UNIVERSITÀ DI TRENTO

PhD Course, 2024

"Emerging Wind Engineering & Energy Technologies at Multiple Scales: From Large Wind Turbines to Miniature Harvesters"

Credits (CFU)	**Total contact hours**	**Role in PhD Civ. Eng., Env engr.**	**Role in PhD Mech. Eng., etc.**	**Prerequisites**
2.5	18+2	General Elective	General Elective	a) Engineering PhD students in good standing b) Basic background in structural mechanics, structural dynamics and fluid mechanics, or advanced courses in engineering or physics

Description: This course introduces students to emerging wind engineering and wind energy technologies that pose several engineering design challenges. The course will describe relevant application examples: from large, offshore wind energy systems to mesoscale wind energy devices and miniature harvesters (for sensor design). The course will emphasize the importance of structural and dynamic design and demonstrate, thorough examples, the similarities that exist among the various applications.

In the first part of the course, lectures will briefly review wind fields, turbulence and aerodynamic loads in wind engineering due to stationary synoptic wind hazards (e.g., hurricanes). Dynamic analysis methods (frequency domain approach, spectral analysis, etc.) under stationary random wind loads will be employed to analyze linear structures.

In the second part, the student will learn the fundamentals of horizontal-axis wind – turbine (HAWT) towers. Current trends are devoted to large offshore systems, with rotors of diameters equal to 200m or more, capable of producing energy up to 15 Megawatts or more. The lectures will integrate aerodynamics and wind turbine design with the structures needed to support them. Topics will include classification of wind turbines and their components, blade aerodynamics (e.g., concepts of angle of attack, lift, drag, pitching moment) as it relates to atmospheric boundary layer flows, structural engineering aspects and vibration problems, aeroelastic instability (flutter) in wind turbine blades. Performance aspects such as estimation of output power will be reviewed.

In the third part, principles of energy harvesting technologies will be presented. Energy harvesting exploits ambient energy sources, primarily wind-based but also other structural vibrations, and studies technological solutions for recovery into electrical energy. Devices are similar to HAWT, but they operate at a much smaller, miniature scale (milli-watts, mainly for sensor applications). The lectures will review basic operating principles of these kinetic miniature generators, i.e., spring-mass systems where electrical power is extracted by employing electric (coupling) mechanisms and stored in a battery.

Finally, the course will discuss new emerging trends such as the engineering design of "meso-scale" devices that could potentially supplement energy at the level of one or two housing units, i.e., to supplement electricity in the case of loss of power from the grid. The nonlinear, "benign" aeroelastic vibrations are harnessed in a mechanical apparatus and subsequently used to produce electric energy. Challenges of these novel devices (scalability, battery storage, etc.) will be discussed.

Lectures will examine both fundamentals and engineering applications. A hands-on tutorial will also be delivered at the end of the course. Lectures will be in English.

Course Delivery: the course will be offered in a hybrid format. In-person lectures will be offered to PhD students at the University of Trento, Mesiano Campus. Synchronous, on-line video-streaming lectures will also be available to other students.

Course Schedule: from April 15th, 2024 to April 24th, 2024. All times are CET (UTC +1)

Schedule	Dates and times	Classroom ‡
Week 1	Monday, April 15th, 2pm-6pm Tuesday, April 16th, 10am-12pm Tuesday, April 16th, 2pm-4pm	1L
Week 2	Monday, April 22nd, 10am-12pm Monday, April 22nd, and 2pm-4pm Tuesday, April 23rd, 10am-12pm Tuesday, April 23rd, 2pm-4pm Wednesday, April 24th, 10am-12pm Wednesday, April 24th, 2pm-4pm (tutorial)	1L

(‡): Each lecture will be held at Mesiano Campus and start at the exact time.
For remote students: link to the online, synchronous lectures is: https://northeastern.zoom.us/my/lucanu

Instructor: Luca Caracoglia, Department of Civil and Environmental Engineering, Northeastern University, Boston MA, USA & *Visiting Professor, Department of Civil, Environmental and Mechanical Engineering, University of Trento, Italy*, lucac@coe.neu.edu
Office hours: via ZOOM, by appointment: https://northeastern.zoom.us/my/lucanu

Registration: Please contact the "Doctoral Programme in Civil, Environ. & Mechanical Engr." at DICAM, dicamphd@unitn.it for course registration. In the email, specify if you wish to attend in person or online**.**

Preliminary Bibliography: (*recommended readings)

Books – wind energy

Aerodynamics of Wind Turbines, 2nd ed., M.O.L. Hansen, Earthscan, London (UK)-Sterling, 2008.

Energy Harvesting Systems: Principles, Modeling & Applications, T. J. Kázmierski & S. Beeby (eds.), Springer, 2011

*Energy Harvesting Technologies, S. Priya and·D. J. Inman (editors), Springer, 2009

*Wind Energy Explained, 2nd Ed., J. F. Manwell, J. G. McGowan and A. L. Rogers, John Wiley & Sons, Inc., 2009.

Wind Turbines: Fundamentals, Technologies, Application, Economics, 3rd Ed., Eric Hau, Springer, 2013.

Books – dynamics and wind engineering

Analytical methods in vibrations, L. Meirovitch, MCGraw-Hill, New York, NY, USA, 1970.

*Random data analysis and measurement procedures (3rd edition), J.S. Bendat and A.G. Piersol, John Wiley and Sons, New York, NY, USA, 2000.

Random Vibrations, Spectral & Wavelet Analysis. D. E. Newland, Longmann, Edinburgh, UK, 1993.

*Wind Effects on Structures, 4th Ed., E. Simiu, and D. H. Yeo, John Wiley & Sons, New York, NY, USA, 2019.

Journal papers – wind energy

Design Considerations for MEMS-Scale Piezoelectric Mechanical Vibration Energy Harvesters, N. duToit, B. L. Wardle and S.-G. Kim. *Integrated Ferroelectrics* 2005, 71, 121–160.

Design of Piezoaeroelastic Energy Harvesters, A. Abdelkefi, A. H. Nayfeh and M.R. Hajj. *Nonlinear Dyn.* 2012, 68(4), 519-530.

Electromagnetic Energy Harvester with Repulsively Stacked Multilayer Magnets for Low Frequency Vibrations S.-D. Kwon, J. Park and K. Law. *Smart Mater. Struct.* 2013, 22(5), 055007.

Examining Adequacy of the Empirical Theodorsen Function for Wind Turbine Blade Section-Model Aeroelasticity, S. Li, L. Caracoglia and J. Møller-Madsen. *J. Fluids Struct.* 2023, 118, 103843

Higher-Order Moment Stability of Large Wind Turbine Blades Under Stochastic Perturbations. L. Caracoglia. Eurodyn 2023 Conference - XII International Conference on Structural Dynamics, University of Delft, Netherlands A.V. Metrikine (Ed)., *IOP Science - Journal of Physics, Conference Series*.

Modeling the Coupled Electro-Mechanical Response of a Torsional-Flutter-Based Wind Harvester with a Focus on Energy Efficiency Examination, L. Caracoglia. *J. Wind Eng. Ind. Aerodyn.* 2017, 174, 437-450.

Piezoelectric Energy Harvesting Technology: From Materials, Structures, to Applications, T. Li and P. S. Lee. *Small Struct*. 2022, 3, 2100128, https://doi.org/10.1002/sstr.202100128.

Stochastic Stability of an Aeroelastic Harvester Contaminated by Wind Turbulence and Uncertain Aeroelastic Loads, L. Caracoglia, *J. Wind Eng. Ind. Aerodyn.* 2023, 240, 105490.

The Lanchester–Betz–Joukowsky Limit, G.A.M. van Kuik, *Wind Energy 2007*, 10(3), 289-291.

<u>Journal papers – wind engineering</u>

3D Wind-Excited Response of Slender Structures: Closed-Form Solution. G. Piccardo and G. Solari G *J. Struct. Eng.-ASCE* 2000, 126(8), 936-943.

Equivalent Wind-Spectrum Technique: Theory and Applications. G. Solari. *J. Struct. Eng.-ASCE* 1988, 114(6), 1303-1323.

The Response of Slender, Line-Like Structures to a Gusty Wind. Davenport AG. *Proc. I. Civ. Eng.-Civ. Eng.* 1962, 23(3), 389-408

Details & Learning Objectives *(supplementary notes will be distributed at the start of the course)*

Topic [time allotted]	Students will be able to:
Course Introduction [1 hour]	1. "Wind engineering" *vs.* "wind energy" systems 2. Classification of emerging wind energy systems, e.g., large-scale Horizontal Axis Wind Turbines - HAWT) 3. Description of main HAWT components
Fundamentals of Structural Dynamics, Random Vibrations and Wind Engineering and [4 hours]	4. Introduction to Wind Engineering (atmospheric boundary layer flows, wind loads analysis and design) 5. Fundamentals of rigid body dynamics, linear structural dynamics & random vibrations (frequency domain) 6. Characterization of wind turbulence and stationary wind loads: the wind turbulence "spectrum" (e.g., Solari). 7. Explain the principles of *Davenport wind loading chain* for linear systems with application to 1DOF and 2DOF generalized structures 8. Davenport's peak effect factor and its developments (EWST – Equivalent Wind Spectrum Technique by Solari).
Fundamentals of HAWT Mechanics and Dynamics [3 hours]	9. Mechanics of HAWT blades: loads, ideal rigid-blade rotor model 10. Dynamics of HAWT blades: hinge-spring blade rotor model 11. Overview on dynamics of wind turbine structures: Hub and Tower
Introduction to aeroelasticity of HAWT blades [4 hours]	12. Introduction to fluid-structure interaction and aeroelasticity 13. Aeroelasticity applications in wind energy: blade flutter ("classical", stall) – fundamentals 14. Recent research trends: flutter of long, flexible, rotating HWAT blades & dynamics stability (deterministic and stochastic stability)
Miniature-scale energy harvesting principles - introduction and basic overview [4 hours]	15. Energy harvesting: principles of piezoelectric effect and materials 16. Modeling of cantilevered piezoelectric energy harvesters: uncoupled lumped parameter base excitation model (ref. 2.2.1) 17. Modeling issues: random wind flow and load artificial synthetic generation, non -linear fluid-structure interaction 18. An example of aeroelastic wind-based, harvester: the "miniature piezoelectric windmill" (ref. 1.9.1)
Meso-scale, energy harvesting devices. [2 hours]	19. Meso-scale flutter windmills: principles, modeling and examples
Tutorial [2 hours]	20. Hands-on application: wind energy systems (MatLab)

Program-level outcomes that students will attain

Student outcome	***Assessed via:***
1. identify, formulate, and solve wind energy engineering problems by applying principles of engineering, science, and mathematics	Homework project assignment

Exams and assignments: A homework project will be assigned to the students at the end of the second week of the course. Students will be required to use MATLAB software to complete the assignment. Each student will submit a *homework report* along with a computer code by the end of the course (electronic submission). The homework report will be in the form of a conference paper (approximately 8 pages). Evaluation of student performance will be based on the content of the report, its originality and preparation. *Homework submission will be necessary to earn the course credits.*

Policies on neatness and academic honesty: University of Trento policies on neatness and academic honesty will be adhered to.

Grading formula: Project assignment (100%). Grades A (excellent) through D- (fair). Specific scale will be provided to students upon request.

Instructor's Bio-Sketch

Luca Caracoglia is currently a Visiting Professor in the Department of Civil, Environmental and Mechanical Engineering at the University of Trento (year 2024). His permanent position is Full Professor in the Department of Civil and Environmental Engineering of Northeastern University (NU), Boston, Massachusetts, USA, where he directs the "Wind Engineering Research Group.". He joined NU in 2005.

Luca Caracoglia's research and professional interests are in structural dynamics, random vibrations, fluid-structure interaction of civil engineering structures, nonlinear cable network dynamics, wind engineering, wind energy and wind-based energy harvesting systems.

He has been author or co-author of 100 peer-reviewed journal publications and book chapters (published or in press) and about 140 conference proceedings / presentations in these fields. He has taught courses at the undergraduate and graduate levels in: Statics/Solid Mechanics, Structural Analysis, Steel Structure Design, Pre-stressed Concrete, Bridge Design, Wind Engineering and Wind Energy Systems. Luca Caracoglia received the NSF-CAREER Award for young investigators in 2009. For his accomplishments in the field of civil – structural engineering, Luca Caracoglia was granted the title of Fellow ASCE (held by 3% of the ASCE members) in September 2020.

Luca Caracoglia is currently a member of the Executive Board of the ANIV – Italian National Association for Wind Engineering. He served as a member of the International Executive Board of the International Association for Wind Engineering in 2012 – 2017, and as a member of the Board of Directors of the American Association for Wind Engineering (AAWE) in 2020-2022. He co-chaired the 3rd Workshop of the American Association for Wind Engineering in 2012, and co-chaired the 8th Int. Colloquium on Bluff Body Aerodynamics and Applications, in 2016.

Luca Caracoglia currently serves as an Associate Editor the Journal of Fluids and Structures (Elsevier), as an Associate Editor for the ASCE Journal of Bridge Engineering. He is also a member of the editorial board for the journals Engineering Structures (Elsevier), Structural Safety (Elsevier) and Wind and Structures (Techno-Press).

Finally, Luca Caracoglia was granted two concurrent Full Professor habilitations (accreditations) by the Italian Ministry of Public Instruction, University and Research (MIUR) in 2019: 1) Scientific Discipline ICAR 08/B3, Civil Engineering/Structural Design, 2) Scientific Discipline ICAR 08/B2, Civil Engineering/Structural Mechanics.