Hybrid Testing for Civil Engineering Structures

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Compared to other engineering systems, civil engineering structures tend to be much larger in size and unique in shape, meaning that only one sample of the same prototype is constructed. Hence, it is not economically sustainable to build other samples at full scale for the purpose of testing. Historically, engineers have been designing such systems to ensure a linear response regime, for which simple analytical models and oversimplified representation of loading may ensure safe design at the price of sub-optimal safety factors. However, today structures are expected to meet higher performance requirements, which are defined for both linear and nonlinear response regimes. The latter is the case, for example, of floating wind turbines exposed to extreme wave and wind loading or tall buildings that must safely collapse under extreme seismic events. At this regime, analytical models utilized for design are far from demonstrating sufficient accuracy, as testified by several blind-prediction contests where teams of experts compete to predict the outcome of a structural testing campaign before its execution. It follows that enabling cost-effective experimentation plays a central role in validating more predictive analytical models and empirically verifying highly optimized design solutions. For the latter case, most likely, pure numerical simulations will never suffice. It comes with no surprise that structural testing developed into a self-standing methodological research area.

My research at Aarhus University, Department of Civil and Architectural Engineering (AU-CAE, hereinafter), develops in this area with a focus on hybrid testing. Instead of a physical model, hybrid testing is performed using a hybrid physical-numerical model of the structural prototype. Specifically, physical models of one or a few structural components of the prototype (physical substructure (PS)) are tested in the laboratory using servo-controlled actuators. Displacement/force boundary conditions are updated in real-time to emulate the interaction with a numerical model of the rest of the prototype (numerical substructure (NS)). In practice, a time-stepping analysis algorithm solves the equation of motion of the hybrid model, which gathers numerical and experimental forces. The structural response of the tested components is not determined a priori, but it comes as the result of the interaction with a virtual yet realistic assembly. According to this philosophy, instead of simplified loading histories, hybrid testing is performed using realistic loading patterns, such as recorded seismic accelerograms. It follows that hybrid testing combines elements of automatic control, numerical analysis, and physical testing.

The aim of this course is to provide both the theoretical and the experimental tools necessary to perform hybrid testing so that the student, in the end, can carry out an experiment independently. The course is organized into 6 modules, and the workload is 20h of in-class lectures + 20h of home exercises (optional):

- **Module 1 – Basic introduction and overview of application case studies**. The module provides a basic introduction of hybrid testing with an overview of all tools (theoretical and experimental) that are necessary to master the methodology.
- **Module 2 – Numerical time-stepping integration.** The module provides the theoretical framework for numerical time integration and presents a few reference algorithms utilized to coordinate hybrid testing (static and dynamic).
- **Module 3 – Actuation and control systems.** The module provides the theoretical framework for model actuation and control systems and presents a methodology for their numerical simulation.
- **Module 4 – Test rehearsal using numerical simulations.** The module demonstrates how to combine the elements developed in Module 2 and Module 3 to simulate a hybrid test prior to its execution.

- **Module 5 – Model-order reduction.** The module provides the theoretical framework for model-order reduction, which is crucial to ensuring the dynamic stability of the hybrid test.
- **Module 6 – Laboratory tutorial using Arduino.** The module demonstrates hybrid testing using a small experimental setup based on Arduino and cheap sensing/actuation equipment.

Modules 2-6 includes both theoretical derivations and numerical/experimental hands-on tutorial developed in the classroom. **Please come with your laptop and install MATLAB/Simulink.**