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**Other Conference Item**

**Author(s):**
Tsokanas, Nikolaos; Stojadinovic, Bozidar

**Publication date:**
2020

**Permanent link:**
https://doi.org/10.3929/ethz-b-000474269



**Funding acknowledgement:**
764547 - Dynamic virtualisation: modelling performance of engineering structures (EC)

# Evaluation of the Seismic Response of a Structure with an attached Pendulum using Stochastic Real-Time Hybrid Simulation

**Nikolaos Tsokanas*, Bozidar Stojadinovic**

ETH Zürich
Institute of Structural Engineering
Stefano-Franscini-Platz 5, 8093 Zürich
tsokanas@ibk.baug.ethz.ch, stojadinovic@ibk.baug.ethz.ch

## ABSTRACT

Stochastic real-time hybrid simulation (SRTHS) is an innovative technique to investigate the statistical characteristics and uncertainties in the dynamic response of prototype structures to stochastic loading taking into consideration the randomness in the parameters of the structure and the excitation, as well as the uncertainties that are inevitably introduced in the experimental procedure involved in hybrid numerical-physical modeling. Importantly, the performance of the transfer system (actuation control system and the reaction frame), interfacing the numerical and physical substructures of the hybrid model, influences the outcomes of hybrid simulations, especially in real-time or fast hybrid simulations. Fast hybrid simulations are needed to investigate the response of rate-sensitive prototypes, with rate-sensitivity manifested through the behavior of prototype materials or components, for example viscous dampers, or through the non-smooth boundary conditions, such as contact interfaces.

The objective of this study is to investigate the effect of discontinuous boundary conditions on the outcome of dynamic response simulations of a hybrid model. The prototype structure is a rigid body that uplifts and rocks in-plane in response to earthquake ground motion excitation. A pendulum is attached to the body above its center of gravity in order to possibly stabilize it. The hybrid model comprises a numerical model of the rigid body and a physical model of the pendulum. During a dynamic seismic response simulation conducted using a time-stepping solution algorithm, a ground motion is applied to the base of the rigid body (the numerical substructure) and the displacement of the point of pendulum attachment is computed and applied to the pendulum (the physical substructure) using an actuator. The actuator force excerpted during this motion, which includes the restoring force of the pendulum, is fed back and applied at the point of pendulum attachment to the rigid body. The impact between the rigid body and its support surface is the boundary condition discontinuity of interest. Advanced control theory techniques will be employed to design a closed-loop actuation system to ensure smooth interaction between the components of the hybrid model and to conduct the simulations in real time. Moreover, the actuation system will be able to deal with the uncertainties encountered in the testing procedure, maintaining concurrently high performance levels and guaranteeing robustness.

Hybrid model parameters of interest, such as the restitution coefficient, will be selected to be treated as random variables. The outputs of the hybrid simulations will be represented using probability distributions of the relevant engineering response parameters, such as the rigid body and the pendulum tilt angles. Data from multiple runs of the stochastic hybrid model will be used to build surrogates of the original hybrid model. Numerous runs of these meta-models will provide the data to perform global sensitive analysis and to give insight into which stochastic input variables affect the hybrid model response the most and in which way.

**Keywords:** stochastic real-time hybrid simulation, dynamic response, uncertainty quantification, close loop control