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Towards an automated physics-regularized model updating strategy applied to the monitoring of civil engineering structures in low-frequency dynamics

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As most of modern systems are now equipped with numerous sensing devices, the integration of experimental data in model-based approaches provides new techniques for monitoring the occurrence and propagation of structural damage in a structural health monitoring context. In particular, the dialogue between physics-based models and experimental data has become of major importance in the last two decades with the emergence of new paradigms such as *Digital Twins* [6] or *Dynamic Data-Driven Application Systems* (DDDAS) [1, 3]. The latter consists in establishing a close online interaction between models and measurements with a dual objective: (i) exploiting model predictions for decision-making operations on the experimental system such as model-based control and, (ii) updating the numerical model using data assimilated in real-time.

For earthquake engineering applications, the CEA/TAMARIS facility carries out seismic tests using shaking-tables moved by high-power hydraulic actuators. However, controlling the hydraulic actuators of the shaking-tables is still a challenging task that emphasizes the need of establishing a DDDAS framework. Indeed, the modal signature of damaging specimens can suddenly change under seismic loading conditions [2]. As modal signature is the key input-feature for linear control law design, the initial control strategy may become inadequate when damage occurs, leading to unstable experiments.

In this context, this work aims at contributing to the integration of Finite Element (FE) models in control loop of shaking-tables by resorting to a dynamical data-to-model interaction. In this talk, we will essentially focus on the identification/update loop of FIG. 1 from sparse and noisy measurements acquired in low-frequency dynamics. A new numerical framework is presented for data assimilation able to operate in real-time, robust to measurement noise as well as easily handleable by non-expert users.

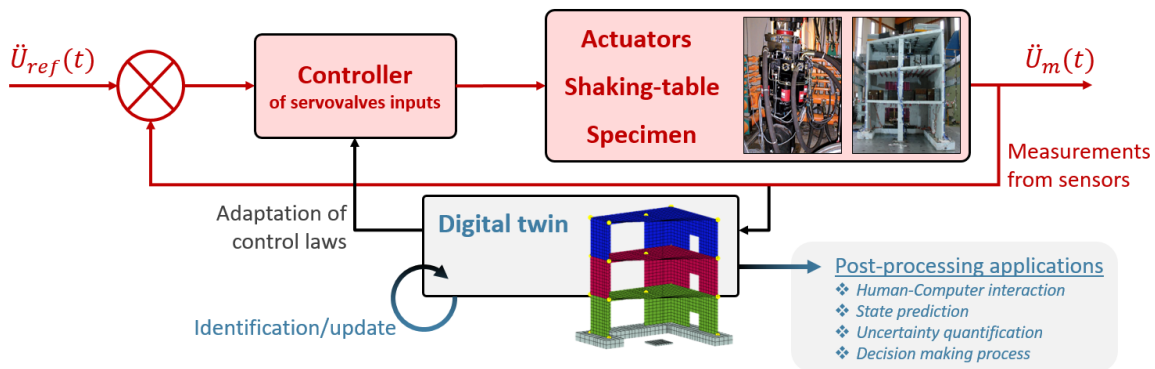


Figure 1: DDDAS framework for the control of shaking-tables - Introduction of a numerical model in the feedback loop for adaptive control law design.

Considering the model updating problem itself, low signal-to-noise ratio measurements from seismic inputs may be hard to integrate for correcting FE models properly. Alternatively to standard deterministic or stochastic model updating techniques, a strategy based on the minimization of a *modified Constitutive Relation Error* functional (mCRE) has been recently tailored to low-frequency dynamics in [4]. Built as a Hermitian data-

to-model distance written in the frequency domain enriched with a CRE residual accounting for model bias, the mCRE functional has shown extended robustness to measurement noise and the ability to process strongly nonlinear datasets (due to occurrence of damage) with reasonably low computational effort. Besides, the mCRE-based model updating algorithm has been made independent of any expert user's *a priori* knowledge: automated procedures permit to define all mCRE internal parameters and the model parametrization itself is adaptively tuned to identify damage at best according to the available measurements.

In order to adapt this model updating algorithm to online structural monitoring applications, following the strategy initiated in [5], we integrate the mCRE as new observation operator within a dual Unscented Kalman filter, leading to a new *Modified Dual Kalman Filter* algorithm (MDKF). It differs from classical nonlinear Kalman filtering techniques for parameter estimation as the metric of the measurement update equation allows to confront indirectly model predictions with measurements, meaning that optimal parameters are sought as mCRE minimizers. Although this new framework seems more complex to operate, general guidelines based on physical meaning and engineering judgement are provided regarding the calibration of internal tuning parameters. In particular, noise covariance error matrices can be quickly and efficiently chosen.

After being validated using synthetic data, the methodology successfully processed actual measurements of the SMART2013 shaking-table test campaign in a real-time context. In the latter, the possibility to perform real-time monitoring of complex structures undergoing nonlinear phenomena is emphasized (see FIG. 2). The good correlation with former identification results [2,4] illustrates the relevance of this new approach for online structural monitoring and suggests promising use of MDKF for adaptive control design purposes.

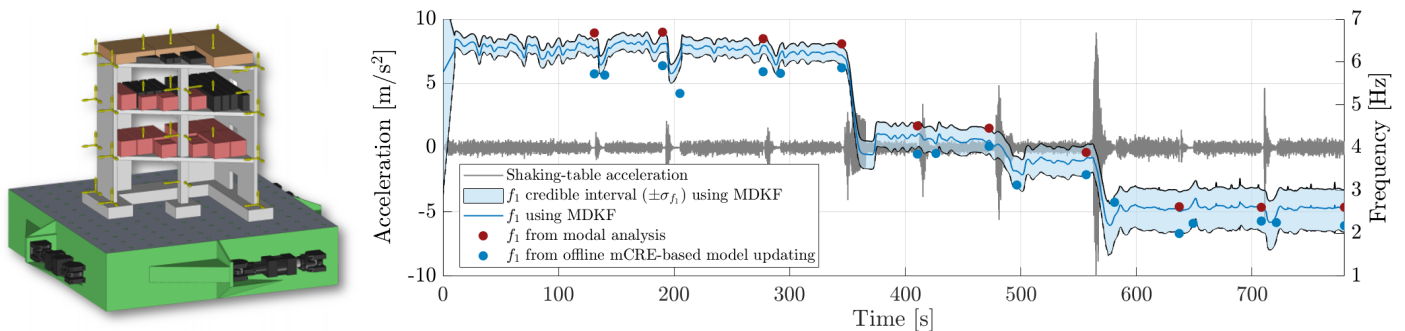


Figure 2: SMART2013 - Tracking the first eigenfrequency of the specimen using MDKF. Former reference identification results are given for comparison purposes: [4] in blue dots, [2] in red dots. An accelerometer measurement is also shown to relate inputs with structural state evolution.

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