHANCE MACHINING PERFORMANCE

**Paolo Parenti -** Supervisor: **Michele Monno, Giacomo Bianchi**

Machine dynamic is a great important issue in modern manufacturing, especially for machining systems, because of its direct effects on part accuracy, surface quality/integrity, tools and machine components wear/breakage and lastly on energy consumption. The work presents the development of different monitoring and control tools that help coping with dynamic problems affecting machine tools and cutting processes, by means of model-based approaches.

**Part A – Grinding:** Major attention is given to cutting instability phenomenon in roll grinding and the related surface waviness formation. The study of this topic is framed in a research project that involves one of the top world-leading manufacturer of roll grinding machines. Chatter is one of the critical aspects that must be taken into account since it hinders the surface quality and the geometrical accuracy of the ground workpiece, which are the main goal of this process. Therefore, Automatic Chatter Detection becomes fundamental for supporting grinding operators in performing chatter-free operations and mitigate the negative effects associated with this phenomenon. Technological synthetic indicators for grinding
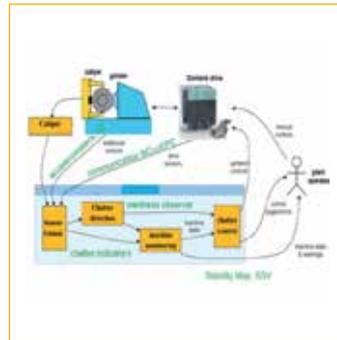


**1. Architecture of the developed process controller**



**2. Waviness Observer online estimation compared with offline direct measurements of the roll waviness**

chatter monitoring have been developed for this purpose, basing on a sensor fusion approach of accelerometers and NC drives data. Automatic Chatter Control represents an additional step ahead toward the achievements of good system performance. Most of all the existing solutions in literature requires strong modifications of the system setup and the use of additional expensive sensors, which often are not suitable for an easy industrial exploitation. In this work a model-based Automatic Chatter Control architecture for waviness avoidance, that is compliant with the constraints imposed by the industrial application, is proposed (Figure 1). The controller works in closed-loop using a waviness observer module as feedback and the

process parameters, such as the workpiece and the grinding wheel speed, as control variables. Stability theory of the grinding process is exploited for supporting the decision actions which consists in the application of speed tuning or continuous speed variation strategies. The waviness observer module is aimed at identifying the surface defects online (during the grinding process) basing on the forced response of the machine structure to force perturbations. The closed loop dynamic behavior of the machine and process is described by models of the open loop system and the linearized grinding process. Thanks to the closed-loop response function, it is possible to extract and quantify the only contributes related with waviness, from the acceleration

response of the structure (Figure 2), supporting the activation of the most proper control action. The control architecture has been implemented in Labview® and deployed on a National Instrument real-time control platform. The solution, tested on a specifically equipped grinder has demonstrated to reduce significantly the negative effects associated with the dynamic interaction between machine tool and chipping process. All the above analyses have taken advantage of a comprehensive time-domain grinding simulation model, used as a reference virtual machine, which has been developed during the PhD work, in collaboration with ITIA-CNR. The model relies on a tridimensional discretization by means of a Z-buffer approach and it is able to provide static and dynamic grinding force components by taking into considerations all the relevant aspects, such as cutting force non-linearities, contact stiffness, process damping and generalized machine dynamics with multiple degrees of freedom (Figure 3). Non-linear grinding wheel wear behavior is under study and will be object of future development. Validation tests has been carried out on a surface grinding machine confirming the good performance of the model.
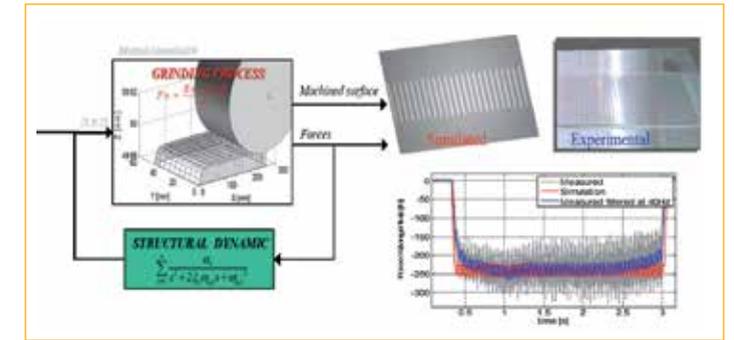


**3. Time-Domain Simulation model of Grinding Process**

**Part B - Milling:** Minor investigations have been devoted to the study of the dynamic behavior of milling process and milling machines. A real-time monitoring module aimed at identifying the onset of regenerative chatter in milling operations and estimate the chatter frequency in real-time is proposed. The approach, based on recursive fitting of a cutting forces model is presented along with simulated and experimental applications that exploit accelerometers, dynamometers and microphones. In general, reducing cutting forces decrease the tendency of the cutting system to develop chatter. The idea is to adopt Ultrasonic Vibration Assisted Machining (UVAM) technique in this regard. A preliminary experimental assessment has been carried out for the micro-milling case to evaluate the actual force

reduction allowed by UVAM. Future studies will be devoted to the coupled effect on cutting stability. Another investigation has been focused on inertial vibration affecting multi-axis milling centers. A feasibility analysis for compensating the dynamic compliance through the application of a model-based feed-forward approach has been carried out. The possibility to use feedback control has also been discussed confirming that both solutions can be adopted on real systems. Surface defects, associated with the structural inertial deformation, can then be actively reduced.

# MULTI-LEVEL OPTIMIZATION OF MACHINE TOOLS CONTROL ARCHITECTURE

**Danial Ramin -** Supervisor: **Prof. Stefano Bruni**

During the last decades manufacturing systems have been rapidly changed as the response to increasing market demands for higher productivity and quality. Simultaneous fulfillment of these contradictory objectives has urged the development of more intelligent and adaptive technologies. Computerized Numerical Control (CNC) units play an important role in this new trend enabling machine tools to perform more complex operations in shorter time without compromising the product quality. Incorporation of advance techniques into CNC architecture has been the subject of many research studies, though in industry CNC machine tools have remained closed systems. Among these efforts are Open Control Architecture, a user oriented CNC system, and soft-NC, an object oriented technology which can be applied in robotics as well. Within this framework this thesis tries to contribute to the research trends evolving machine tools control structure by addressing existing challenges and proposing new methodologies. CNC command generation is typically consisted of three stages: Interpretation of geometrical data, motion generation and drive control. Traditionally CNC trajectory generation is performed by linear and circular interpolations. This approach produces line

segments for contouring and as a result causes feed fluctuation at the junction of those segments and hinders high speed machining due to segment-wise feed planning. Moreover, higher order discontinuities produce high acceleration and jerk which can saturate the actuator and induce structural vibration. These drawbacks drastically increase operation time when complex trajectories are to be executed. On the other hand at servo level, mostly simple controllers such as PID are implemented which have limited bandwidth and are not capable of tracking aggressive trajectories with high frequency content and delivering robust performance in the presence of disturbances and uncertainties. To alleviate the shortcomings of simple linear interpolations, parametric interpolation techniques like spline and NURBS have recently gained significance in delivering machine drives the desired feed motion smoothly and accurately. To cope with the issue of feed generation in real-time lookahead module is adopted to increase the speed while taking care of only geometric and kinematic compatibilities. Just recently manufacturing literature directed some efforts toward optimal motion planning, which is a well-studied problem in robotics,

but little has been achieved in practical implementation of similar techniques in CNC architecture. Regarding the feed drive control, robustification has been the major concern of research community. Advanced controllers have been substituted for classical ones in order to achieve higher positioning accuracy and satisfy multi-objective performance criteria within the larger range of dynamic variations. As a result, lighter mechanical components can be used to decrease energy consumption in spite of their higher compliance. Of course implementation of these controllers has been made possible only through powerful computers and high resolution sensors on the one hand and innovative identification techniques enabling precise modeling in the other hand. In spite of all these efforts, there still exist a great gap between state-of-the-art control theories and their implementation as reliable controllers in machine tool feed drives. Most of the existing solutions at each above-mentioned module deal with the corresponding challenges independently without considering their interactions and how they can affect the global efficiency of the system. One of the common issues among the motion generation and servo-control level, which

is handled in this fashion is the problem of vibration. Motion trajectories are made smooth and conservative in order to prevent structural vibration and controllers are designed to have higher bandwidth to mitigate it. This approach is less than optimal when it comes to the trade-off between precision and productivity.

To overcome these shortcomings, this thesis proposes a multi-level control architecture in order to exploit the full capacity of machine tools regarding different constraints at each level. In this context, a self-scheduling controller, namely Linear Parameter Varying (LPV), has been implemented which takes into account dynamic variations due to different configurations of the machine. For this purpose, in order to identify the position dependent dynamics of a motion generation system, two LPV model identification techniques are proposed based on the availability of a priori knowledge of the system. In the first approach a block box identification method has been formulated, in which the LTI models identified by subspace techniques are interpolated with minimum conservativeness. The second approach assumes the structure of the system is known, so based on this data a gray-box identification

procedure is presented using a heuristic search solution for minimization of discrepancies in the frequency domain. Based on the obtained LPV model of a ball-screw, as the most common component of machine tools, an LPV-H∞ controller is designed, where through the proposed weighting functions –earlier tuned by the synthesis of different LTI controllers– certain time domain specifications are incorporated with an ideal outcome maintained throughout the operation space. Eventually, a piecewise-affine (PWA) approximation of the controlled system is integrated into a novel trajectory generation algorithm which not only optimizes but also systematizes the procedure of motion planning. Integration of system dynamics into the motion generator for a multi-axis machine, intrinsically a non-convex problem, is reformulated as a Mixed Integer Linear Programming (MILP) model, which can be efficiently solved using several powerful solvers. While minimizing time (or possibly any other objective function such as energy consumption) this approach makes it possible to maintain any desired performance once the corresponding dynamics are stated as linear or PWA constraints. This may include the saturation of control system components, backlash,

friction induced vibration and residual vibration of the mechanical structure. Another advantage of this method, comparing to the existing motion generation techniques, is the direct mapping from time to parameter space. Consequently, not only the trajectory generation structure is simplified without compromising the contouring precision, but also the time spacing can be optimally adjusted without being restricted to profiles with predefined multiple segments as of the standard methods. Hence, the kinematic compatibility is automatically handled by the optimizer. The efficiency of this method has been verified for a positioning system with the LPV servocontroller, when an optimal trajectory was generated, while the tracking error remained within the predefined bounds. Though the main goal of this project was improving the performance of machine tools, the proposed methodology do not fall within a specific family of machines and can be applied to any multi-axis motion generation system.

# ADVANCES IN LIFE PREDICTION AND DURABILITY OF RAILWAY AXLES

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Railway axles are components adopted since mid-nineteen century and which have occupied and still occupy a large place in the scientific research. On one hand, they are safety components, whose failure can lead to tragic consequences, and are consequently designed with an infinite life approach; on the other one, there is an increasing needing of optimizing the costs and operations connected to the in-line inspections during the working life, especially considering the more recent applications to high-speed trains. Despite the great amount of studies, railway axles are nowadays still designed against fatigue limit and mostly based onto pregressed experience. By such approach, even if a high safety standard has been reached, it's not possible to make a step further in the direction of optimizing the design and all the costs related to production and exercise. For this reason, the traditional design against infinite life is being more and more complemented by the relatively new, at least in the railway field, damage tolerant approach, able to take into account the degradation or damaging of the axle along lifetime. Several aspects contribute to a reliable estimation of the prospective lifetime and, consequently,

a correct design and plan of the inspection intervals, such as the definition of the load history on the component, the mechanical properties and behaviour to crack propagation of the adopted steel grade, the knowledge of the SIFs at the crack tip and the qualification of the NDT techniques adopted during inspections.
Aim of this research was trying to improve a few points among them: firstly, an attempt to correlate the three methodologies of calculation was carried out, then, the effect of residual stresses and variable amplitude loading onto lifetime calculations was considered, in comparison to dedicated experiments. The allowable damage sum $D$, and the choice of the right fatigue curve onto which calculations should be carried out was firstly discussed, comparing the experimental results, from VA loading tests onto small-scale specimens, against predictions. It was found that a damage sum equal to one led to not conservative predictions: the dispersion of the experiments could better be represented by a damage sum set to 0.5. Calculations performed onto the 2.5% percentile of the fatigue curve, with an allowable damage sum equal to 0.3, in agreement to FKM guidelines, led to sufficiently conservative

predictions, being adequate as design criterion.
Limitations and contradictions of the current regulations were highlighted, and the need of, at least, complementing the traditional approach with the novel damage tolerant one was proved by an example of application of the approach to old axles, no longer complaint with the current regulations, in order to show how to manage their service life extension. A simple application of a damage sum criterion, based on the Haibach's rule, but adopting realistically derived load spectra, returned very long predictions, according to the evidence (none of these axles failed over more than 30 years of service), but in contrast to the European Standards, which are, maybe, too conservative. By use of appropriate crack-propagation models, in conjunction with the realistic derivation of the loading spectra, a procedure for the evaluation of a reliable inspection plan was proposed and discussed. Finally, a simple parameter was proposed, more indicative of the inspection intervals than the Safety Factor proposed by the current regulations.
In the last few decades, several surface mechanical procedures, generating compressive residual stresses, have been adopted to increase the service life

of mechanical components subjected to fatigue. This approach has been more and more adopted also in the railway field, with deep-rolling as the adopted technological process. In the PhD thesis, the effect of the residual stress onto crack propagation was addressed: full-scale specimens, made of the medium strength steel grade A4T, were machined and deep-rolled adopting the parameters of axles from production. Then, crack propagation tests, under VA loading, were carried out in order to compare the experimental results with dedicated simulations, by the meaning of a no-interaction model taking into account the effect of the residual stresses onto the stress intensity factors at the crack tip. Depending on the initial notch size with respect to the depth of compressive residual stresses, no crack initiation could be observed for small flaws (R=2 mm), while unusual crack shape development, characterized by crack branching and wide yielded regions, happened for the largest ones (R=3 mm and R=4 mm). In any case, crack propagation occurred only at very high and unusual $\Delta K_{max}/\Delta K_{th}$ ratios. Regarding the crack growth simulations, results obtained by a simple no-interaction crack propagation model, taking into account the measured stress field, were successfully compared to the full-scale experiments, opening the possibility of accurately planning the inspection intervals for deep-rolled axles.
Finally, the effect of variable amplitude loading onto crack propagation was considered. In dependence of the applied

load sequence, a certain amount of retardation or acceleration onto fatigue crack growth rate is usually observed, mainly addressed to the local plasticity at the crack tip and explained by adopting the plasticity-induced crack closure concept. Crack growth tests under variable amplitude loading were carried out onto companion SE(T) specimens, showing the same constraint effect at the crack tip as a railway axle. The variable amplitude loading was applied in the shape of time history or equivalent load spectrum, with different lengths of the blocks, in order to check the retardation effect due to the load sequence. No evident retardation effect arose, in dependence of the shape of the VA loading, when considering the medium strength steel A4T: results from Time History and equivalent block loading agree, as well as results from longer or shorter block lengths. Regarding the two high strength steel grades, an evident effect of retardation appeared when considering the high strength steel 34CrNiMo6, tested at stress ratios different than 1 and at high $\Delta K$ values, while no evident retardation appeared on the similar (at CA) 30NiCrMoV12 steel grade, tested at lower $\Delta K$ values. Crack growth simulations were carried out, trying to approximate at best the experimental evidence, adopting the threshold definition from different experimental techniques, CPLR and $\Delta K$-decreasing. Firstly, crack growth simulations were carried out by the meaning of a no-interaction model, then, an attempt to simulate the retardation effect was carried out adopting

the Strip-Yield (SY) model. A convergence analysis on the α parameter permitted to define the most appropriate values, regarding A4T, stay around 2.5Ö2.7. The high strength steels were, instead, better represented by lower values, depending on the amount of retardation, variable between 2 and 1. This was in agreement with the higher retardation of these steel grades. A simpler approximation was finally adopted, trying to match the experimental outcomes by translating upward the threshold $\Delta K_{th}$ from CPLR. This approximation, which gave good results, according to the more complex Strip-Yield model, is suggested as a 'rule of thumb', for basic calculations of the perspective lifetime.
Finally, the increasing distance between inspections, possible by an accurate representation of the retardation effect, was discussed, considering the equivalence between SE(T) specimens and railway axles. In particular, it was found that, for a given failure probability, inspection intervals could be increased by 60% respect to predictions made with 'no interaction' and CPLR data.

# DESIGN OF A MINIATURE INFRARED FTS FOR MARS OBSERVATIONS

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This work is devoted to the design of the miniaturized Fourier Transform Spectrometer "MicroMIMA" (micro Mars Infrared MApper), intended to be mounted on a descending module to Mars of the ESA mission "ExoMars 2016. The scientific goal of the instrument is the spectral characterization and monitoring of the Martian atmosphere, bound to investigate its composition, minor species abundances and evolution during time. The spectral resolution of MicroMIMA is of 2 cm$^{-1}$ (with the option to be extended up to 1 cm$^{-1}$) that allows to recognize the spectral features of the main elements of interest in the atmosphere and in particular to assess methane abundance with ppb resolution. The atmosphere spectra are obtained in sun transmission mode by pointing the sun from the Martian surface. The instrument mechanical design constraints are quite strict:
· limited mass, size and power budget (mass limit of less than 250 g and a power budget inside 5 W);
· high stress resistance for the landing shock (expected shock loads described as a quasi-static acceleration of 1000 m/s$^2$);
· withstanding of severe environmental conditions without any power for thermal control;
· resistance for strong vibrations of the high acceleration levels in wide frequency range.

The mechanical design was carried-out by means of finite element models simulating the static and dynamic loading conditions on the instrument and providing as a result the optimized shape, for mass and size minimization, of the mechanical components. The thermoelastic analysis was performed in addition in order to evaluate the thermal field during operating process and the resulting optical misalignments, considering the worst predicted Martian environment scenario. Such analysis verified negligible decreases of instrument optical efficiency even in the most critical operating conditions. Moreover, an optimization of the vibrational isolation system was performed.

The optimal instrument configuration has been set in order to achieve the highest sensitivity in the 2 to 5 μm spectral range, along with the reduction of noise, i.e. the Signal-to-Noise Ratio (SNR) has been used as figure of merit. The theoretical SNR has been maximized starting from the analytical expressions of the Noise Equivalent Spectral Radiance (NESR). NESR reduction was achieved by means of the optical layout geometry optimization and by selection of optical elements that offer highest efficiencies for the instrument wavenumber range of interest. Afterwards for the proposed optical layout we performed evaluation of the theoretical SNR for different application cases: laboratory observations by the instrument on the Earth and actual acquisition of Martian atmosphere spectrum during the mission.

At first the typical terrestrial spectrum has been assumed as signal and the theoretical SNR was evaluated for a perfectly aligned instrument under different incident radiation conditions (accounting also for different meteorological conditions). As second step the expected SNR during the Martian observations has been evaluated, taking the spectrum of the Solar Black Body radiation as the approximate Martian atmosphere transmittance spectrum. The estimated SNR levels were in range of 10$^4$, showing the high efficiency of the instrument for the intended application.

The third step of the instrument performances evaluations was focused on the trace gas detection capability of the instrument, taking the methane component as the example with its expected concentration varying around 10-20 ppbv.

Having the expected depth of the methane absorption band as the signal, the evaluated SNR for both nominal and enhanced spectral resolutions was in range of 100, proving the instrument capability of low-concentration gases detection.

An instrument mock-up has been created in order to verify experimentally the optical layout performances. This mock-up was simplified from the structural point of view but with detailed representation of mounting, regulation and positioning of optical elements and piezoelectric actuator group. Its assembly, adjustment and a set of preliminary verifications has been made using the infrared lamp as a radiation source. The first instrument verification proved its functionality in the wavenumber range of interest with the specified nominal spectral resolution. However the rough and simplified design of the testing set-up did not permit to arrive to definitely assess the matching of the declared performance characteristics. Their realization requires additional work for a finer optical alignment.

Knowing that sensitivity to the mechanical vibrations is a well-known drawback of all the FTS family instruments, an innovative data treatment technique was created in order to deal with vibration borne undesired spectral distortions (so-called ghosts) and allowing the single spectrum correction. Such a technique would increase the spatial resolution of the mapping process and can become crucial when the desired information is linked to a particular mapping area associated to an individual spectrum.

The research included the detailed study of the ghost nature and mechanisms of their formation, resulting in an explicit mathematical description of the interferogram modulations generated by the mechanical vibrations. The obtained model allowed implementing the post-processing algorithm.

The proposed approach of vibration effect correction was based on the semi-blind deconvolution method – an iterative numerical algorithm of the series of consecutive deconvolutions. The method was qualified as a semi-blind because of the use of the generally known spectral information ab initio. The whole problem of the data post-processing was subdivided into three separate sub-problems: definition of the vibration kernel, recovering of the original spectrum from the distorted one and the results validation.

This technique was tested on the data from the PFS (Planetary Fourier Spectrometer onboard Mars Express 2003). The key-point of the procedure was the kernel determination. The lack of information about the vibrations and their nature is the main difficulty: frequency, intensity and phase with respect to the main signal interferogram are only statistically known from PFS calibration measurements that are performed at most once per orbit.

The initialization for the algorithm was the guess of the Martian spectrum at a large scale, approximated by two Planck functions (representing the Martian thermal emission and the solar energy reflected back by Mars) and the major absorption feature: the CO$_2$ absorption band.

The first step of the iterative procedure of kernel definition was performed on smoothed spectral data, as the initial estimation of the Martian spectrum can be done only in the large scale (all absorption lines may differ from spectrum to spectrum due to non-homogeneity of chemical compounds in the atmosphere/surface of Mars). Further iterations were performed on the original unfiltered data, each iteration loop including constrained deconvolutions of measured distorted spectrum with signal and kernel estimates. Proposed general constraints were the ones of spectrum smoothness and kernel sparsity. The final deconvolution step retrieved the original spectrum from the distorted one. Efficiency of the adopted technique strongly depended on the initial guesses for the semi-blind deconvolution input (i.e. on the actual knowledge of the Martian spectrum). Also the correct definition of the deconvolution constraints was important. Utilization of additional information about the expected spectral features (e.g. some gas absorption bands, regions of detector low responsivity, any known vibration components, etc.) would make the proposed algorithm more robust.