

DOCTORAL PROGRAM IN MECHANICAL ENGINEERING

Chair: **Prof. Bianca M. Colosimo** Within the current global economic scenario, still striving to recover from general slowdown and uncertainty, Mechanical Engineering stands out as one of the leading and driving sectors of industrial manufacturing in Italy. In terms of per-capita manufacturing production (2013), our country ranks 2nd in Europe and 8th on a worldwide scale (Confindustria, Scenari Industriali n.5, June 2014).

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 physicsbased 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 longer research periods. 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.

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), Universidad EAFIT (CO), AGH (Akademia Górniczo-Hutnicza) University of Science and Technology (PL).

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FRICTION I AWS FOR HIGH-PERFORMANCE TIRE RUBBER COMPOUNDS

Erfan Afrasiabi - Supervisor: Francesco Braghin

Contact between macroscopic surfaces occurs on asperities and local nano/micro-scale asperity. Tribological phenomena like friction and wear are highly scale dependent.

Two principal strategies in tire friction estimation are "Top-Down" and "Bottom-Up".

"Top-Down" approaches start from tire dynamics and rely on statistical mechanics and experiments. Their outcome are typically empirical or semiempirical friction models. In this approach friction identification is carried out relying on macroscopic kinematic quantities and the dynamics of the entire tire, i.e. longitudinal and lateral contact forces.

"Bottom-Up" approaches, instead, start from first principles and use fundamental mechanics and physics to link the atomic scale to the macroscopic aspects of deformation and energy dissipation in material. Such an analysis is based on the understanding of the fundamental physics behind the contact mechanisms, load distribution, stress and strain patters, elastic and plastic material response, surface topography, interaction of contaminants and surface chemistry. Adhesion forces play a controversial roles in microdomain

In this research, identification and sensitivity analysis of friction **2.** Normalized lateral force in time domain for "Left" tire



1 Normalized lateral force versus slip angle

law for high-performance tire rubber compounds at both macro-scale and micro-scale have been carried out. For macro-scale, nine physical factors (i.e. slippage, slip angle, camber angle, vertical load, inflation pressure, tire bulk and tread temperatures as well as road surface roughness and road & Fig.2). The high stability and temperature) were identified as being effective from a sensitivity analysis carried out on telemetry data. Thus, a non-linear tire

model able to predict tire contact forces as a function of these nine parameters has been developed and validated. Results show that the proposed model is able to correctly predict tire-road lateral forces with a correlation coefficient higher than 91% in all working conditions (Fig.1 fast simulation time allow to use the proposed model in real-time conditions.

Starting from a literature review



of existing models (empirical, semi empirical and theoretical) the most promising approach for micro-scale friction model (both hysteretic and adhesive) has been identified. This model allows to account for the effective pressure distribution, the asphalt properties, the sliding velocity and temperature distributions in the footprint area. Sensitivity analyses to surface topography, background temperature and road roughness cut-off wavelength have been carried out. Some criteria for objectively determining the road roughness cut-off wavelength have been proposed and tested. The main improvements with respect to the literature are a complete model accounting for both the hysteretic and adhesive energy losses as well as the extension of hysteretic losses to 2D deformations (Fig.3). It is shown that, considering 2D instead of 1D deformations. increases the estimated friction coefficient by 7% to 21% according to the surface roughness.



3. Estimated total friction coefficient for two models of asphalt

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MECHANICAL ENGINEERING

FRACTURE ASSESSMENT OF CRACKED COMPONENTS UNDER BIAXIAL LOADING

Diya' Zohdi Ratib Arafah - Supervisors: Prof. S. Beretta, Dr. M. Madia (BAM, Germany)

The PhD activity has been devoted devoted to the thorough investigation of the effect of biaxial loading on the fracture assessment of cracked components. In particular, the research aims to address unsolved issues in the assessment of pressurized components.

The analyses have been carried out onto different levels, starting from the failure analysis on the tested cracked specimens, the analytical assessment based on current standards, up to the higher level represented by the numerical investigations by means of finite elements. In the analytical and numerical assessment particular care is

dedi- cated to the estimation of the crack driving force, in terms of J-integral, and the variation of the local constraint along the crack front. A major effect of the biaxial loading on these two quantities is observed. The following main results that have been achieved in this work: 1. Extension of reference stress method to biaxial loading through the development of reference yield stress solutions for plates with semi-elliptical surface cracks subjected to biaxial tensile loading.

2. Importance of carrying out fracture toughness tests on dedicated specimens, which are able to reproduce nearly the same constraint condition of the component under investigation.

- 3. Development of an analytical assessment methodology for fracture instability anal- ysis of pressurized components with longitudinal external surface cracks.
- 4. Application of cohesive zone modeling to simulate the ductile tearing in thick- walled components (Fig. 1).



^{1.} Comparison between the computation (left) and experimental result (right) of burst pressure for tubes subjected to biaxial loads.

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OPTIMAL STRUCTURAL DESIGN FOR IMPROVING SAFETY OF ROAD VEHICLES

Federico Maria Ballo - Supervisor: Prof. Giampiero Mastinu

co-Supervisor: Prof. Massimiliano Gobbi

In this doctoral thesis Multi-Objective optimization and Topology Optimization techniques are applied for solving actual engineering problems related to the lightweight design of vehicle components relevant for safety.

The thesis proposes a double stage approach for performing the optimal structural design of vehicle components, i.e. the minimization of the mass and the maximisation of the structural efficiency (e.g. stiffness, integrity etc.) of such components. Simplified models (either analytical or numerical) are always derived to guide the applications involving Topology Optimization, i.e. the optimal structural design problem is at first dealt with a simplified model and then Topology Optimization is performed. So both analytical and numerical methods are derived in order to solve a number of optimal structural design problems referring to simple models of vehicle components. The simplified models are used in a preliminary phase of the design process and have a great importance since they provide

the designer important and useful indications for solving the problem.

Moreover, results obtained in this phase, are also important since can help the designer to handle more complex numerical models that are then employed in the subsequent and more detailed analysis.

A novel analytical method based on the matrix formulation of the Fritz John conditions for Pareto optimality is applied for minimizing the total mass of a cantilever beam loaded at the free end while maximizing its structural stiffness. Maximum stress together with buckling are treated as design constraints. Unreferenced analytical expressions of Pareto optimal sets for beams with different cross sections are derived by means of this method and compared.

Fig.1 shows the analytical expressions of the Pareto optimal sets plotted in the objective functions (compliance and mass) domain for the four analysed cross sections. Results show that the I-shaped beam exhibits the best structural performances.

An original multi-objective optimization approach is used for the structural optimization of the simple model of a brake caliper, i.e. a simplified finite element model of the caliper is developed and used for the optimization.

The design variables are the dimensions of the cross sections of the beam elements and the position of some nodes of the structure in order to account for shape variations. The Parameter Space Investigation (PSI) method is adopted for computing Pareto optimal solutions.

Topology Optimization techniques have been used in conjunction with the original simplified model to obtain optimal layouts at the very beginning of the design process (Fig.2).

The preliminary design of the brake caliper and the front upright of a race car as well the design of a new front wheel for a race motorcycle are performed by means of topology optimization approaches and simplified structural models.

Regarding the design of motorcycle wheels, the knowledge of loads acting on the component during its real working situations and also the knowledge on how these contact forces are transferred from the tire to the wheel rim are of crucial importance for the design of an optimized lightweight component. For this reason a proper in-depth study has been performed before structural optimization. New original simplified analytical and FEM models of a motorcycle tire are developed and validated. In the Finite Element model the actual structure of the tire

has been considered (Fig. 3), i.e. the beads, the 0 degree (circumferential) steel ply and the 90 degree (radial) ply have been considered in the model. An incompressible Neo-Hooke model has been employed for describing the rubber material property.

Subsequently a new prototype of motorcycle Smart Wheel is developed and realized (Fig.4). The device is able to measure tire contact forces on a front motorcycle wheel.

The measured data were of great interest since represent actual loading conditions of the component and are used as reference loads for the topology optimization of a new motorcycle wheel.

The combination of topology optimization approaches with proper simplified models has been effective for the refined structural optimization of a number of lightweight vehicle components relevant for safety. Pareto optimal solutions of the minimum mass and compliance problem in
the objective functions domain for four cantilever beams with different cross









3. Finite element model of a race motorcycle tire.



4. New Smart Wheel able to measure tire/terrain contact forces and moments on a race motorcycle.

"THE SETUP OF A MULTIHEAD WEIGHER MACHINE"

Alessia Beretta - Supervisor: Prof. Quirico Semeraro

A Multihead Weigher Machine (MWM) is mainly composed of a system of feeders, a set of H pool hoppers, a set of Hweight hoppers and a discharge chute to the packaging machine (Figure 1). The product is continuously fed via a central dispersion feeder and *H* radial feeders to the pool hoppers. The role of the pool hoppers is to stabilize the product before dropping it into the weight hoppers. Each weight hopper is equipped with a load cell that weighs the product and transmits the information to a computer. The computer then selects a subset of hoppers whose total weight is equal to or greater than the target weight *T*. Then, the computer opens the material cost, scrap or rework selected hoppers releasing the product through the discharge chute into the downstream packaging machine. For customer protection, the law requires that the weight of each package must be no less than the target weight. Consequently, a package filled with a quantity of product below the target weight is defined ``non conforming" and cannot be sold in the market.

A MWM is a complex machine which needs a setup strategy and a suitable operation software. The control software works in real time and its goal is to select the best hopper subset to open in order to achieve

the package target weight, according to the product, the cycle time constraint and the objective function. This problem is equivalent to the well-known knapsack problem. Instead in my thesis we want to tackle the setup strategy which is still an open problem.

The setup problem of a MWM deals with the determination of the optimal average weight of product to be delivered to each pool hopper. This setting may change according to the type of product to be packed and the target weight of the package. An improper selection of the machine setup affects the machine efficiency in terms of "non conforming" rate,

cost and possible losses due to the deviation of the product performance from customer's and/or producer's target. Thus, the initial setting of the machine is a very important decision affecting the general economic performance. Currently, the setup procedures adopted in industrial practice mainly rely on the operator's skill and experience during a trial-anderror manual setup which does not guarantee the best performance. To the best of our knowledge, the setup problem has not been addressed in the scientific literature apart from some preliminary results.

Thanks to the definition of the setup problem and its main



1. A multihead weigher machine.

variables together with the expression of the objective function (expected production cost per ``conforming" package) to minimize, the problem to find out the optimal setup of a MWM has been formalized. The Solution Space of the problem has been characterized. Its deep analysis allows us to discover an interesting symmetry property to reduce its dimension and, consequently, to tackle the setup Lastly, the optimal solution problem faster. According to the characterization of the Solution Space, five algorithms have been considered: gradient based practice. The expected cost algorithms (SPSA and RSM), a "Brute Force" (BF) algorithm and two random sampling algorithms (RC and RD). Their performance (Figure 2) in terms of median and standard deviation of the expected cost have been compared using the same number of objective function evaluations *n*, which is used as a proxy of the computational effort. As easily predictable, the increasing of *n* causes the values of both indicators to diminish. In fact, a greater number of evaluated machine setups allows for an improvement of the algorithm performance. We can surmise that the

performance of BF and RSM algorithms become more and more comparable as *n* decreases. Moreover, the performance difference between

the two random sampling algorithms (RD and RC) remains irrelevant by varving *n* and their performance are always worse than the BF and RSM ones. These conclusions have been generalized changing the MWM main parameters. Instead, the SPSA has always the worst performance regardless the number of objective function evaluations. found with the RSM algorithm is compared with two "rule of thumbs" used in industrial of the RSM solution and its standard deviation are lower than the two industrial solutions allowing a firm to save money

0.0045

0.0015

0.0005

g 1,0025

8,5825

2,0013

3.0020

15,0050

as much as the number of packages per minute increases.



15:5025

15,9090

2. Scatterplot of the performance of the different optimization methods. The median of the expected cost obtained thanks to the 50 replicates, is plotted on the x-axis. Instead, on the y-axis, the value of the standard deviation of expected cost is plotted for each optimization method.

Mediat

13,8971

15,9000

AN INNOVATIVE APPROACH TO EVALUATE PEOPLE'S EFFECT ON THE DYNAMIC BEHAVIOR OF STRUCTURES ANNA CAPPELLINI MEASUREMENT AND EXPERIMENTAL **TECHNIQUES**

Anna Maria Chiara Cappellini - Supervisor: Alfredo Cigada

In recent years, problems related to in-service vibrations have gained a growing attention. Since brand new structures have become more and more slender, an increasing number of problems related to unexpected vibration amplitudes have been recorded. Indeed, people acting on pedestrian structures behave as dynamical systems capable of modifying the dynamics of the structure itself as well as of introducing a load. This phenomenon is commonly known as Human-Structure Interaction (HSI). At present, however, the knowledge of HSL is still limited Indeed the determination of vibration amplitudes of structures occupied by people is a very complex task. Particularly, at least two main critical issues can be identified. The first aspect regards a correct characterization of the active forces induced by people on the structure. The majority of standards and codes suggest to model human-induced forces as harmonic forces. However, this assumption is too simplistic and does not reflect the real trend of human-induced forces. The second aspect regards the influence of people on the dynamic properties of the structure they occupy. Few attempts were made to include the effect of people. However, a model capable of providing

an accurate prediction of the experimental evidence does not currently exist in literature. This work aims at proposing and validating an innovative approach to include the effect of people's presence when simulating the dynamics of joint Human-Structure systems. First, the work focused on the analysis of the effect of passive people on the modal properties of the joint Human-Structure systems. An appropriate analytical model was proposed to include the effect of people's presence. The method only requires the knowledge of the modal model of the empty structure as an input. Each subject is then added locally on the structure by means of his/her a force plate, while a second apparent mass. The proposed approach places no constraints on the number of structural degrees of freedom taken into consideration. Two slender staircases and

data available in literature were used to validate the proposed approach. The experimental results showed that passive people's presence could produce a significant increase of damping ratios with respect to the empty structure. The predicted modal parameters and Frequency Response Functions (FRFs) were in good agreement with the experimental values in all the considered cases, as exemplified in Figure 1.

The proposed approach was then extended to predict the structural vibrations. First, tests under controlled conditions were performed to validate the proposed approach. One subject was asked to march on subject was standing still on the structure. The actual force induced by a single subject and the structural response were measured at the same time. Results showed that the



1. Experimental and predicted FRFs

use of the proposed model highly improved the predictions of vibration amplitudes with respect to the use of the model of the empty structure, as exemplified in Figure 2. The proposed approach was also hardly quantified a-priori if the applied to predict vibrations in operating conditions. Also in this case results showed that the use of the model of the empty structure to simulate the structural response causes an overestimation of the vibration amplitudes. Conversely, the use of the proposed methodology led to results much closer to the experimental measurements. The analytical matrix of the joint H-S system was then analyzed in order to highlight its properties. The observation of the analytical form of this matrix allowed to evidence the differences between the use of the complete model proposed in this work (Multi Degrees Of Freedom - MDOF - structure) and the superposition of Single Degree of Freedom (SDOF) structures to predict the dynamic behavior of MDOF structures occupied by passive people. An approximate approach based on the analysis of the apparent mass curves was also proposed to predict the type of influence due to people's presence on the modal parameters of the joint H-S system. Results showed that under the hypothesis of

solution introduces small errors with respect to the complete model. Conversely, the use of the modal superposition of the effects for MDOFs structure can introduce errors which can be modes are not well separated. An analysis of the effect of people in different postures and for different directions of vibration through the analysis of various apparent mass curves was also proposed. Results showed that people can both increase and decrease the natural frequencies and damping ratios of a structure. The method was also verified considering a grandstand of the San Siro Stadium as test case structure. Thus, an extension of the model to a different and more complex case was proposed. The impact of the number of people on the structure on its dynamic behaviour was analysed and

estimated lemote structure

SDOF structure the approximate **2. Experimental and predicted structural vibrations**

the effect of different people's distribution was evaluated by means of simulations. Results showed that people's effect increase with the occupation rate. However, it was also proved that the modification of modal parameters is highly influenced by people's distribution.

AI UMINUM MATRIX COMPOSITES REINFORCED WITH ALUMINA NANOPARTICLES

Riccardo Casati - Supervisor: Maurizio Vedani

Aluminum alloys show a great number of remarkable properties, such as low density. good resistance to corrosion, low thermal expansion. These characteristics make them verv attractive materials for several industrial fields where important applicative constrains have to be satisfied. For example, light weight (higher performance and lower consumption) and improved mechanical and functional properties (strength, corrosion and wear resistance) are essential features that materials have to possess in order to be employed in many applications in the mechanical, automotive, and aerospace field. Another important feature of Al alloys is their recyclability, as reprocessing does not damage their structure. Moreover, CO2 emission limitations and energy cost make lightweight materials a priority condition. In this view, Al based metal matrix composites are considered very interesting. These hybrid materials show opportunities to design lightweight structures with precise balance of mechanical and physical properties, with a relevant improvement on the tribological characteristics and also high temperature strength. Furthermore, the reinforcement particles are generally thermodynamically stable at the elevated temperatures, making

these materials suitable for high temperature applications. A novel concept of composites. which further enhances the properties of conventional composites, is given by the design of metals reinforced by nanoparticles. Due to their verv small size, the nano-fillers are able to interact with the lattice defects, i.e. dislocations, enabling new strengthening mechanisms to be activated. Their impact can be of great relevance either from the scientific or the technological point of view. Since metal matrix in metal matrix is primarily nanocomposites (MMnCs) are a very novel class of materials, the lack of knowledge associated to them has still to be filled up. Several technological issues have to be overcome in order to produce bulk nanocomposites characterized by homogeneous dispersion of nanoparticles and high mechanical performance. The comprehension of the physical phenomena related to their improved mechanical behavior and functional properties is still incomplete and needs a deeper understanding. The aim of this thesis work consisted in the development of Al nanocomposites with enhanced damping and mechanical properties and good workability. The nanocomposites exhibited high strength, good ductility, improved damping behavior and the capability of

being worked into wires. Since the production of MMnCs by conventional melting processes was considered to be extremely critical because of the poor wettability of the nanoparticles, different alternative powder metallurgy routes were adopted. Alumina nanoparticles were embedded into Al powders by severe grinding and consolidated using several techniques. Special attention was directed to the structural characterization at micro and nanoscale since uniform nanoparticles dispersion important. Moreover, some of the billets produced via powder metallurgy were also rolled to prepare wires as an example of final product. The Al nanocomposites revealed an ultrafine microstructure reinforced with alumina nanoparticles produced in-situ or added ex-situ. The work had a strong empirical basis. Different sintering methods and parameters were employed to produce MMnCs characterized by well dispersed nanoparticles in the Al matrix. In particular, different powder metallurgy routes were investigated, including high energy ball milling and unconventional compaction methods (ECAP, BP-ECAP, hot extrusion). The physical, mechanical and functional behavior of the produced

materials was then evaluated by different mechanical tests (hardness tests, instrumented indentation, compressive and tensile tests, dynamo-mechanical analysis) and microstructure investigation techniques (scanning and transmission electron microscopy, electron back scattering diffraction. X-rav diffraction, differential scanning calorimetry). The experimental results were then theoretically discussed. Literature equations and models were also used to predict the mechanical behavior of the material and the numerical and experimental results were compared.



1. Proposed mechanisms about the effects of milling and consolidation processes on the composite powder reinforced with in-situ and ex-situ nanoparticless: I) after drving, the aluminum powders, which are covered by an oxide passivation layer, are supposed to be additionally surrounded by γ -Al,O, clusters; II) after milling these clusters and the oxide passivation layer (square fragments) are broken up into small debris; III) after ECAP compaction the fragments of passivation layer and the γ -Al,O, NPs are dispersed into the aluminum matrix.

THE HEDGEHOG SHAPE MEMORY ALL OYS BASED SHOCK ABSORBER

Marco Citro - Supervisor: Gaetano Cascini

Despite Shape Memory Allovs are a guite young technology, after the invention of Nitinol Stent in the 1990s, they became a standard in the biomedical field thanks to their unusual characteristics known as Superelasticy and Shape Memory of Shape Memory Alloys in the Effect. Both these characteristics are attributable to the Shape Memory Alloys capability of recovering large displacements through a phase transition between two intermetallic solid states. However, in the industrial field, only few successful applications exist. Since 2000, the industrial market has shown a growing interest for such material. Some prototypes have been developed but they did not really achieve the market. Psychological inertia is often responsible to push potential users toward more conventional solutions notwithstanding the numerous advantages that these based on this idea exploits the alloys are capable to offer if used for some applications. The lack of classification standards is another reason that does not help the diffusion of Shape Memory Alloys. Today, two kinds of industrial applications exist; they are the electro and thermalactuated devices. The analysis of such products has underlined that electro-actuated devices use small diameter wires with more complex electronics while thermo-actuated devices are simpler but usually they perform

higher forces. No successful applications, which make use of Superelastic Allovs have been found in the industrial market. The goal of this research work is to identify an application that exploits the key features industrial field. To achieve this result, it is necessary to search a new field or to investigate among those already explored. For the research. Biomimetics has been used, getting inspiration from the different examples provided by the Biomimicry taxonomy. The latter is a classification of animals and plants that have been studied and classified based on the functions they perform. Among the diverse examples taken into consideration, the hedgehog, and its spines, have led us to devise a new concept of impact absorber. The device Superelasticity of many Shape Memory Alloy wires arranged with the same configuration of the spines of a hedgehog. To characterize the behavior of such absorber, the field of impacts has been investigated. The goal was to better understand the phenomenon and the protection mechanisms currently exploited and to find an application to make a comparison. Five protection mechanisms have been identified and different

applications have been classified based on the protection mechanisms detected. Among all the applications, the crash box has been selected as the reference one, since the crash boxes and the hedgehog absorber showed a similar impact response. Afterwards, several tests have been carried out, in order to prove the concept and eventually the device has demonstrated to be capable of absorbing large amounts of energy. The first tests carried out have shown an absorption capability equal than 85% with respect to the energy provided. Such capability has been subsequently verified through compression tests and impact tests. All the collected data have been processed through ANOVA in order to verify the significance of the parameters that turned out to be significant. Afterwards, the same values have been used to calculate some regression models. The obtained results have been also compared with those of the crash box, a device commonly used to absorb shocks in the automotive field. It is important to state that, since the test method used for the crash box is different from what has been done for the hedgehog absorber, the comparison has been made only partially.

Comparison between some



values of current crash boxes and the results obtained with the drop weight tower for the specimen LD3510.

	TEST ENERGY [J]	PEAK[N]	AVERAGE [N]	%E. AB	E.ASS. (J)	SAE	LR
LD3510	20,7	6296,0	926,8	62,5	14,0	0,7	6,8
LD3510	64,8	8439,0	1459,6	81,7	53,7	2,5	5,8
LD3510	121,3	9602,0	1844,9	89,8	109,5	5,2	5,2
LD3510	181,5	22500,0	1184,1	99,9	181,1	8,6	19,0
C.Box A	15000,0	49350,0	20830,0	8,3	1250,0	6,1	2,4
C.Box B	15000,0	67040,0	40000,0	16,0	2400,0	7,4	1,7
C.Box C	15000,0	50010,0	25000,0	10,0	1500,0	5,8	2,0

However, the results have shown the excellent potential of the developed device. Subsequently, a very simple design has been proposed. The latter is just a hypothesis aiming at verifying if the hedgehog absorber can respect the energetic specs of a crash box.

Despite all the tests done so far, before switching from the applied research to a precompetitive development, further tests are needed in order to increase the level of confidence with the hedgehog absorber behavior. If the results obtained in this research work will be confirmed for higher impact energies and for different layouts, fields such as the automotive or the military one could benefits from the use of the hedgehog absorber.



FAULT DIAGNOSIS OF THE RUNNING GEAR IN HIGH SPEED RAILWAY VEHICLES

Livio Gasparetto - Supervisor: Prof. Stefano Bruni

Evolution in high-speed rail transportation is aimed towards increased efficiency and optimisation, to reduce life cycle cost (LCC) of rolling stock, while maintaining high standards of reliability, availability, maintainability and safety (RAMS). To his end, traditional maintenance strategies, based on pre-determined travelled time or distance intervals, are not sufficient anymore, and focus is moving towards modern techniques of condition monitoring for the components, to achieve the so-called Condition Based Maintenance (CBM), in which critical wear or fault of components is estabilished by analysing data generated during the normal service of the vehicle using fault detection and isolation (FDI) methods. The objective is to perform maintenance only when needed, thus reducing costs of component fixing or substitution on one hand, and off-service of the vehicle on the other. Examination of State of Art in the field shows a large variety of approaches to the problem. Some methods make use of wayside mounted sensors to examine the rolling stock while it transits in certain spots on the rail network. The advantage is that an entire fleet can be monitored while in service with few sensors, but only a limited range of faults (e.g. out of

roundness wheels, hot boxes) can be detected by wayside monitoring units, whereas for other fault types the diagnosis would not be reliable and/ or accurate enough to allow resolving the kind, location and degree of severity of the fault. Other methods make use of on-board measurements, generally by accelerometers or gyroscopes, and can be divided in two categories: datadriven and model-based. Data driven techniques use several algorithms to analyse data to produce significant indexes tied to faults or malfunctioning of various components. These indexes are then compared to addressable ranges that may be defined, e.g. based on a statistical treatment of available fault records, to achieve fault detection and, less frequently, fault isolation. In model-based methods instead, measurements are used in combination with a mathematical model of the system to generate a residual, and the FDI process is then based on the examination of the residual function. Results are encouraging, but faults isolation is generally difficult, and few or no results with application measurements performed on rail vehicles have been presented. Other model-based methods use more complicated filters to assess the estimation of the proper value of some parameter

important for the vehicle dynamics (damping, stiffness, or wheel conicity). These methods show generally good performance at the price of some degree of complexity. In this thesis two methods for the condition monitoring are presented. One model-free (data-driven) and one modelbased. Both of them consider a railway bogie in the horizontal plane and have the aim to assess the condition of the wheel-rail profile and of the secondary dampers, particularly the antivaw damper. The aim of the model-free method is to detect the incipient instability of the bogie well in advance of the traditional instability detectors, when oscillations have not reached critical amplitudes. The method is based on the combined use of the random decrement technique (RDT) to approximate the auto-correlation of the acceleration signal of the lateral bogie frame, and of the Prony method to identify the characteristic exponents of the system for the RDT output. The output of this analysis is the estimate of the (possible) haunting motion frequency and the residual stability margin. These results are in turn analysed by a fault classifier that, using an addressable database of possible component status combinations, determines the most probable

condition. For this work, the database was built using a multi- purposes. A multi-body model body model of the high-speed trailed ETR 500 class car and included various wheel profile conditions and different levels of degradation of the vaw damper. The proposed model-based method identifies the values of some parameters fundamental for the lateral and yaw motion of the bogie, using a multistep approach based on the linear Kalman Filter and on the Extended Kalman Filter. To this end, a simplified dynamic model of the bogie has been developed, that reproduces also the lateral track irregularity dynamics affecting the two wheelsets. Such irregularity is estimated in one step, and then given as an input to the following step, that estimates three important parameters: lateral damping of the bogie, yaw damping of the bogie and wheel-rail conicity, used as a linearization of the relationship between the rolling radius variation and the wheel-rail relative displacement in lateral direction. Both the methods have been tested with data collected by a prototype CBM system that was installed on board of an ETR 500 class high-speed train called ETR 500-Y1, owned by RFI (the company managing most part of the Italian rail infrastructure),

which is used for track

maintenance and experimental of one single car of the same train was used to simulate faults and conditions that could not be introduced on the real train. The model-free method has been applied on ETR 500-Y1 experimental data, and it was able to distinguish the cases of a bogie with new profile from the case of a bogie with worn profiles. Next steps for this research include an improvement of the database used for fault detection, using data measured during line tests, the inclusion in the method of other fault types and the extension of the method including new indexes other than frequency and residual stability margin such as the modal shape, by using both the lateral accelerometers mounted on the bogie. The same method could also be applied to the vertical dynamics of the bogie, to assess condition monitoring of primary and secondary vertical suspension components. The model-based method was tested by means of virtual and in-line measurements. While line test measurements were possible only for the vehicle running in a condition presumably close to nominal, virtual measurements, performed using multi-body simulations, allowed the application of the method to data generated with components in both faulty

and nominal conditions. The results of the tests performed on virtual and real data show unambiguous detection of the proper condition for the yaw damper and for the wheel conicity. On the other hand, estimation of the lateral damper coefficient does not allow the detection of a fault for this component. Next steps for the model-based method are the test of valid alternatives to the Extended Kalman Filter and the application of the method to the vertical dynamics of the vehicle.

PROFILE MONITORING OF MULTI-STREAM SENSOR DATA

Marco Luigi Giuseppe Grasso - Supervisor: Prof. Bianca Maria Colosimo

Tutor: Prof. Paolo Pennacchi

In the framework of industrial quality management, traditional Statistical Process Control (SPC) procedures depend on quality characteristics measured on the product of manufacturing processes. They also assume that a number of parts may be collected during In-Control (IC) operations to estimate the process parameters and to design the control charts. Nevertheless, the evolving market demands and the development of novel technologies have been leading to productive scenarios where traditional SPC methods are no more appropriate or even not applicable.

In different discrete-part manufacturing applications (e.g., in the aerospace sector), the production of high-value-added products implies extended machining times (e.g., several hours for a single part, possibly longer than the tool life). It also involves expensive tools and materials, together with high precision requirements. The use of traditional SPC procedures, based on postprocess measurements, implies a delay between the possible occurrence of a fault and the detection of its effects on the product. This yields unacceptable costs for wasting expensive materials and time-consuming re-manufacturing operations. In addition, high customization

requirements in various sectors impose small lot productions or even one-of-a-kind productions (i.e., the production of lots that consist of a single item). In that case, there is no possibility to perform a control chart design phase based on repeated processes, and hence novel quality control procedures must be considered.

A viable solution consists of sensorizing the machine tools and the production systems in order to collect data about the quality and stability of the process during the process itself. This is possible thanks to the continuous technological developments that are leading to data-rich industrial environments, where several sources of potentially useful information are easily available. The result is a paradigm-shift from product-based SPC to in-process SPC.

A quality monitoring based on in-process data may provide a faster reaction to out-of-control shifts, thanks to conditionbased control strategies aimed at quickly mitigating (or even suppressing) the effects of faults, with a consequent reduction of wasted parts. Furthermore, in-process SPC provides a potential 100% production coverage as it allows collecting data during each process run, instead of evaluating the quality characteristics on sampled products at the end of the process.

However, such a paradigm shift implies a number of novel challenges and critical issues with respect to the



1 – A paradigm shift in SPC: from product-based to signal-based monitoring

traditional SPC practice, because of the high sampling frequencies of sensor signals, the computational constraints, the complexity of the signal patterns, the time-varying properties of industrial processes, the streams of data from different sources, and the multiplicity of operating conditions. Those challenges and critical issues push the need to develop novel SPC approaches and to improve the existing ones.

This thesis is aimed at studying and developing novel signalbased SPC methods in order to deal with those challenges. A particular family of industrial processes in considered, i.e., the family of discrete-part manufacturing operations that exhibit a cyclical behaviour. In that case, the IC state of the process can be described by cyclically repeating patterns of acquired signals, known as "profiles". Therefore, this study deals with the use of profile monitoring methods for inprocess sensor signals. Different inter-related research problems are discussed and faced. In the first part of the study, the focus is on signals from a single sensor that exhibit complicated patterns or undesired misalignments. In this frame, the two following problems were faced: (i) the integration of registration information in a profile monitoring framework, to guarantee a proper management of different signal variability sources; (ii) the enhancement of profile monitoring performances in the presence of complicated signal patterns characterized by information contributions on

different time-frequency scales. The analysis is then extended to signals coming from multiple sensors, which must be properly integrated and fused together in order to achieve a better and more synthetic representation of the on-going process.



2. Ultra High Pressure (UHP) pump of a waterjet plant (top panel) and multistream signals from water pressure and plunger displacement sensors (bottom panel)

In the last part of the study, the analysis is focused on the development of profile monitoring methods for processes that exhibit multiple IC states, which represents a challenging violation of traditional SPC assumptions. This analysis if motivated by the fact that, in different manufacturing applications, parts of the same quality can be produced by processes can not be characterized by a unique IC state. The existence of multiple IC states is due to operating modes that vary in time (e.g., different cutting parameters, different tools, different ambient conditions, etc.), and hence novel profile monitoring methods are required. All the proposed approaches are driven by actual industrial

challenges and designed for in-process utilization. They were tested by means of Monte Carlo simulations and compared with benchmark techniques. Real data from different industrial case studies, including waterjet cutting, grinding of cylindrical rolls and end-milling processes, were used to demonstrate the performances of the proposed methods in actual industrial scenarios.



PhD Yearbook | 2015

SMART TYRE DATA: IDENTIFICATION OF RELEVANT PARAMETERS FOR VEHICLE HANDLING **IMPROVEMENT**

Davide Ivone - Supervisors: Prof. Stefano Melzi, Prof. Federico Cheli

Research context

The introduction of modern digital electronics in the automotive industry has increased the integration of intelligent systems in the vehicle design. The availability of new technologies is pushing the automotive sector to constantly invest in developing new innovative solutions aimed to improve the vehicle efficiency in terms of safety and performances.

Tyres play fundamental key when characterizing the vehicle dynamics since they constitute the only parts of the vehicle which maintain contact with the road. One of the most challenging and innovative aspect of the automotive sector is to use the tyre as a sensor able to identify useful information as it is located in a very privileged position. The emerging concept of smart tyre basically describes a tyre equipped with sensors and digital-computing systems for monitoring thermal and mechanical parameters which are eventually extended to the vehicle electronic control unit while driving.

Pirelli Tyre is pushing technology for sensors embedded in the tyre inner liner able to focus on vehicle dynamics and security devices. The Cyber[™]Tyre project developed by Pirelli Tyre has the main purpose to make the tyre an active part of the vehicle by

installing a suitable number of sensors capable to collect useful information from the interaction between tyre and road. The innovative measurement system is based on a single three-axial accelerometer installed inside a rubber support and then glued onto the inner liner of the tyre as Figure shows. This device is able to transmits the acquired signals via wireless to a suitable receiving system.

Cvber[™]Tvre for active vehicle control systems

Since tyre forces estimation is a decisive and challenging feature in the automotive sector, a strategic Cyber[™]Tyre objective is the fulfillment of this tyre-road friction coefficient

aspect by directly measure the tyre-road contact forces. The accelerometer signals, collected during the tyre rolling motion, include information about the tyre-road contact as they are strongly correlated to the macrodeformation of the tyre inner liner which is directly generated by the contact forces and slips quantities. To assess the benefits induced by the smart tyre, tyre-road contact forces measurement are included

into an extended kalman filter which are added to the ones usually present on-board vehicle as the steering angle, lateral and longitudinal acceleration and yaw rate. In particular, more precise and prompt



1. Cyber™Tyre sensors glued onto the tyre inner liner

and consequently vehicle side-slip angle estimations are appreciable if results are compared with a standard case where information from the smart tyre are not available. Moreover, robustness analysis performed by introducing the road bank angle and by changing some tyre and vehicle parameters shows how accuracy of the estimated quantities is maintained. Manoeuvre simulations of a validated vehicle model have been run in Matlab[®]/Simulink[®].

Another important developed argument is the introduction of new relevant parameters in order to maximize the tyre cornering performances by studying the tyre contact patch dynamics behavior by means of Cyber[™]Tyre. Particular attention is given to the tyre inclination angle (IA) which has significant influence on tyre lateral forces especially in lateral limit conditions. Indoor testing had a strategic role for the topic development since it allowed to approach the problem in controlled dynamics conditions as well as finite element analysis (FEA) gave very helpful support for the phenomena comprehension. The and furthermore the power introduction of a different signal filtering method is a crucial aspect of the treated argument: both time and frequency domain are considered for the data elaboration and features extraction. Eventually, a new index (CPI) of tyre contact patch exploitation is defined and based on numerical model of the tyre portion in contact with the road able to describe the normal stresses distribution in the contact patch domain.

The Cyber[™]Tyre capabilities to characterized the normal stresses distribution have been compared with an optical measurement system for tyre footprint stress field: results are in very good agreement between the two measuring methods. The CPI index is a synthetic parameter which defines how far the tyre is from the maximum tyre cornering condition. Results of the proposed exploitation index are presented in a series of sweep of inclination angle and vehicle manoeuvre simulations both performed with the Flat-Trac[®] machine from MTS[®]. Figure depicts the CPI trend in function of IA at imposed inflating pressure (P), vertical load (Fz) and tyre slip angle (SA): moving towards negative IA, lateral force increase while the index is minimized and it tends to the same value for all testing conditions. Figure shows a step steer manoeuvre run at different IA but same entity of lateral force: in this situation the maximum cornering condition is identified by the SA which has to be minimized and this trend is well described by CPI. In fact, lower values of SA, on equal terms, allow to have a margin for applying higher lateral force dissipation due to lateral slip is reduced.

Conclusion

A first step towards the correlation of the tyre contact patch exploitation from the Cyber[™]Tyre point of view is presented in this research activity. Next steps are aimed to make the CPI more robust and reliable: in many studied cases the index seems to identify the best tyre configuration for the

cornering performances. Once CPI is trustworthy, it might be used as reference for control logics for active suspensions: the IA is real-time actuated so that tyre cornering performances are improved. Nevertheless, an intermediate development step could be considered: realization of an hardware in the loop with the Flat-Trac[®] machine and Cyber[™]Tyre in order to experiment the active control logics based on CPI.



2. CPI trend for a sweep IA test



3. CPI trend for a step steer manoeuvre at different level of IA

PhD Yearbook | 2015

A METHODOLOGY TO SUPPORT THE MODELING AND DESIGN OF MATERIAL SEPARATION SYSTEMS FOR RECYCLING

Ali Jadidi - Supervisor: Prof. Marcello Colledani

During the recent years due to the significant technological innovations, the production of electric and electronic equipment (EEE) has been marked as the fastest growing area in industrialized countries. This results in an increased amount of waste electric and electronic equipment (WEEE). In EU countries WEEE is the fastest growing waste stream having an annual growth rate of 3% to 5%.WEEE are considered critical waste streams due to their hazardous materials contents. Therefore in case of a non-proper waste treatment, they can generate negative environmental impacts. The need for treating end-of-life products is also highlighted in other sectors such as automotive Smart mechanical treatments, industry. It is estimated that over 15000000 vehicles retired per year in the USA and 15-25% of their total weight is landfilled. Taking into account the potential environmental impacts of the waste disposal many countries have set up new regulations and legislations in terms of end-oflife management and in order to improve the recycling process and reduce the waste disposal. Waste treatment is an important issue not only in terms of environmental concerns but also from the recovery aspect of valuable materials. In fact WEEE and end-of-life vehicles (ELV) are mixture of various materials

that potentially can be seen as a resource of metals, such as copper, aluminum and gold. Due to the complex and variable material mixture of WEEE and ELV, their material recovery is a very challenging task that has not been solved yet. For instance talking about the PCBs that are widely used in electronic products, currently only about 30-35% of metals represents in the PCBs are recovered with purity level varying between 85% to 95% depending on the

element.

Indeed efficient treatment of these complex mixtures requires automated multi-stage systems composed of different size reduction and material separation stages. In this regard, that are considered in this work. are ideal techniques for recovery of materials in WEEE and ELV since they involve very limited environmental impacts, energy consumption and production of by-products. Mechanical separation systems use different material properties such as conductivity, size and density for treating the input mixtures. In spite of the extensive research works dedicated to analysis of different material separation and comminution technologies, design and performance evaluation of these systems have been rarely studied from system engineering pint of view.

In M. Colledani and T. Tolio (2013) a multi-level framework that is illustrated here is introduced for integrated modeling of the material separation systems considering the interaction among process and system levels. Indeed in mechanical separation systems there is a strong interaction between process and system levels.

In the proposed model, in the system layer the dynamics of the material flow in the recycling system is considered. This layer considers in input from the process layer transformation matrices that are required for analysis of material flow. In the process layer the physics of the process is used in order to predict the transformation matrix based on the updated estimate of the material flow dynamics calculated in the system layer. The interaction between two layers is captured through parameter exchange between two layers. Although the proposed multilevel model is useful in capturing the process-system interaction, following relevant aspects are neglected. Uncertain separation matrixes The quality of the separation

processes that can be determined by the separation matrixes is not constant and can be affected by particleparticle interactions. The real

experiments that are reported in this work confirm that the quality of the separation process may be degraded by increasing the material flow rate as it can increase this kind of interactions.

· Effect of the material reprocessing

In material separation systems it is common to re-process the materials in order to improve the output quality or increase the amount of the recovered materials. In spite of the importance of the material re-processing, this aspect is not included in this model. In this work a multi-level approach is taken considering these aspects and other system logistics issues such as machine breakdowns, machine processing rates, starvation and blocking propagation, and role of conveyors as finite buffers. Therefore, a comprehensive model is developed that is capable of predicting the performance and support the design of the separation systems used in recycling. Material flow rate is considered as a system level parameter than can affect the separation quality. Indeed, on the one hand at process level the separation quality and the size-reduction efficiency is degraded with increasing flow rates. Therefore the material flow rate which is a system level parameter can affect the process level

performance. On the other hand, the separation quality at process level affects the material routing in the system. The decomposition method that breaks the system into the small sub-systems, composed of two machines and one buffer, is used in order to calculate the system performance. Moreover a methodology that is called "linearization" is introduced for quantitative analysis of the material re-processing. In this method the behavior of the reworking loop is approximated by a transfer line composed of desired number of machines. Developed methods are implemented in Matlab. The methods are validated by comparing the results with simulation models, under different system configurations. The results confirm that the precision of the proposed methods. Another important process in recycling systems is the

comminution process for shredding the input particles. Comminution processes directly affect the material routing and the efficiency of the downstream separation processes. In this work different experiments on comminution process are performed to help providing a better insight to different aspects of these processes. The assumptions of the model and some of the key

results are validated by the experimental analyses performed at the ITIA-CNR laboratory for demanfuacturing, within the cell 3 on recycling technologies and systems.

The assumption related to the effect of the flow rate on separation quality is validated thorough the corona electrostatic separation of a binary mixture composed of plastic and copper. The same process is also used for experimental validation of the linearization method. The experiments that are performed on CES process also confirm the importance of the material re-processing in material separation systems. It also proves the criticality of choosing the right set of process parameters for material reprocessing.

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MECHANICAL ENGINEERING

EXPERIMENTAL METHODS FOR THE ASSESSMENT OF STRUCTURAL INTEGRITY OF COMPOSITE BONDED JOINTS

Md Kharshiduzzaman - Supervisor: Prof. Andrea Bernasconi

In-situ structural health monitoring methodology provides continuous monitoring of technical structures, helps to optimize the use of the structure and minimize downtime. This PhD work introduced an in-situ monitoring technique based on backface strain field which is capable of evaluating the structural integrity of adhesively bonded joints and also enables monitoring of crack propagation under fatigue loading. The concept of monitoring method for single lap (SL) joints is based on a known relationship between the crack position and position of the negative minimum of backface strain (BFS) profile, usually found by finite element analyses. For an Aluminum-Carbon fibre reinforced polymer it was found that the corresponding backface position of the negative minimum strain value of BFS strain profile along Al substrate follows the crack tip with an offset of approximately 2 mm. By means of this correlation, it was possible to detect the presence of crack in static tests and this allowed for real-time monitoring the crack propagation in the bonded joint during fatigue test. After the specimen had undergone 150,000 fatigue cycles, the crack length from the monitoring technique was noted and compared with measurements

obtained by optical microscope which verified the crack position monitored by this technique. In the first place, an array of electrical strain gages was used for acquiring BFS profile. An identical framework was also adopted and tested experimentally by replacing the electrical resistance strain gages with FBG sensors which confirms the applicability of the monitoring system with FBG optical sensors. It was also observed that, the use of an array of FBG sensors produced more accurate results compared to electrical strain gages. This is because of their multiplexing capability which enables to insert all the FBG sensors within a single optical fibre. Hence it was possible to place all the sensors along the centerline of

the backface of Al substrates of the SL joint and therefore minimizing the effect of any possible misalignment. With the goal to apply this BFS based technique using FBGs to bonded joints made of more complex materials such as woven composites, the assessment of strain sensing using FBG sensors onto the backface of such material were performed where strain field is not uniform and local strain gradients exist. We adopted T-matrix method coupled with DIC technique in our study. DIC technique was used to capture the strain field in woven composite and that strain field was used to simulate the FBG response for a given gauge length. It was seen from T-matrix



1. BFS based monitoring technique using an array of strain gages.



2. BFS based monitoring technique using an array of FBG sensors.

simulations that, spectral response of 10 mm FBGs does not perform well in high strain gradient fields. This is because they fail to produce distinguishable single peak which is mandatory for strain estimation. Whereas 4 mm FBG sensor seemed to retain the main characteristic needed for strain measurement. Even though small chirping effect was still present in this case, however it was not as dominant as of 10 mm case, which caused Moreover, experimental results the peak to split. Finally, for 1 mm FBG sensor, it is seen that reflected spectra produce a distinctive peak which is vital for strain estimation. Besides the chirping effect is completely eliminated in this case thus making this configuration very much suitable for high strain gradient applications such as in woven composites.

In order to confirm our observations, experimental tests were carried out for woven composite strips using FBG sensors for all three gauge lengths. For 10 mm FBG sensors, it was seen that the experimental results does not match well with simulated results as suspected. For both 4 mm and 1 mm FBG sensors, good agreements were found between experimental and T-matrix simulated observations. confirm that, strains read by both type of sensors are close to the averaged strain of the strain field over their corresponding gauge lengths. Although peak splitting phenomenon was eliminated for smaller FBG gauge lengths, but due to their small size, they sense rather local strain values

which were confirmed while

comparing with global nominal results. This problem can be overcome by using an array of FBG sensors keeping the intermediate distance between the sensors as small as possible. Difficulty remains as the exact position of the sensor within the optical fibre is still a concern. Also local strain values produces by smaller FBGs can differ from global values obtained by continuum mechanics. In order to eliminate all these concerns, in the last past of this thesis, distributed optical sensing using optical backscatter reflectometer (OBR) was adopted. BFS profiles for CFRP-CFRP SL joint were experimentally obtained using this technique and compared with FE analyses. As OBR interrogates thousands of sensing locations along a single optical fiber simultaneously and thus transforming an ordinary optical fiber into a high spatialresolution distributed strain sensor, it was seen that this method can capture BFS strain profile with higher accuracy. Comparison with FE analyzed results confirmed. Finally, the FE model was validated by comparing with 2D DIC experimental results.

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MECHANICAL ENGINEERING

COLD SPRAY COATING: PROCESS EVALUATION AND WEALTH OF APPLICATIONS; FROM STRUCTURAL **REPAIR TO BIOENGINEERING**

Atieh Moridi - Supervisor: Prof. Mario Guagliano

Cold spray is a promising technology to obtain surface coatings. Development of new material systems covering a wide range of required functionalities, from internal combustion engines to biotechnology. brought forth new opportunities to the cold spraying. This thesis goal can be divided into two main categories:

The first is understanding the fundamental features of the cold experimental observation, a spray. In this regard, the focus was on two issues: assessment of critical and erosion velocities and also the mechanical behavior of cold spray coating under indentation loading. In cold spray, bonding is obtained when the impact velocity of particles exceeds critical velocity, but it is less than an upper limit beyond which erosion happens. A new model is proposed, combination of numerical and analytical solutions, to calculate the critical and erosion velocities. This model was based on energy approach. However, different phenomena have been proposed as the indicator of adhesion and coating build up. What most approaches agreed upon is that a material jet is formed during high velocity impact. However, excessive deformation of elements in the material jet makes it extremely mesh dependent in simulation. To this end, Eulerian framework is used in which elements are fixed

and material can flow (Figure 1--.a). Variation of temperature and plastic strain as well as jet formation and instability are presented.

Mechanical behavior of consolidated coating under indentation loading conditions is also explored. Cold sprav deposited coatings show strong dependency on the indentation size scale. To interpret the damage based finite element model consisting particle interior and particle boundaries was developed (Figure 1.b). This phase of the thesis was accomplished with two comprehensive reviews (Figure 2). First on different material systems that have been cold sprayed. This includes metallic, ceramic, metal matrix composite, polymer and nano structured powders. The second

review is on cold spray to mitigate corrosion. The effect of deposition temperature and pressure, particle size, carrier gas, post-treatment and co-deposition of metals and ceramic particles on corrosion behavior is discussed. The second goal is investigating the application of cold spray on repairing damaged parts and biomedical engineering. There has been some efforts in repairing structural parts using cold spray. Most of the time only visual inspection has been performed since simulating real loading conditions are not possible. In the present investigation, a systematic study of defect shape and ability of cold spray to fill it is done (Figure 3.a). Furthermore, repaired part must retain bulk material properties. Fatigue represents one of the most intricate



1. Von Mises stress distribution a) impact simulation of single particle using Eulerian framework b) Consolidated cold spray coating under indentation loading and progressive damage at interparticles.

types of damage to which structural parts are subjected in service. The effect of cold spray deposition on fatigue life of Al alloy is studied and 15% improvement was achieved. The enhancement of fatique life by means of shot peening is also considered. It was found that conventional shot peening (SP) and severe shot peening (SSP) are more efficient if they are performed prior to cold spray deposition. SSP+CS (best combination) increased the fatique strength up to 26% in comparison to as received condition.

For biomedical application, guidelines are proposed for deposition of porous coatings. The porous-coated implant can be stabilized by biological fixation as a result of bone ingrowth. Experiments were carried out at 'under-critical' impact conditions, using rather coarse powders and fast gun traverse speeds. Thick, macro rough, sufficiently high strength coatings, suitable for implant applications, with porosity of up to about 30% was successfully deposited using marginally low impact conditions (Figure 3.b).



2. Critical reviews on a) cold spray material system and b) important parameters on corrosion behavior of cold spray coating



3. Applications of cold spray coating a) Studying ability of cold spray in cavity filling for repair applications, b) Under critical cold spray deposition to obtain porous coating for biomedical application.

DESIGN OF A 6-DOF FLOATING MOTION SIMULATOR FOR HARDWARE-IN-THE-LOOP WIND TUNNEL **TESTS ON NAUTICAL COMPONENTS**

was performed with genetic

Navid Negahbani - Supervisor: Hermes Giberti

In recent years the development of CFD simulations has increased the knowledge of the problems of fluid-structure interaction. This trend has been particularly important for floating body research fields such as offshore wind turbines and sailboats. involving two fluids. Moreover, the reliability of CFD software requires further experimental validations. To reach t, as a complementary approach to that of the test tank, there is the need to perform dynamic aeroelastic tests in the wind tunnel.

project of a parallel kinematic machine that emulates the fluid-structure interaction: the architecture of the machine has been chosen according to the specifications and behavior of the sail boats and offshore wind turbine in floating situation of sea; kinetostatic optimization

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1. 3-D view of Hexaglide

algorithms in MATLAB environment: the dimensioning of the motor-reducer was conducted downstream of a dynamic simulation of the motion in Simulink, whereas the operating conditions are more severe: ADAMS MSc software small movement. Parallel Kinematic Machines (PKMs) are commonly used for tasks that require high precision and high stiffness. In this sense, the rigidity of the drive system of the robot, which is composed In this thesis has been addressed by actuators and transmissions, plays a fundamental role. In this thesis, ball-screw drive and belt drive actuators are considered and a 6 Degrees of Freedom (DoF) parallel robot with prismatic actuated joints is used as application case. A

mathematical model of the

ball-screw drive and belt drive

most influencing non-linearities: sliding-dependent flexibility. backlash, and friction. Using this model, the most critical poses of the robot with respect to the kinematic mapping of the error from the joint- to the task-space are systematically investigated to was used for vibration analysis in obtain the workspace positional and rotational resolution, apart from control issues. The error sensitivity analysis will do with respect to the most influencing non-linearities parameters. Finally, a non-linear adaptive robust control algorithm for trajectory tracking, based on the minimization of the tracking error, is described and simulated. The dynamic parameters are learned during the motion and introduced in the inverse dynamic model of the robot. which is used as a feed-forward compensator. Optimal geometrical parameters of robots were found considering kinetostatic performance index. Drivers and motor-reducer was chosen for the robot by considering the efficiency of the reducer. The robots were considered flexible and first natural frequency of the

are proposed considering the

robot were calculated. Actuators were analyzed for dynamic problems considering nonlinear parameters such as flexibility, backlash and friction and error evaluation of the robot. Selected robot was controlled for

tracking the complex trajectory with considering nonlinear parameters.

Taking everything into consideration, Hexaglide (figure 1) was chosen for using in the wind tunnel as a sea simulator. because it can be covered the desired workspace with different ioint motion ranges. Also, it is more rigid than the Hexaslide and Hexaglide that can satisfy all limitations of the commercial linear transmission. Ball-screw drive was the best selection as a Hexaglide linear actuators (figure 2), but it depends the required accuracy of the wind turbine researcher. If belt drive satisfy their accuracy, they can use the belt drive because it is cheapest linear transmission.

The presented control method can control the robot precisely. The PID adaptive-robust control has lowest error and consequently the precision is best among the other applied control methods (figure 3).



screw-driven unit.





A METHOD FOR FORECASTING DESIGN REQUIREMENTS BASED ON EXPERTS' KNOWLEDGE AND LOGISTIC GROWTH CURVE.

Christopher Nikulin - Supervisor: Gaetano Cascini

The rate of technological innovation increased considerably in the last years. This situation forced companies to quickly adapt their organization, processes and products to better answer the emerging demands from the society. In such a continuous fight to survive, companies need to anticipate the main features of future products and related manufacturing processes as essential mechanisms to keep their market position, competitiveness, and moreover to support the innovation process.

In this dynamic scenario, the constant evolution of products and processes create emerging and non-obvious problems challenging those who conceptualize, develop and implement the new solutions, known as design engineers. In this scenario, a relevant research goal in the engineering design domain is the definition and identification of suitable methods and tools to anticipate main features of products and processes, which have to be capable of driving, with more efficiency, the design process and also support decision makers about technological choice. This mentioned need is pushing design engineers for methods, models, and tools to better answer emerging demands and changes by

(TF) methods. In this scenario, understanding which forecasting methods,

exploring Technology Forecasting

techniques and tools can be suitably introduced in general design process emerged as a research opportunity in the design domain. In specific, this PhD thesis attempts at shed light on the forecasting methods suitable to be used and adopted by design engineers, by taking into account their skills, knowledge and background.

Research method and contribution

The first contribution of this research concerns the formalization of knowledge among different domains. The major contribution of the present research, in turn, consists in the consequent introduction of a method for forecasting design requirements usable by design engineers without previous experience in forecasting. The research proposal has been structured in the following tasks: i) Formalization of the semantics of the requirements. This allows keeping a structured and systematic description of the requirements during the elicitation process, simplifying the transfer of knowledge; ii) Formalization of forecasting methods compatible with design engineers' knowledge.

This approach offers a frame useful to synthesize and create recommendations for design engineers bringing the knowledge from forecasting experts to the design users; iii) Proposal of a method for forecasting design requirements capable to support design engineers to anticipate information about design requirements. The latter is the main contribution of this research. It should be intended as a contribution to the design theory and practice to generate solutions that are capable of having a more resilient response to product changes, but can be useful also to drive R&D strategies and related investments. The proposed process is organized according to the core elements of a forecasting method, as proposed by Martino (1993), to keep a more structured and systematic approach to develop a forecasting analysis. Specifically, this contribution focuses on three main aspects: identification of relevant requirements; identification among the requirements of the variables possibly behaving according to a logistic model; logistic growth analysis. The proposed method for identifying requirements suitable

identifying requirements suitable for representing the evolution of the technical system under study consists of seven sequential steps; requirements can be both quantitative and qualitative.



1. Management of knowledge for design requirements in the framework of the system operator. Circled numbers refer to the steps of the procedure of the method, and arrows represent the logical flow from one screen to the other.

The achievements of the research activities have been subdivided into three different criteria: i) Theoretical structural validity (Pedersen et al., 2000): i) Empirical performance validity (Pedersen et al., 2000): iii) Capability of the method to guide the design engineers without experience in forecasting.

Results and conclusions

The proposed objectives and goals of this research have been achieved by using different approaches. First of all, "theoretical structural validity" has been achieved by the individuation of a set of techniques from the forecasting research field in order to properly carry out the regression analysis to support the early design phases. Several contributions were developed as a theoretical framework for the organization of design requirements i.e. Element-

Name-Value logic was used to describe requirements with time perspective and formalization of knowledge for the application of logistic growth curve. Moreover, test with students allowed validating the suitability of the adopted models in this research. Regarding the empirical performance validity, case studies were developed in two different industrial contexts as white good in the context of the FORMAT-project and mining industry in the context of Cluster Mining-project. Industrial partners recognized the usefulness of the approach in producing results that clarify the directions of development for their product and process. For what concerns the FORMATproject, the method has been useful in order to support the overall methodology of the project at bringing new information about vacuum forming technologies. Moreover, the proposed method has brought positive amendments to the overall FORMATmethodology, mainly for what concerns the analysis of information, known as stage-A. For what concerns to the Cluster Mining-project, the method has been useful to clarify directions of R&D about mining mill. Regarding the ability of the method to guide design engineers without experience in forecasting, the control group test has been useful to validate the method steps. The method steps allowed gaining new insights and conclusions about the product of which

testers were not aware before.

Moreover, the group working

bring better results than those

freely working. Remarkably,

with the method was capable to

the testers with the method exploited in a better way the data available in order to drive conclusions for product (i.e. washing machine). In terms of repeatability, the testers with the method have demonstrated to be capable to follow all the steps without the presence of a facilitator. The results of the NASA task load index showed that the method does not require so much workload demand, and consequently it can be used and adopted by design engineers without a deep forecasting expertise (as the testers were).

Finally, the author did not have the opportunity to explore the benefits of the method application in the overall design process, starting from elicitation of requirements until the final design proposal. Nevertheless, given the overmentioned results, the author considers that the method can be embedded in any Product Development Process or used as a complementary analysis as demonstrated during the different case studies along this research. Noteworthy, the method is able to support different users with lacks of knowledge in statistics (i.e. not only design engineers).

DATA FUSION FOR PROCESS OPTIMIZATION AND SURFACE RECONSTRUCTION

Luca Pagani - Supervisor: Bianca Maria Colosimo

Last years are characterized by the impact of global trends and manufacturing technology is faced with a number of different challenges. The topics of customized products, reduced life time, increased product complexity and global competition have become essential in production today. The changing in modern manufacturing towards a customized productions is characterized by high-variety and high-quality products, a paradigm shift in metrology is coming on.

Information that concerning the state of the products and production processes is obtained with the aid of metrology. Due to this paradigm shift, the complexity and accuracy of the product requirements are increasing.

At the same time, smart sensorization of equipment and processes is providing new opportunities, which have to be appropriately managed. A large amount of data can be available to aid production and inspection and appropriate methods to process the "big data"' have to be designed.

In this scenario, multisensor data fusion methods can be employed to achieve both holistic geometrical measurement information and improved reliability or reduced uncertainty of measurement

data to an increasing extent. The main purpose of this thesis is to explore new approaches for reconstructing a surface starting from different sources of information, which have to be appropriately fused. Surface is meant in a broad sense, both as the geometric pattern of a physical object to be inspected and as the surface representing a response function to be optimized.

The first part of the thesis focuses on the reconstruction of the surface geometry via data fusion. In this case, it is assumed that multiple sensors are acquiring the same surface, providing different levels of data density and/or accuracy/ precision. The thesis starts exploring the performance of a two-stage method, where Gaussian Processes (also known as kriging) are appropriately used focuses on using data fusion as modeling tool to combine the information provided by two sensors. Figure 1 shows the reconstructed surface, with the error map, using only one sensor are fused to reconstruct the (Lo-Fi and Hi-Fi models) and properly combining the available information (Fusion model). Then, the thesis faces the problem of suggesting a data fusion method when large point clouds, i.e., "big data" (as the ones commonly provided by non-contact measurement systems) have to be managed. In this case, the use of

Gaussian Processes poses some computational challenges and this is why a different method based on multilevel B-spline is proposed.

As a second contribution, the thesis presents a novel method for data fusion, where the uncertainty of the specific measurement system acquiring data is appropriately included in the data fusion model to represent the uncertainty propagation. Eventually, the thesis faces the problem of using surface modeling to guickly detect possible out-of-control states of the machined surface. Starting from a real case study of lasertextured surface, an approach

to combine surface modeling with statistical quality control is proposed and evaluated. The second part of the thesis for process optimization. In this second application, data provided by computer simulations and real experiments response function of a process. In this case, the aim is to find the best setting of the process parameters to maximize the process performance. It is shown how data fusion can be effectively used in this context to reduce the experimental efforts.



1. Prediction of the surface with error map

MICROSTRUCTURAL EVOLUTION OF AUSTENITE DURING AND AFTER HOT DEFORMATION OF **STEELS**

Alessandro Angiolo Paggi - Relatore: Maurizio Vedani

In the last 50 years, economic and technical demands have forced the steel industry to develop innovative processes to supply the transportation, energy and construction market with high strength. high toughness and costeffective steels. This has led to the development of thermomechanical processes (TMP) able to refine the austenitic grains and the final microstructure after phase transformation through the control of rolling temperature of microalloyed steels. To design a TMP schedule it is necessary to have detailed models describing the recrystallization kinetics and the evolution of the size of recrystallized and unrecrystallized such as optical microscopy austenitic grains of steels during and between each deformation pass. Moreover these models, to be industrially effective, have to be coupled with Finite Element Modelling (FEM) for the rolling mill design. Up to now, only empirical models have proved to give satisfactory results, but these rely on a huge quantity of

parameters that have to be

methodologies usually give

calibrated by ad-hoc laboratory

tests. Unfortunately different

tests and different test analysis

different calibration parameters

for the same phenomenon and

therefore different FEM results.

Therefore, the aim of this work has been to gain an effective knowledge of the metallurgical mechanisms at the basis of steel microstructural evolution during hot rolling and to compare their hot characterization methods, in order to identify the most accurate ones to be used together with FEM. Since the approach adopted in this research work is mostly methodological, to simplify the comparison of testing methods, an AISI 304L austenitic stainless steel has been studied in torsion and compression at temperatures between 900 °C and 1200 °C and strain rates from 0.001 s-1 to 10 s-1. The recrystallization kinetics has been studied using direct methods, and Electron Back-Scattered Diffraction (EBSD) and indirect ones, such as double hit and stress relaxation tests. The first part of this work has been devoted to a critical review of the wide literature on these metallurgical phenomena, focusing on recovery and recrystallization of steels. Despite the numerous publications, it is still lacking a detailed knowledge of nucleation mechanisms of recrystallized grains and a framework of differential equations describing the flow stress curves of a recrystallizing material. However, empirical

models supply to these deficiencies, organizing the metallurgical understandings in equations that can be used for steels microstructural evolution modelling. The main weakness of this approach is that the models calibration parameters are dependent on the laboratory testing methods. For example, researchers can decide to characterize the hot flow stress-strain behaviour of steels by torsion or by compression tests. Since, as shown in this work, the flow stress curves are different due to the different response of materials to these deformation modes and to the presence of friction in the compression tests, this kind of decisions have an impact on the constitutive parameters used to summarize the hot deformation behaviour of steels. Beside these issues, also the combination of experimental uncertainties and analysis methodologies have a significant influence on constitutive parameters. It was demonstrated, using a Monte Carlo method, that not all the techniques can be used with the same trustworthy. In particular, it has been found which method is the most robust against the propagation of experimental uncertainties and that the errors in the determination of the flow stress are the most important aspects to be minimized in the

equipment design. Also the assessment of the recrystallization kinetics can be performed in different ways. Direct methods, based on the observation of the evolution of microstructure, can give many details about nucleation and growth mechanism, but they are very time-consuming and not always applicable. Indirect methods, based on the study of the effect of recrystallization on mechanical properties, are faster, but they can give only an average information about the behaviour of the material. Concerning the microstructural evolution during deformation, the application of indirect methods, such as the differential analysis coupled to the Quelennec model, has permitted to calculate the flow stress curves for different combinations of temperature and strain rate with very good agreement with experimental results and to evaluate indirectly the recrystallization kinetics from by the deformation, has the flow stress curves shape itself. On the other hand, the recrystallizing microstructure has been characterized in terms of change in the diameter and shape of grains by optical microscopy. It was shown that nucleation occurs at triple junctions and serrated grain boundaries and after the formation of the first necklaced structure the grain growth limits

the final refinement. All these finding are in good agreement with literature and theoretical results. Finally, the comparison of dynamic recrystallization kinetics measured by direct and indirect methods has shown a reasonable agreement. Regarding the microstructural evolution after deformation, the comparison between indirect methods has confirmed that double hit test can measure slower recrystallization kinetics than those obtained by stress relaxation method. Direct observation by optical microscopy has shown that nucleation of new grains occurs at grain boundaries and triple junctions with a rate proportional to the strain applied. After an initial refinement, the microstructure coarsens and the final grain size is reduced proportionally to the nucleation rate. EBSD analysis, giving more details on substructures produced identified in the distribution of deformation inside grains the mechanism promoting and limiting the growth of new grains. The recrystallization kinetics measured by EBSD has shown to be more reliable than the one measured by optical microscopy and similar to the ones measured indirectly. The differences with double hit and stress relaxation tests have been

explained in terms of gradient of deformation inside compression samples.

According to the present work, the direct analysis is the most accurate way to study the high temperature microstructural evolution needed for the design of a TMP. but a complete characterization, taking into account different temperatures, strains and strain rates, grain sizes and chemical compositions, would require such a large investment in time and research efforts to be incompatible with industrial product development times and requirements. However, a careful indirect analysis of the changes in the high temperature mechanical response can give many information in a quicker time and can significantly reduce the metallographic campaign efforts.

DESIGN AND MOTION PLANNING OF MULTI-ROBOT ASSEMBLY CELLS FOR BODY-IN-WHITE SPOT **WELDING**

Stefania Pellegrinelli - Advisors: Prof. Tullio Tolio, Prof. Anath Fischer

The number of industrial robots worldwide is constantly increasing. According to the International Federation of Robotics, 160,000 new robot installations were sold in 2012. leading to the second highest level ever recorded for one year. The majority of these robot installations (about 40% of new installations in 2012) are related to the automotive sector and to multi-robot cells for body spot welding.

Multi-robot cells for spot welding cells are robotic cells in which several parts are assembled by spot welding (Fig. 1). They are characterized by different robots working at the same time on a single body that is handled by a transporter. The body is generally composed of two or more components that are blocked during the welding process by ad-hoc fixtures. The design of the multi-robot cell for spot welding relies on two main steps: cell design and off-line multi-robot motion planning. Given the fixture, the body and the welding points, cell design concerns the selection of the resources, such as robots and welding guns, and their displacement in the space cell while considering productivity, costs, flexibility and reconfigurability. Motion planning concerns the allocation of the welding points to the resources, i.e. a robot and its

welding gun, and the definition of a motion plan for each robot so that the body is correctly assembled, while coping with cycle time and avoiding collisions copes with the following topics: between the robot and the fixture or among robots. Currently, cell design and motion planning are sequential and completely manual activities, generally managed from different industrial functional units. Moreover, due to these activity subdivisions, several cycles are needed for obtaining a feasible final solution. However, each cycle causes delays and errors that could be avoided through better integration of these activities. The proposed approach aims at defining a methodology for optimizing the cell design while reducing time and error due to the lack of integration between the design and the motion planning. The idea is to exploit existing motion planning

techniques in order to define a new cell design approach that is highly integrated with motion planning. The research cell design, motion planning for single-robot cells, motion planning for multi-robot cells, collision detection and multiresolution simulation. The thesis proposes a 5-stage approach (Fig. 2) able to provide the cell design and the coordinated robot motion plan. Motion planning is based on an off-line decoupled motion planning techniques for high-dimensional spaces and articulated robots in order to grant applicability to multirobot cell for spot welding. The motion plan for each single robot is defined through existing techniques (Stage 1), whereas the coordination of the robot is based on a new developed model applied to articulated robots (Stage 2 and 3). The



1. Multi-robot cell for car body spot welding.

existing techniques employed in Stage 1 (probabilistic roadmap) have been modified in order to best adapt to the high complexity of the environment that characterizes multi-robot spot-welding cells. Several algorithms were developed exploiting the information coming from the technological process of the spot welding. The motion plan is based on the Open Robot Realistic Library that, representing the virtualization of the robot motion planner, catches the real robot behavior during trajectory generation. OBB hierarchical decomposition (Stage 5) is employed for collision checking and as a basis for multiresolution simulation. *Cell design* this methodology can provide is solved simultaneously to multi- useful support for robotic and robot motion planning in Stage 3. It copes with the selection of the best resources among a set of preselected resources according to a cost minimization criterion, the definition of the position of the resources in the systems (position/orientation of the robot and allocation of the welding guns to the robots) and the allocation of the welding points to the robots. The approach does not currently take into account the flexibility and reconfigurability of the system. The final provided solution is validated through simulation (Stage 4).

The approach was tested on

three ad-hoc cases and two industrial cases provided by the Italian company COMAU S.p.A. The three ad-hoc cases were successfully solved. The influence of the environment complexity on the single-robot motion planning and on the final solution was addressed through a detailed study of the first industrial test case. Specifically, the need for motion planning algorithms taking into account the technological problem of the spot welding was proved. The resolution of the second industrial case represented a successful test bed for the whole approach. According to the analyzed cases, the employment of automotive companies. The time







VIRTUAL HOMOLOGATION OF HIGH-SPEED TRAIN **AERODYNAMICS: EXPERIMENTAL AND NUMERICAL STUDIES**

Antonio Premoli - Supervisor: Prof. Federico Cheli

Interest in the aerodynamics of trains has grown in the last 30 years, especially with the introduction of new high-speed rolling stock. The necessity to increase run safety and train interoperability between European countries has led to define standards like CEN and TSI. So. a new train that is designed to run on the European high-speed line must fulfil requirements on its aerodynamic force coefficients. In this study, behaviour defined in the TSI. The requirements usually ask for full scale experiments or experimental tests on reducedscale models in wind tunnel or moving model test rig. Especially for full scale experiments, the cost for homologation tests is very high since they have to be carried out during the night in absence of commercial traffic and performed several times over a long stretch of the line in order to consider the different features that could be encountered such as slope, tunnels, curves and different infrastructures.

In the present research an investigation of the possibility to rely on *virtual homologation*, consisting of CFD methods and wind tunnel tests, to simplify homologation procedures with respect to three aerodynamics features of high-speed trains is performed.

Regarding the effect of the wind acting transverse to the

train, called crosswind, both reduced-scale models in wind tunnel and CFD simulations are already provided by the CEN norm. However, both the approaches do not take into account of the relative motion between the train and the infrastructure when the wind is blowing. Neglecting this effect may have an impact in the definition of aerodynamic the guantification of the differences in the coefficients has been investigated by means of CFD simulations with a moving reference frame approach, considering different infrastructure scenarios: the Single Track Ballast and Rail (STBR) and the 6m high embankment (EMBK). The deflection of the flow induced by the relative motion changes the incoming flow conditions on the front part of the train.

while in the rear part this effect is less important. Since the effect is limited to a small part of the whole train, the impact on the aerodynamic coefficients is not so pronounced. The comparison between the results of the simulations with still and movina models highlighted that considering the relative motion between the train and the infrastructure lead to larger aerodynamic coefficients. The variation is larger the larger is the infrastructure dimension with respect to the train dimension. In fact, considering the EMBK scenario, it has been found an underestimation in the aerodynamic coefficients of the order of 10% in the considered range of yaw angles, as shown in Fig.1. The underestimation of the aerodynamic coefficients will lead to an underestimation of the Characteristic Wind Curves that represent the



1. ETR500 leading vehicle force (C_{er}) and moment (C_{erv}) aerodynamic coefficients with EMBK scenario.

limit conditions for the train overturning.

generated by the train passing trackside structures and people, called *slipstream*, TSI standard requires at least 20 independent full scale measurements with major restrictions on environmental and infrastructure overestimate the numerical conditions. These tests are very expensive both in terms of time and costs. In the present work the possibility to study the slipstream problem using a still model in wind tunnels will be investigated. The benefits from working on a still model in a wind tunnel are that ambient conditions can be controlled during all the test runs and it is possible to avoid the problem of small measuring time, but an appropriate measuring system should be adopted. In this case CFD simulations can be used as a useful tool for designing the wind tunnel experiment and testing different solutions in advance. Since the slipstream strongly depends on the generated turbulence, a DES numerical model has been applied, in order to capture the smaller flow structures that form near the surface the train with an adequate computational effort. Different CFD models have been developed and the results have been compared to the full scale measurements. It was found that the boundary

layer on the ground and the ballast plays an important role Regarding the effect of the wind for the slipstream assessment and in Fig. 2 it is shown how the vorticity develops in the rear part of the train. The wind tunnel setup has been defined according to these information and it was found that WT measurements results. Again, the development of the ground boundary layer represented the major problem. BL could be better controlled by reducing the splitter plate in the upstream direction and using a porous floor on the splitter plate in order to prevent its generation.



2. Vorticity generated by the train reproduced by means of CFD . simulations.

The flow generated in the underbody region of the train lead to a phenomenon called ballast lifting and it has been recognised in the TSI as an "open point". Ballast pick-up

depends not only on the train underbelly geometry but also on the track conditions, so there are lots of parameters that need to be taken into account. In order to better understand this phenomenon. an experimental set-up has been defined to measure air flow and forces in the train underbody region during different test campaigns. Then a numerical CFD model, composed of a full scale model of ETR500 put on the STBR scenario, has been defined to simulate the undercar flow. Effects of ballast stones and sleepers have been taken into account through rough wall functions. Results showed a good agreement between experimental measures and numerical model, both in terms of velocity profile and of forces acting at the ballast level. This tool could be used to perform forecast analyses. For instance, with the numerical model it should be possible to consider different train speeds or different train underbelly geometry, without the necessity of performing full scale tests,

that are much more expensive

and time-consuming.

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MECHANICAL ENGINEERING

A METHODOLOGY FOR AFFORDING USER EXPERIENCES

Francesco Pucillo - Supervisor: Prof. Gaetano Cascini

"We don't sell product. We sell *experiences*". Sentences like this one are increasingly common in companies' advertisements. In a same fashion, the number of scientific publications about User Experience (UX) is quickly raising: the research "user experience" on Scopus returns about 11.500 entries, but less than one fifth of them are older than 2005. UX can be defined as "a person's perceptions and responses resulting from the use and/or anticipated use of a product, system or service". However, the design for the UX has gained several criticisms, related to some limitations that both researchers and practitioners aim to overcome. Firstly, an experience cannot be designed, nor guaranteed. The purpose of designing experiences could thus lead designers to attempt to design something that is not there to be designed, such as the user. Secondly, the design of an interactive artefact. to a certain extent, impacts users' behaviours, habits and eventually experiences. Hence, every designer or design engineer developing interactive artefacts acts as a UX designer. From that perspective, systematic approaches can result with being valuable support to those which have to deal with the UX, albeit not being properly UX designers. Nevertheless,

there is a lack of systematic approaches suitable to support design engineers in designing for the UX.

This thesis deals with these issues and tries to address the following main research question: "How can we support design engineers and companies in effectively and efficiently designing for the UX?". The research question is thus addressed as follows. The first step arises from the consideration that designing experiences implies some risks. In order to overcome said risks, a novel formalisation for the UX is outlined. More in detail. after a critical discussion about the role of the UX designer and her/his designs, the relation between the user and the artefact is represented by means of the concept of affordance; a formulation in affordance is thus proposed as a possible solution to overcome the above discussed issues. Hence, the concept of Experience Affordance is postulated as follows. An artefact affords an experience to a user when the user has a certain psychological need and the artefact has a feature capable of fulfilling it. A schematic representation of Experience Affordances is shown in Figure 1. Such a formalisation gives a prominent role to the satisfaction of user's

psychological needs. In this fashion, on the one hand it takes into account the subjectivity of experiences, whilst on the other hand it allows building a systematic approach upon. From this perspective, in order to develop a systematic approach, the concept of Experience Affordance is expanded beyond its definition and a theoretical model that describes how Experience Affordances "work" developed. To this purpose, it is assumed that Experience Affordance can be seen as proposals for needs satisfaction made to the users; then, it is argued that the process through which the artefacts offer these possibilities to the users can be described as a communication one. Hence, a novel design-as-communication model is proposed. Basing on the Jakobson model of communication, Experience Affordances are then modelled in a fashion that not only highlights the elements that play a role in providing users' with experiences of needs satisfaction, but also the roles these elements play. Eventually, the main research question of this thesis is addressed through the development of a systematic approach, based on said designas-communication model. Subsequently, such an approach is implemented into a computerbased tool. This tool, called User Experience Design Supporting Tool (UXDST), aims to foster the ideation of novel artefact features capable of addressing user's psychological needs. Some exemplary screenshots from the UXDST are shown in Figure 2. Hence, the tool is tested in order to preliminarily verify its capability of supporting the design for the UX and individuate the most suitable paths for future improvements. Finally, a complementary discussion is carried out: in spite of being outside the main contribution of this dissertation, two further systematic methods are proposed and discussed. The first one is based on the narrative analysis of user stories, and aims to support designers and design engineers in individuating and highlighting user's psychological needs. The second one, instead, roots in Experience Affordances and proposes such a formalisation as a tool for evaluating the possible experiences for needs satisfaction offered by artefacts to users. Therefore, after a theoretical discussion an exemplary application is shown. The methods and tools proposed in this dissertation refer to different time phases of a design process. Whilst the main part deals with the synthesis of novel solutions, the other methods are related, respectively, to the

need-finding activities and the evaluation stage. This offers, as a main future opportunity, new hints on the possibilities for a novel integrated approach for supporting design engineers throughout the whole UX design process. This opportunity, as well as the main limitations of the work, are critically discussed in the final chapter.



1. A schematic representation of an Experience Affordance



2. Exemplary screenshots from the UXDST

METHODS FOR LCF LIFE PREDICTIONS IN PRESENCE OF DEFECTS

Silvio Rabbolini - Supervisor: Stefano Beretta, Huseyin Sehitoglu

loadings.

Nowadays, gas turbines and other components employed for power generation are subjected to several load cycles during their lifetime, since they are switched on and turned off several times each day, in order to meet the peak loads requested by users. High plastic strain can be present in these components, since high loads, applied to the structures during start-ups and turn-offs, can generate yielding in certain regions, such as near notches. In order to take into account these conditions, state-of-theart procedures consider fatigue life assessment as a crack propagation problem. Fatigue crack growth is usually described taking into account material elastic-plastic behavior and crack growth rates are described as a function of elastic-plastic parameters, such as the applied plastic strain range or the cyclic J-Integral.

These models, however, present several limits. First there are simplified equations based on fatigue load cycles calculated by adopting Masing's hypothesis, a feature that does not take into account transient phenomena, such as ratchetting and mean stress relaxation. Then, they consider the effects of crack closure, but opening levels are usually calculated by adopting analytical models, known to be precise only under fully reversed

These conditions represent the

motivation and the starting point of this Ph.D. thesis, which aims to study crack propagation in plastic zones. In this work the attention is mainly focused on the effects of crack closure and material cyclic behavior and to the possibility to apply the general formulation of ΔJ in fatigue life assessment for components subjected to LCF conditions.

In the first part of this work, a general formulation of was obtained, starting from Dowling's original proposal. This formulation, which does not depend on Masing's hypothesis, allows the direct extraction of the cyclic J-integral from the remote fatigue cycle. This model was employed to study fatigue crack growth in presence of plastic strain. It was found that short crack propagation could be accurately described only if effective stress and strain ranges were considered in J-integral range calculations. This means that, even during propagation in the LCF regime, crack closure plays an important role. As proposed by stateof-the-art procedures, it was found that crack growth rates, experimentally measured during short crack propagation, lie on reference curves obtained from tests performed at high stress ration on standard

compact tension specimens. This condition was not met when tests performed at high temperature were considered. In particular, it was found that experimental data-points exhibit a marked speed increment. This increment was related to a damage mechanism present at crack-tip, which consisted in a pattern of micro-cracks surrounding defect main body. Additional experimental campaigns underlined the fact that this phenomenon is temperature dependent. Because of this, a speed factor was introduced in the calculations for describing the enhancement of crack growth rates.

The same observations were obtained in the second part of the work, in which crack propagation in presence of notches was studied. This activity was developed in order to provide a crack propagation model suitable for real components. An accurate study of the stress/ strain field of a compressor disk, performed in order to check material behavior near the most critical parts of the components, showed that disks experience an elastic shakedown condition. This situation is related to the particular spinning tests performed before final installation and implies that an approach based on LEFM can

be adopted, even if residual strains are present. The strains recorded during the experiments single crystal plasticity. Good confirmed the elastic shakedown agreement was found, condition numerically simulated. In particular, it was found that the crack propagation model accurately describes fatigue crack growth when the stress/ strain cycle registered at the notch root is fully reversed, whereas it provides wrong estimates when an applied mean In the final part of this work, stress is present. This fact was related to the wrong crackclosure estimates provided by the current analytical model. Because of this, the attention was shifted on the experimental determination of crack closure. An innovative technique based on computer vision, digital image correlation, was employed to study crack-closure in a Ni-based superalloy, Haynes 230. In this phase, single crystal structure was considered. in order to remove the effects of grain boundaries in crack opening/closing levels. Two different techniques were adopted: virtual extensometers, placed along crack flanks, were employed to check crack-closure levels, whereas a regression algorithm was used to extract the effective stress intensity factors from the singular field present at the tip. In order to validate the technique, cyclic plastic zones were calculated from extracted and compared to with constraint conditions

considered.

propagation model based on

. An experimental campaign

opening and closing loads

of very high plastic strains.

DIC was employed during

this activity, by adopting an

innovative technique based on

virtual strain gages positioned

that the levels calculated by the

effective stress and strain ranges

applied to the crack at Re=0.5.

In particular, it was observed

open for almost the whole

fatigue cycle. At this point,

that, during LCF, a crack stays

specimens containing defects

near crack tip. It was found

analytical model proposed by

Newman underestimated the

was performed to study crack

during propagation in presence

those calculated from numerical similar to those present in the simulations, which considered linepipes were tested. It was found that good estimates could be obtained only if experimental underlining the capabilities opening/closing levels, together of DIC in the study of fatigue with experimental stress crack growth. Moreover, it was and strain amplitudes, were found that crack propagation considered. behavior of single crystals is similar to the one observed when polycrystalline structure is these techniques were applied in the study of fatigue crack growth in linepipes subjected to severe loading conditions. The particular loading condition experienced by the tubes implied the adoption of the crack

I OW FREQUENCY VIBRATIONS ANALYSIS AS A METHOD FOR CONDITION BASED MONITORING SYSTEM FOR RAILWAY AXLES

Paweł Rolek - Supervisor: Prof. Stefano Bruni

Introduction:

Railway axles are one of the crucial elements providing safety and functionality of railway vehicles, thus special attention to their health needs to be paid. To prevent failure of the axle periodical inspections are performed. Railway axles in modern vehicles are not only transferring load but also providing support for brakes and other auxiliary elements, thus their proper inspection against faults requires complete disassembling process and use of one of the nondestructive diagnostic techniques (like ultrasonic scan, eddy current test, etc.). This approach has significant disadvantage: inspection needs to be performed in workshop which is time, effort and money consuming. Due to the lack of information about the state of the axle during its operation the inspections are performed periodically on time or kilometer basis, which can cause either money loss for operator in case of unnecessary check (no problems found) or serious accidents in case of axle failure due to overcome of critical condition before planned inspection. In presented work analysis of application of the Low Frequency Vibration measurement approach for railway axle online condition based monitoring system is presented.

1. Low Frequency Vibration analysis (LFV)

LFV is based on the measure of harmonic components in the axle bending vibration having periodicity which is an integer sub-multiple of the revolution period. These vibrations are induced by the "crackbreathing" mechanism and by asymmetry in the bending inertia crack propagation tests could be of the axle, as produced by a stiffness reduction introduced by LFV signals have been acquired propagating transversal crack. Abovementioned vibrations have transducers to monitor possible a low-frequency nature, and due damage occurrence and its to this fact the measurements can be conducted by using simple, robust and inexpensive transducers. This method was initially proposed for crack detection in the shaft of turbo-machinery [1], and was demonstrated to provide reliable results for this kind of application based on experiments performed on a laboratory test rig, however due to different work specification of railway axle (speeds much lower than first critical, not stable working conditions due to additional excitation sources. weather condition influence. etc.) successful application in railway field was not obvious.

2. Experimental tests and results

The experimental full-scale tests have been carried out by means of the "Dynamic Test Bench for

Railway Axles" (BDA) available at the labs of Politecnico di Milano – Department of Mechanical Engineering. In particular, a three point rotating bending was applied to the full-scale specimen via an actuator group and an electric motor: in this way, both constant amplitude and block loading fatigue or carried out.

by means of three laser development during the axle operation under load. Because of difficulties to monitor axial vibration in real application authors have focused only on vibration measurement in radial direction. Two laser transducers have been mounted in vertical direction and one in horizontal direction pointing to the central region of the axle, which allowed to obtain the highest displacements produced by the applied loads. For speed detection and absolute phase lag analysis Tachometer signal (one per rev signal) has been obtained from the electric motor used to rotate the axle. During experiment campaign a number of nxRev harmonics appeared in the measured signal and after trending process the increase in the level of vibration became evident for some of them.

The 1xRev component showed the largest increase in amplitude at the final stage of the tests (and hence with the abrupt increase of the crack size). The amplitude of the 2xRev component was also sensitive to the number of cumulated loading blocks. The 3xRev component showed a lower sensitivity to the number of block loading repetitions, still a nearly monotonically increasing trend, but the trend was less clear, probably on account of disturbances such as thermal effects that may produce a bow of the rotating axle. Finally the amplitudes of the remaining 4xRev to 7xRev components remained very low during the whole tests with a slight increase in the final stage of the test. In conclusion, the 1xRev, 2xRev and in some cases also 3xRev harmonic components of vibration signal appear to be the best suited to be set in relationship with the presence (and possibly with the size) of a propagating crack in the axle. It is necessary to keep in mind that not only increase of amplitude of vibration signal can indicate presence of fault. Some experimental results are showing decrease in amplitudes during initial stage of crack development, which could be explained by influence of opposing phases of generated signals [2].

3. 3D model analysis and results

3D analysis by finite element method was used to investigate vibrations inducted by breathing mechanism of crack existing in railway axle under working conditions (applied loads and rotations). Finite element model

of axle was discretised by means of reduced integration C3D8R elements. Due to the fact that model was experiencing high number of revolutions second order accurate formulation elements from explicit library were used. Axle crack was introduced in model as fixed size discontinuity in finite element mesh. Since crack breathing mechanism was most important phenomena to investigate during simulation contact parameters were defined at both sides of cracked specimen walls (crack lips), which allowed to simulate opening and closing of crack lips caused by rotational bending. During simulation analysis campaign two scenarios were investigated: laboratory test equivalent scenario and railway case scenario, where the latter one including additional excitations raised by wheel and rail irregularities was representing more closely real working conditions of railway axle.

The 'laboratory' scenario simulation results appeared to be in good gualitative agreement with the measurements performed in the full-scale tests on cracked axles. In particular the ratios of the amplitude for the 1st and 2nd harmonic were in good agreement with these that can be observed during laboratory test. The absolute amplitude of vibration obtained at the end of the tests performed on cracked axles was consistent with the amplitude obtained by means of Finite Element simulations for a crack in the range of 25% to 35% which was roughly consistent with the final crack amplitude found on the specimen at the end of the

laboratory test.

Simulations including additional sources of excitation coming from wheel-rail interaction (railway simulation case) showed that irregularity levels reported on worn railway wheels are not overcoming vibrations caused by 35% deep crack in the axle, thus allowing to assume that the detection of a crack in similar size is highly probable during vehicle service. 1xRev and 2xRev harmonics occurred to be the most suitable to indicate presence of crack. Comparison of two cases with different crack depth (30% and 35%) revealed that NxRev vibration components are undergoing higher rate of change of amplitude due to crack propagation than from developing out-of-roudness profile of wheel allowing to assume that that axle condition monitoring based on LFV is capable of delivering diagnostic results even during further degradation of wheel profile.

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MODEL BASED COMPLIANCE SHAPING CONTROL OF LIGHT-WEIGHT MANIPULATOR IN HARD-CONTACT INDUSTRIAL APPLICATIONS

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Light-weight manipulators are increasingly used in interacting robotic tasks where reduced mass and (controlled) compliance are required to ensure safety and adaptability. Interacting tasks are generally referred to both human-robot interaction (e.g. handling assistance) and robot machining (e.g. automatic assembly or surface finishing). Moreover, lightweight manipulators are often mounted on flexible structures or mobile platforms. In such applications the dynamics of the interaction is affected by the robot base and the environment, in addition to the dynamics of the controlled robot.

The critical compliant scenario (i.e., compliant robot base, controlled robot, environment and, eventually, human operator) may cause the presence of natural frequencies in the operating bandwith of the manipulator due to the coupled dynamics, significantly influencing the interaction accuracy in a wide critical bandwith. Such condition may give rise to excitation of resonances of the coupled system that could hinder the stability of the task execution (especially during contacts transients). Moreover, the base elasticity is remarkably crucial from the controller performance point of view. Both dynamic

and static deformation of the robot base may affect the task execution, resulting in decreasing performance (e.g. steady-state errors) and task failures (e.g. instabilities).

Interaction control has long been contexts). investigated in order to safely execute such applications. Impedance control is particularly suitable for interacting applications, allowing to define a target dynamics (i.e., mass, stiffness and damping parameters). Although impedance methods are proved to be dynamically equivalent to explicit force controllers, a direct tracking of the interaction is not straightforwardly allowed. To overcome this limitation preserving the properties of the impedance behaviour two different families of methods have been mainly introduced: class (a) force (or position) tracking controllers and class (b) impedance *variable impedance* controllers.

Limitations of class (a) are related to the limited bandiwth of the controllers to avoid instabilities dealing with changing environments. Limitations of described class (b) are related to the absence of the runtime estimation of the environment stiffness. Additionally, both class (a) and (b) are not considering force

overshoots avoidance. Moreover, compliant robot base state-of-the-art methods do not consider contact tasks or consider the use of external sensors (i.e., reduced applicability to industrial

The purpose of this Thesis is to extend (a) and (b) algorithms to a global impedance shaping to overcome described limitations: avoid force overshoots/

- instabilitie:
- compensate for compliant robot base.

The novelty of the defined approach is the possibility to track a target interaction force (or deformation) while modifying the impedance of the global interacting scenario, having a complete estimate of the complete plant. This is defined as impedance shaping. This is done evolving from class (a) and (b) methods, tuning online both the position set-point and the stiffness and damping parameters of the impedance control based on both the force error and the on-line estimated stiffness of the interacting environment, obtained implementing an Extended Kalman Filter (EKF). Eventually, such control scheme is capable to consider the compliant robot base scenario in order to compensate for the

compliant robot base dynamics. In this case, the defined control strategy takes into account the estimated position of the manipulator base to correct the position set-point of the impedance control, obtained implementing a Kalman Filter (KF) to avoid the use of external sensors.

The proposed control scheme has been developed based on an incrementally study of the described complex scenario. Firstly, the *rigid robot base* scenario has been taken into account (focusing on the robot - environment interaction). Then, the compliant robot base scenario has been taken into account (focusing on the compliant robot base dynamics). A complete model of the interaction dynamics is needed as the proposed control strategies are model-based and to design the observers. Developed dynamic models have been validated, especially the impedance control model of the closed-loop robot dynamics (i.e., static and dynamic impedance behaviour validation). Then, observers and control strategies have been developed, using the developed models to synthesize the algorithms and to study the closed-loop stability.

Developed control strategies have been validated in a

real assembly tasks. Results show the effectiveness of the proposed control strategies, compared with control schemes in literature (in particular, a second order explicit force tracking controller based on the impedance control), that show force overshoots, instabilities and lower dynamic performance.

Topics covered in this Thesis have been developed and tested at ITIA-CNR, IRAS group.

INNOVATIVE TECHNIQUE TO ASSESS TENSILE **AXIAL LOAD IN TIE-RODS BY MEANS OF DYNAMIC MEASUREMENTS**

Matteo Scaccabarozzi - Supervisor: Prof. Alfredo Cigada

This thesis deals with a new method to estimate axial load in tie-rods by means of indirect measurements. The knowledge of this information is of great importance to assess the health of the tie-rod itself and of the whole structure, which the beam is inserted in

The method is based on dynamic measurements and require the experimental estimation of the tie-rod eigenfrequencies and mode shapes in a limited number of points. Furthermore, the approach requires to develop a simple finite element model. which is then cross-correlated with the experimental data by means of a model updating procedure.

The aim of the present work is to design, develop and validate an innovative technique to asses the tie-rod axial load, based on dynamic measurements and able to overcome most of the problems and limitations of the previous approaches. Particularly, the method is expected:

- \cdot to be simple to apply (both experimentally and numerically);
- to give accurate assessment of tensile force (results as good as or better than those achieved by the best methods in literature)
- \cdot to be effective with different kinds of tie-rods (e.g. with both uniform and non-uniform beam cross-sections):

 that should not need any accurate estimation of material data, working properly even with rough nominal data; to work even with operational modal analysis in order to apply an effective continuous monitoring of tie-rods. In order to achieve a method based on dynamic measurements, the modal behavior of tie-rods was investigated. The tensile load is the object of the analysis, but the tie-rod dynamic behaviour is affected also by other parameters: some are measurable and therefore considered as known (e.g. the cross section area) and others are unknown (e.g. the actual free beam length , the Young's modulus and density of the material). The behaviour of the constraints at the end are unknown as well. The stiffness of the constraints is represented by the equivalent torsional stiffness in the model of the tie-rod . The following method was developed to assess the axial load:

- i. identify the first tie-rod eigenfrequencies by means of experimental tests;
- ii. asses by identifying the eigenvector components in two points:
- iii. build a FE model of the tie-rod where the material properties are fixed to nominal values and the geometry is assumed

to be measured. The value of comes from point ii of this list iv. use the FE model to build the relationship between the value of each eigenfrequency and the axial load . The tie-rod axial load is estimated as the mean of the various values .

v. the value of is refined by means of a modal updating procedure, by cross-correlating the FE model results with the experimental data in terms of eigenfrequencies.

The method takes into account a reasonable range of uncertainty for each unknown parameter. Two methods for assessing were investigated. One is effective also working with environmental forcing, the other led to a feature useful to estimated the actual beam free length Extensive numerical simulations and experimental were carried out tests in order to validate the method.

Numerical validation was carried out by means of Montecarlo simulations on different case studies. Results are represented in terms of, where is the true value of axial load in the beam. For a case study, Fig. 1 shows the results in terms of average value of and the results distribution pointed out by the interval and the boundary values and , for different value of axial load and constriant stiffness Results before and after the model updating are shown.



1. Errors in estimations before and after the updating procedure

The experimental validation was performed on a test rig as similar was the starting point to design as possible to an actual tie-rod. The tests were carried out with different levels of axial load and different stiffness of the constraints. In order to simulate also a real low level of stiffness. some rubber layers were put between the elements of the clamps which constraint the beam ends. The experimental tests were performed by measuring the input force on the beam as well as by providing only the environmental forcing. Results are shown in Fig. 2. The experimental tests show that the maximum discrepancy (after updating) on load estimation was lower than 10%, in strict accordance with the numerical validation. In conclusion, the comprehension of the basic effects of geometrical and mechanical variables on the

the new method to assess the axial load. The eigenfrequencies of the beam were found to be suitable to estimate the axial load but the analyses also showed that an estimation of the stiffness of the constraints was necessary prior to any other task. Hence, methods two assess the stiffness of the constraints

modal behaviour of a beam

Montecarlo simulations were thus performed in order to check the reliability of the designed method and to understand the level of confidence of the achieved results. The results showed that this new method is able to guarantee an accuracy close (or even better in some cases) to that associated to the best methods in literature with less constraints (e.g. the necessity to know the Young's modulus of the material with a verv high accuracy). Finally an experimental validation of the method was carried out and the results confirmed those coming from the Montecarlo simulations.

Therefore, the designed method reaches all the goals fixed at the beginning of the work and it is noticed that the developed procedure does not require to measure the input to the structure. Furthermore, the number of sensors required to measure the response of the beam is limited to two. This makes the current method much cheaper with respect to most of the referenced techniques, even enabling to carry out continuous monitoring of the tie-rods.





TITLE: "HUMAN BODY RESPONSE TO MULTI-AXIAL DYNAMICAL VIBRATIONS".

Stefano Solbiati - Supervisor: Giovanni Moschioni

Body-transmitted vibrations could lead to serious consequences on health. Vibration transmitted to the body generate cyclic stresses critical for the spine and may lead to musculoskeletal disorders (i.e. low-back pain) besides physical and psychological fatique.

Many studies focused on understanding the dynamics of the body both in seated and standing postures. These studies evidenced a general nonlinear behaviour which was investigated under different experimental conditions (i.e. vibration magnitude, postures and other anthropometric parameters). Despite the huge amount of material, the variability of the human body dynamics was not still clearly understood, being the issue more complex than expected; the main open issue, is that the variability due to the nonlinear behaviour of the biodynamic response has not been systematically compared to the inter- and intra-subject variability.

Aim of this work was the identification of the nonlinearities affecting the response of the human body exposed to whole-body vibrations. The research was entirely addressed to the characterization of the response for standing persons using a

novel approach for the study of the nonlinearities of the bodytransmitted vibrations. This field was not completely explored and few works were reported in the literature. Besides the lack of material, the largely described nonlinear behaviour was often in contrast or not fully supported with a set of nonlinear functions by the experimental results: e.g. nonlinearities with respect to the acceleration and the force were vibration magnitude were found even if the ordinary coherence function was close to unity. The research activity was carried out according to the following steps:

- 1. characterization of the apparent mass in case of vertical whole-body vibration;
- 2. identification of the nonlinearities:
- 3. design and realization of a suitable excitation system and setup for measuring the apparent masses in the basicentric reference system;
- 4. characterization of the full (three-by-three) matrix of apparent masses for the standing persons;
- 5. characterization of the response in case of multi-axial vibrations (no more than two axes contemporarily excited). The study of the nonlinearities was performed for both singleaxis and multi-axial vibrations. The reference parameter for the biodynamic response of the human body was the apparent mass (hereafter APMS), i.e. the

frequency response function between the transmitted force and the applied acceleration. In the first part of this work. nonlinearities were identified by conditioning the APMS deriving from the vertical whole-body vibration (WBV) of the acceleration: both the measured only along the vertical direction.

Afterwards, the full (three-bythree) matrix was identified with a purposely-designed excitation system composed by two electrodynamic shakers and a triaxial force plate. The excitation was initially mono-axial and the force was measured along the three coordinated axes. Both the symmetry of the APMS matrix and the effect of the vibration magnitude were assessed with paired t-student and Wilcoxon signed-rank tests. In the last part of the research, the response (forces along three mutually perpendicular directions) was measured with the uncorrelated excitation along two axes. The APMS derived in these conditions has been compared with the one obtained upon exciting a single axis. Nonlinearities in the human body response to vertical WBV were analysed using the conditioned output spectra and the multiple coherence functions. The contributions

of the nonlinear terms to the APMS were nealigible (i.e. the modelled nonlinear terms did not take part in the definition of the response) and the nonlinearity was associated to the variation of the modal parameters in time, due to low frequency motion during the tests and involuntary muscular actions. Both in the standing and legs bent postures, the responses modelled with conditioned and linear models were very similar and differences between the ordinary and the multiple coherence functions were comparable to the intrasubject variability.

The full three-by-three APMS matrix was derived by exposing subjects to independent vibrations along the three orthogonal axes. Such task involved the design of either a dual-axis excitation system. made by the junction of two electrodynamic shakers, or a tri-axial force plate, for the measurement of the transmitted forces in the reference system. For each axis, both the direct and the cross-axis APMSs were computed by the use of linear estimators.

Generally, the normalized APMS decreased in amplitude towards higher frequencies, except for the case of vertical WBV where both the direct and the frontal cross-axis APMSs increased to a main resonance peak (at about 5-6 Hz) and then decreased to lower magnitudes. Such coupling may suggest a common vibration mode in the xz-plane but it did not occur under a reciprocal condition (i.e any resonance rose on both axes due to a frontal excitation). No more couplings were found between the direct

and the cross-axis APMSs under excitations along the other axes. Unexpectedly, along the vertical direction (z-axis) the human body was found more sensitive to vibrations. Independently on the excitation axis, the direct vertical APMS and both the vertical cross-axis APMSs were higher in magnitude than the corresponding direct APMSs. In facts, one would expect that the maior inertial contribute occurs along the direction of excitation. No differences occurred within the APMSs being the vibration magnitude not a driving parameter for the modelling of the biodynamic response. Secondly, the same statistical analysis were performed on the APMS matrices of a single individual. In this case, it was observed a more dependence of the response on the vibration magnitude. Many differences occurred at frequencies where the aggregate responses were found equal. Definitely, the comparison between the population and the individual's APMS matrices evidenced the more dependence of the individual's response on the vibration magnitude. This finding may depend on the scatter in the population's biometric data whose uncertainty introduced on the response is such to overlay magnitude dependent effects. The frontal cross-axis APMS under vertical WBV was conditioned for assessing whether nonlinearities in the response occurred. Results from the linear estimators and the conditioned quantities were found similar. Further analysis evidenced that the drop in the coherence function was not attributable to some nonlinearity but the response was not

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along either a primary or a transversal directions (i.e. with increasing magnitudes of acceleration). Results from the comparison between the APMSs taken under singleaxis and dual-axis exposures confirmed that the biodynamic response was influenced by the addition of a secondary transversal acceleration. Such dependence cannot be extended either to all the directions of excitation or within a specific response path. It was found a marginal contribute of the overall magnitude of vibration since dual-axis APMSs were almost equal. As for the APMS under single-axis excitations, nonlinearity in the response due to the addition of a secondary vibration was more evident for the individual rather than in the sample population. Such behaviour may again depend on the variability in the population's biometric data whose uncertainty is such to overlay the effects due to the addition of extra-axis vibrations.

stationary. Consequently, the

APMS matrix of an individual

the same aim of proving the

extent of the nonlinearity. The differences between the linear

estimators and the conditioned

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The APMS matrices in case

characterized by exposing

to independent vibrations

subjects contemporarily

of dual-axis excitations were

was fully conditioned with

UNCERTAINTY EVALUATION AND PERFORMANCE **VERIFICATION OF A 3D GEOMETRIC FOCUS-VARIATION MEASUREMENT**

Wahyudin Permana Syam - Supervisor: Prof. Givanni Moroni

Quality is an important aspect of a product. High quality product ensures the functionality measurement results. of assembled products and the interchangeability among products from different manufacturers. To verify product quality, tolerance verification (geometrical measurement) by means of coordinate measuring systems has to be carried out. Advancement of manufacturing technology enables a significant reduce of critical dimensions, together with an increase of geometric complexity. This creates challenges in coordinate metrology: tolerances become tighter. Optical-based metrology instruments are a potential option to verify these tolerances. But of course also in this case

traceability is a fundamental aspect to ensure reliable

This thesis addresses the problem of traceability of a focus-variation microscope as 3D coordinate measuring system. First, the traceability of the instrument will be discussed considering its performance. Proposals for reference artifacts and procedures to conduct performance verification according to the ISO10360-8 and ISO10360-3 standards are presented. These proposals consider both 3-axis and 4-axis configurations of the instrument.

Second, an approach is

presented for task-specific uncertainty evaluation by simulation, coherent with the ISO15530-4 standard. The proposed simulation approach is based on spatial statistic model considering the correlation among captured points. To support the simulation and consider all significant error sources, characterization studies to investigate the influencing factors of measurement by focus-variation microscopy are presented, too. Finally, industrial case studies are carried out to validate the simulator developed. The validation conforms to the ISO15530-4 standard.

As a by product of this study, algorithms to associate



ideal substitute geometries to sampling points will be discussed. An improvement of non-linear least square fitting is presented, based on the optimization of the initial solution through chaos method.

DEVELOPMENT AND IMPLEMENTATION OF OPTICAL MEASUREMENT SYSTEMS FOR TYRE FOOTPRINT **STRESS FIELD**

Andrea Zanoni - Supervisor: Federico Cheli

Tyre testing is an essential part of option, both suitable to static the tyre development process: its goals are both the refining and validation of numerical models of the tyre thermomechanical behaviour and the direct verification of the effectiveness of the design choices. In particular, tyre footprint stress field acquisitions offer the potential advantage of encapsulating a great amount of information: the details of the stresses exchanged between the tyre and the road surface are of fundamental importance in a vast area of the tyre's and vehicle's dynamical behaviour. Normal stress maps in the tyre footprint are routinely measured in static conditions by tyre manufacturers with different methodologies: the most commonly used are pressure-sensitive papers and piezo-resistive matrix systems, initially developed in the field of biometrics. Much less common is the availability of contact stress or deformation fields in dynamical conditions (i.e. with the tyre rolling), limited to date essentially to miniature force transducers line arrays that upon the tyre passage. This method offers the advantages of giving information about stresses in all three directions, however it is very expensive both in implementation and in maintenance costs. Another

and dynamic conditions, is represented by contact pressure sensing devices base on the frustration of total internal reflection of light.

1. the optical static footprint tests bench.

reflected inside a transparent medium, an exponentially decaying wave is present at the boundary interfaces. If an object is present in the portion of space material. Each acquired image occupied by the evanescent wave a portion of the reflected light can be reflected back through the medium, reaching a camera framing the opposite boundary surface. Since the operate a "burst" of acquisitions decaying constant is in the order of magnitude of hundreds of mm, for an object to occupy the region of the evanescent wave it has to be in practical terms in contact with the medium surface. The effect of the deformability and of the

superficial roughness of the object is to redirect light on the unit area in direct proportion to the applied contact pressure. Therefore, in the case of a pneumatic tyre, a measurement device for the footprint contact pressure can be realized, based on this physical phenomenon. This work focuses on the development of two such testing systems and their implementation at Pirelli Tyre Testing Department facilities in Milano Bicocca. A static tests bench has been implemented by supporting a glass plate illuminated form the sides by an array of LED lights and framing its underside with a calibrated camera.

The intensity values of the When light is forced to be totally pixels are correlated to contact pressure magnitude via the interposition between the tested tyre and the glass surface of a calibrated polymeric is then processed by a customdeveloped software that isolates the footprint area, either automatically or with the intervention of the user, and converts the image intensity values into normal stress values. The conversion is made constraining the integral of the normal stresses to equal the normal load applied during the tests, acquired by the test bench reading the output of load cells placed on the wheel hub.

2. Comparison between normal stress maps obtained in statical conditions by the developed test bench (left) and a commercial piezo-resistive matrix system (right). Values displayed are normalized with respect to the inflation pressure.

A second testing system, aimed at dynamical conditions, is implemented on a tyre testing drum by inserting in its structure a frame supporting a curved glass sheet, aligned with the drum surface, also illuminated by the sides by LED lights arrays. A calibrated camera, fixed to the wheel hub, frames the underside of the glass plate. Both the camera and the LED lights are triggered to acquire an intensity map of the tyre footprint upon the passage of the tyre on the glass window. As in the static measurements case, a polymeric material sheet is fixed on the outer surface of the glass. The material is not the same as in the static case, since the sensitivity and mechanical resistance requirements are very different. Also in this case, the software for the processing of the acquired frames has been custom-developed based on the Open Source C++ computer vision library OpenCV: in addition to the functionalities present in the static tests bench software it allows for the recovering of motion blur degradation effects up to

moderate intensity. Currently, straight free rolling tests at speeds up to 120 km/h with camber angles up to 4° in magnitude are possible.

3. fv coefficients comparison referring to rolling resistance measurements obtained by the developed optical system (on the abscissae) and via a standard certification system (on the ordinates).

A first validation of the systems has been performed by comparing their results to those of established commercial measurement system in the case of the static tests bench. For the drum testing system, a comparison was made on rolling resistance estimates based on

the analysis of the contact patch normal stress field acquired by the dynamical system, i.e. evaluating the forward displacement of the normal stress field resultant with respect to the vertical plane containing the wheel screw axis, obtained via standard certification procedures. The results of the validation processes and their repeatability proved to be very encouraging and the static tests bench has been advanced to the industrialization process and CE certification. The dynamical system is still in active development while its industrialization is undergoing. Future developments are especially focused on the extension of the range of testing conditions allowed, in terms of wheel tangential velocity, longitudinal and lateral slip and torgue applied.