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Research activities of the Applied Mechanics group of the University of Genova

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Within the Italian academic system, the sector of Applied Mechanics ("Meccanica Applicata alle Macchine") represents one of the engineering disciplines with the most significant historical background. It encompasses scientific, technological, and educational aspects related to the mechanics of machines, both from the perspective of their components and their operation as complex systems. The methodological approaches employed are varied: theoretical, numerical, and experimental.

Regarding the educational aspects, the sector of Applied Mechanics is fundamental (characterizing) for Bachelor's Degrees in Mechanical Engineering (L-9 class) and for Master's Degrees in Mechanical Engineering (LM-33 class) and Automation Engineering (LM-25 class). Additionally, it is essential for the PhD Degree in Mechanical, Energy, and Management Engineering at the DIME Department of the University of Genova.

The professors of the Applied Mechanics group at the University of Genova are actively engaged in research projects funded at the regional, national, European, and industrial levels. Collaborations are ongoing with Stellantis, Ansaldo Energia, Fincantieri, Leonardo, Hitachi, among others. In this context, the Applied Mechanics sector advances both innovative theoretical contributions and experimental studies aimed at practical applications and technology transfer. The research topics are highly interdisciplinary and include:

- modelling, design, prototyping, and control of innovative industrial robotic systems (two robotic lines developed in collaboration with Stellantis are currently operational in final car assembly);

- modelling, design, and prototyping of service robots for inspection, agriculture, and demining;

- modelling and analysis of micromechanical systems, including compliant mechanisms optimized through analytical and numerical approaches;

- dynamic analysis of systems characterized by vibrations, variable contacts and impacts (e.g., gear trains);

- numerical analysis techniques for mechanical and aeromechanical systems;

- definition and application of methodologies for dynamical analysis, model identification, diagnostics, and monitoring of structural integrity (a monitoring system for turbomachinery rotor blades, developed in collaboration with Ansaldo Energia, is currently in use in several plants).

1. Introduction: the sector of Applied Mechanics in the Italian academic system

In the worldwide academic scenario, the Italian academic system is one of the most structured. Every professor or researcher belongs to an academic sector ("Gruppo Scientifico Disciplinare", GSD), which strictly defines its research and teaching competencies. The research themes of every GDS are clearly stated by its "Declaratoria". In the whole Italian academic system, the GSDs are divided into 14 "Areas". The Area 09 refers to Industrial and Information Engineering and collects 20 GSDs. Among these, the GSD of Applied Mechanics ("Meccanica Applicata alle Macchine") represents one of the engineering disciplines with the most significant historical background. According to its Declaratoria, it encompasses scientific, technological, and educational aspects related to the mechanics of machines, both from the perspective of their components and their operation as complex systems. The study is approached with a unifying systemic approach, utilizing methods of theoretical, applied, and experimental mechanics, leading to technological and industrial applications, with a focus on environmental and energy sustainability.

The types of mechanical systems considered are entirely general: power and operating machines, mechanical devices, mechanisms, transmissions and drives, automatic machines and robots, vehicles, transportation and lifting systems, energy production systems, biomechanical systems, and components and systems at the micro/nanoscale.

Theoretical and experimental methods and applications are developed regarding the analysis of mechanical behaviour, synthesis, and design, particularly functional design, of machines and mechanical systems, through the study of kinematics, statics, dynamics (both linear and nonlinear), interactions with the environment (force fields, fluid interactions), and between material surfaces (lubrication), automation control, and identification.

The implementation of the developed methods through analog and digital hardware and software systems is an integral part of the sector's knowledge. In response to the needs of designing, developing, and realizing innovative systems and components, phenomena such as vibratory, vibroacoustic, and tribological effects, control of mechanical systems, mechatronics, fluid-structure interactions, monitoring, diagnostics, and prognostics of mechanical systems, fluid automation, and robotics, fluidics and microfluidics, eco-friendly systems, and renewable energy are also studied.

The sector further explores issues related to pneumatic, hydraulic, electric actuation systems, and systems based on unconventional technologies (e.g., smart materials), which have now become an integral part of machines, mechatronic systems, and many structures, along with control systems. Strong interrelationships are established with the methodologies and algorithms developed in the design sector, industrial engineering methods, dimensional design and machine construction, fluid dynamics, bioengineering, motor sciences, orthopaedic and prosthetic surgery, rehabilitation and assistance methodologies, and finally, with the interpretation and analysis of historically significant machines.

2. The Applied Mechanics group of the University of Genova

At the University of Genova, the professors and researchers of the Applied Mechanics sector belong to the Department of Mechanical, Energy, Management, and Transport Engineering (DIME). "Integration of knowledge and sciences of understanding" best represents the spirit of this Department, which combines research, dissemination and transfer of technologies, teaching, and training.

The Department of Mechanical, Energy, Management, and Transport Engineering was founded in 2012, but its origins are much older, rooted in the tradition of studies in Industrial and Mechanical Engineering, in the cultural heritage of the Institutes of Technical Physics, Systems and Mechanical Technologies, Applied Mechanics to Machines, Machines, Mathematics for Engineering, and Transport, which were active in the Faculty of Engineering in Genoa since the 1950s. The excellence of the past has been crucial in synergistically guiding both research and teaching.

The Department groups 88 professors and researchers, and is divided into five Sections:

- Management Engineering (DOGE)
- Industrial Systems, Mechanical Technologies, and Mathematical Models (ITIMAT)
- Machines, Energy Systems, and Transport (MASET)
- Mechanics and Machine Construction (MEC)
- Thermoenergetics and Environmental Conditioning (TEC).

The eight professors and researchers of the Applied Mechanics GSD belong to the MEC Section. Within this Section, the research activity is organized in five laboratories; three of these five laboratories mainly work on themes in the area of Applied Mechanics:

- Dynamo Lab
- MCAE Lab
- PMAR Lab

Their research topics are highly interdisciplinary and include:

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- modelling, design, and prototyping of service robots for inspection, agriculture, and demining;
- modelling and analysis of micromechanical systems, including compliant mechanisms optimized through analytical and numerical approaches;
- dynamic analysis of systems characterized by vibrations, variable contacts and impacts (e.g., gear trains);
- numerical analysis techniques for mechanical and aeromechanical systems;
- definition and application of methodologies for dynamical analysis, model identification, diagnostics, and monitoring of structural integrity (a monitoring system for turbomachinery rotor blades, developed in collaboration with Ansaldo Energia, is currently in use in several plants).

3. Research activities at the Dynamo Lab

DYNAMO (Dynamics and Monitoring laboratory) is active in the scientific and technological research on mechanical vibrations, working both from the experimental and numerical side. The most common applications include rotating machinery, aerospace components, vehicles and structures.

The research on experimental dynamics includes the formulation of methods for the analysis of the vibration of mechanical systems in resonance crossing with application to turbomachinery rotor components. The mathematical approaches employed involve the time-frequency representation of the system response by wavelet transform [1-3] (Figure 1a), the concept of local stationarity of the random response [4] (Figure 1b), the use of asymptotic formulations to obtain reference mathematical models for fitting [5]. Specifically for the turbomachinery applications, data measurements and analysis methods based on the Blade Tip Timing approach are actively investigated and developed [6].

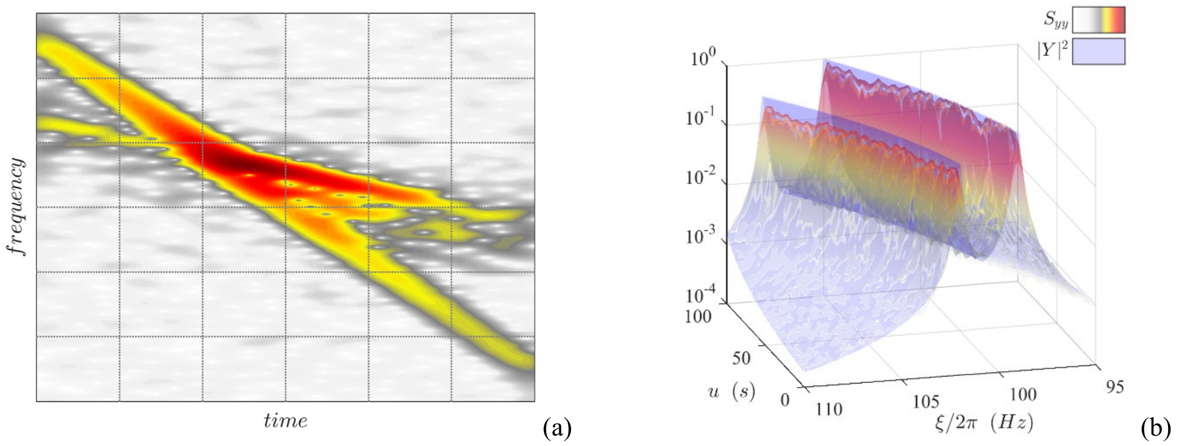

Figure 1: Time-frequency analysis of a rotor blade in resonance crossing [1] (a); fitting of the time-varying model with the evolutionary power-spectral density function of the response [4] (b).

Numerical research is mainly addressed to the development of methods for the dimensional reduction of finite element models, including reduction of interfaces in component-mode synthesis [7] (Figure 2). This common need is studied in conjunction with the representation of the geometric imperfections and the evaluation of their effects on the structural behaviour [8-10] (Figure 3).

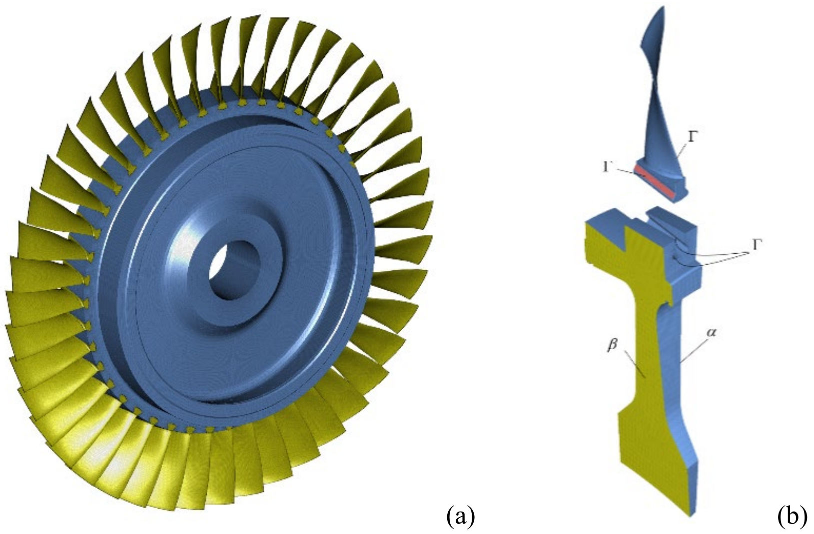

Figure 2: Finite-element model of a bladed disk (a) and
its reduction by substructuring and interface reduction (b) [7].

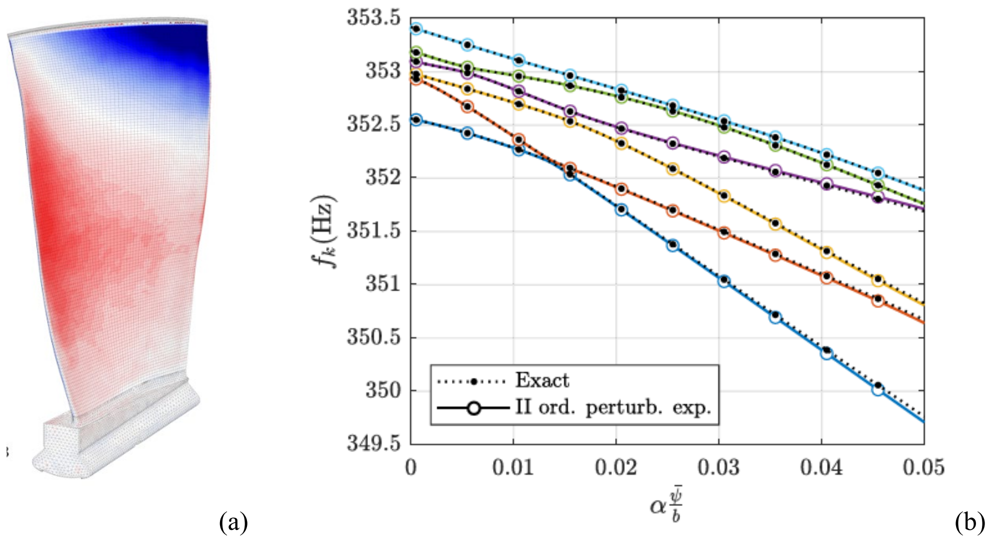

Figure 3: Geometric imperfection of a rotor blade (a) and
its effects on the natural frequency (b) [8-10].

4. Research activities at the MCAE Lab

One of the research themes of the MCAE Lab is service robotics, particularly the development of innovative hybrid locomotion systems capable of combining the speed and energy efficiency of wheels with the obstacle-climbing capability of wheels and tracks. The research in this field started in 2009 in collaboration with the research group of the Politecnico di Torino. The researchers of the University of Genova provided a support for the constructive design and testing of prototypes belonging to the Epi.Q mobile robots family [11] (Figure 4a). These robots, designed primarily for surveillance and inspection tasks, are based on the same Epi.Q locomotion unit; this unit is characterized by three wheels placed at 120° and actuated by a single gearmotor through an epicyclical mechanism. Each locomotion unit is underactuated since the same actuator drives two degrees of freedom: the simultaneous rotation of the three wheels with respect to the three-spoked planet carrier, and the rotation of the planet carrier itself with respect to the robot body. Since the system is underactuated, it automatically switches between wheeled locomotion on flat ground and legged locomotion to climb a step or a generic obstacle, depending on the dynamic conditions.

Figure 4: Hybrid leg-wheel robots Epi.Q (a) and Mantis (b).

Starting from this experience, the researchers of the MCAE Lab developed other innovative hybrid locomotion systems comprising wheels, legs and tracks, such as the Mantis robot (Figure 4b). This robot combines high speed and efficiency on flat grounds in wheeled mode, high manoeuvrability in narrow spaces thanks to the differential steering, and high obstacle-crossing capability thanks to the rotating legs with a praying mantis shape. As a matter of fact, it exhibits one of the highest ratios between maximum climbable step height and robot body height, in comparison with other architectures discussed in the scientific literature [12]. Moreover, it can recover operativity after a capsize rotating properly the legs.

In the case of soft terrains, the use of tracks greatly enhances the motion performance of mobile robots thanks to their large contact surface with the ground. The locomotion system of the WheTLHLoc robot (Figure 5a) includes actuated tracks, wheels, rotating legs, and two passive omni wheels [13]. In wheeled mode, the legs rotate to suspend the robot body on the actuated wheels and on one omni wheel, obtaining higher speed and manoeuvrability on flat and compact surfaces; in tracked mode, the legs point upward (Figure 5a) and the robot exploits only the tracks to transverse small obstacles or yielding terrains, while in case of large obstacles or steps, the coordinated use of all the degrees of freedom of the robot is necessary.

Figure 5: Tracked mobile robots WheTLHLoc (a) and Porcospino (b).

In the case of surveillance in narrow spaces, an interesting bio-inspired locomotion system is that of the Porcospino robot (Figure 5 b). It is characterized by a single peripheral track rotating along a vertebral column [14]. The vertebral column exhibits active steering capability obtained by an internal wire system, while retroflexion is passive, to cope with the terrain irregularities. The track modules are equipped with flexible spines to increase traction and protect the robot structure from shocks.

Another research theme of the MCAE Lab is compliant mechanisms. In the last decades, compliant mechanisms gained notable recognition because of their advantages with respect to the traditional rigid-body mechanisms, such as the absence of backlash and friction, possibility of monolithic fabrication, and compatibility with micro-scale technologies. For this reason, they are being increasingly implemented in the fields of robotics, aerospace, optics, manipulation, and micro-electromechanical systems. The research of the team focuses on the design of high-accuracy compliant rotational joints ([15], Figure 3a and 3b) and on the development of advanced analysis and synthesis methods for compliant mechanisms with complex topology, characterized by arrangements of series and parallel substructures composed of rigid and elastic elements ([16], Figure 3c).

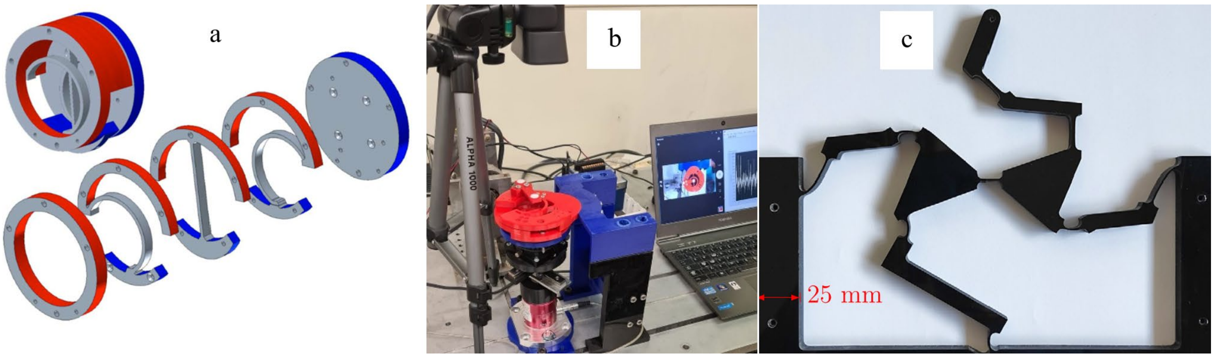

Figure 6: Design (a) and testing (b) of high-accuracy compliant joints, and design of compliant mechanisms with complex topology (c).

5. Research activities at the PMAR Lab

The work of the Robotics Research Group PMAR is, in part, project-driven and in part based on methodological/theoretical contributions to the fields of cable-driven robots and kinematics fundamentals of robotics [17-25]. The project-driven activities develop robotic systems with a focus on system architecture and design, up to very detailed and turn-key demonstrators. The end users in these projects are companies, in particular the final assembly of Stellantis and the automotive sector. The applications range, further, to exoskeletons for specific tasks (operation of long tools, lift of boxes), automatic quality checking (in particular for robotized welding), and a variety of manipulation tasks on which the lab has a long-dated and unique experience, after about 40 years of continuous work on task-specific robotic grippers. This comprises the development of tactile sensing and rigid-soft fingers on original and proprietary designs. For the automotive industry, recent demos, developed within EU-funded projects, have focused on the cooperation of robots and human operators on tasks to be carried out together in promiscuous conditions that exceed the allowance of the current standard on human-robot cooperation.

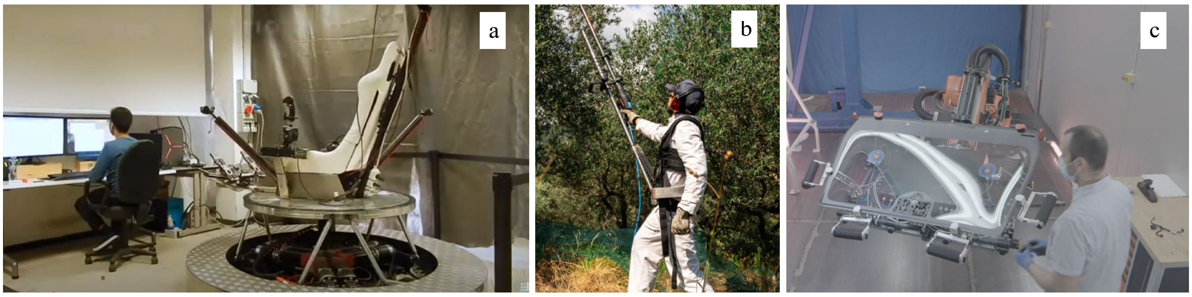

Figure 7: PMAR Lab research prototypes: a parallel robot for motion simulation in VR (a), an exoskeleton for the operation of long tools (b), and a special-purpose end-effector for collaborative assembly of an automotive windshield (c).

6. Conclusions

This paper presents the research activities of the Applied Mechanics group at the University of Genoa, highlighting both project-driven and theoretical contributions to the field. The research is conducted within the Department of Mechanical, Energy, Management, and Transport Engineering (DIME) and across three laboratories: Dynamo Lab, MCAE Lab, and PMAR Lab. The group's work encompasses dynamic analysis, diagnostics and monitoring of turbomachinery, the development of compliant mechanisms, the design and prototyping of industrial and service robots, and the creation of devices for human-machine collaboration. Given the highly interdisciplinary nature of these research areas, the Applied Mechanics group actively welcomes new collaborations.

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