Recent developments in Real-Time Hybrid Simulation (RTHS)

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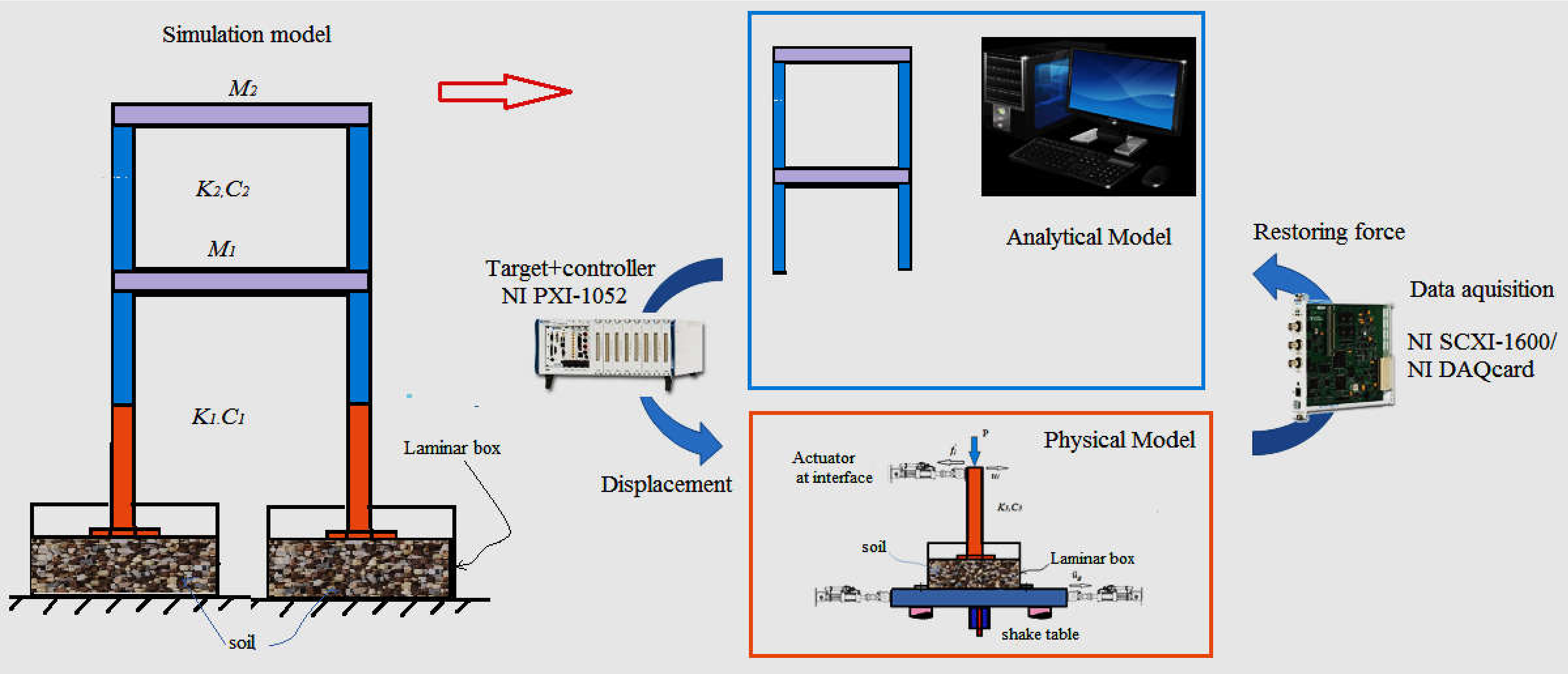
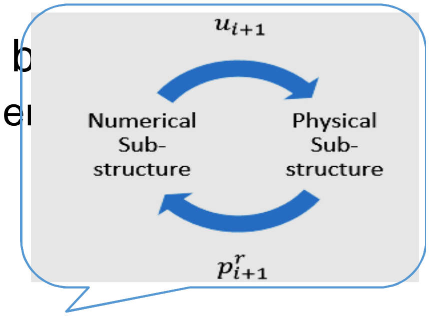
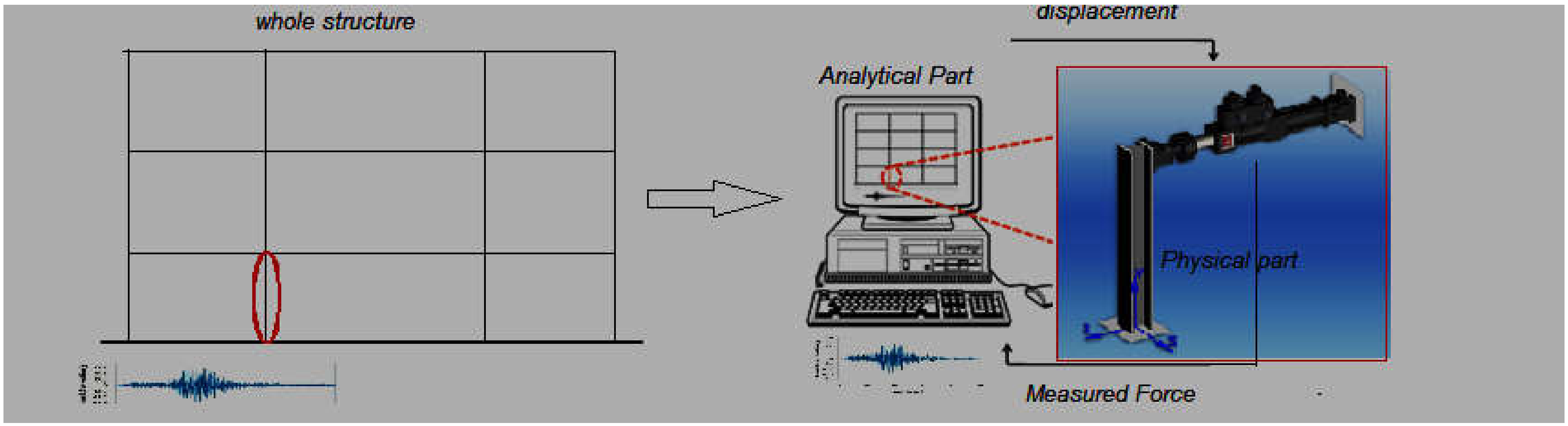


Hybrid simulation - a bridge between numerical analysis and laboratory testing!

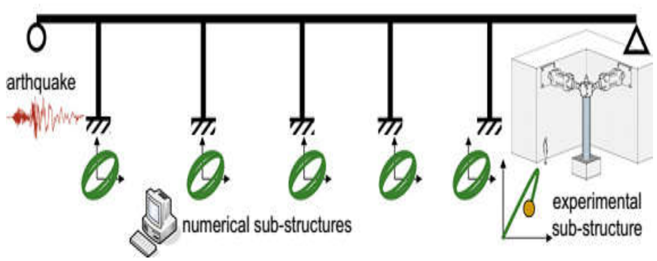
- Part of a structure whose behavior is not well-understood is tested physically (e.g., soil-structure interaction, isolators, dampers, components with high non-linearity, etc.), while the remaining is modelled numerically
- Rate of test execution (λ=test duration/ground motion duration) can b
  - Slow (pseudo-dynamic testing, λ=50-200) - cannot capture rate-depende
  - Fast (λ=10-50)
  - Real-time (λ=1)
- Test formulation and mode of actuator control:
  - Displacement-based → displacement control - easy and common in practice
  - Force-based method → force control - difficult but appropriate for stiff structures
- Hardware performance and software efficiency are essential

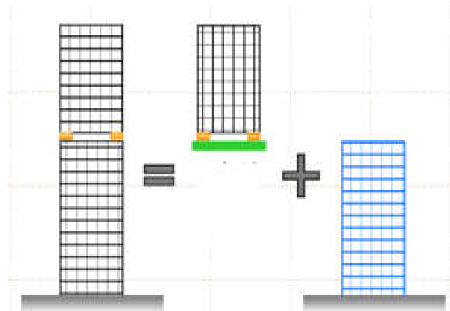


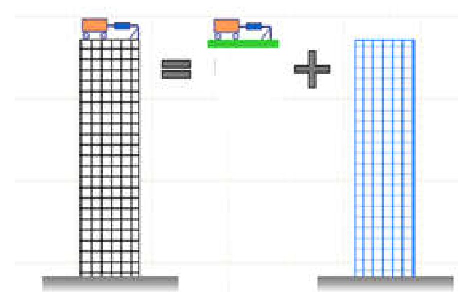


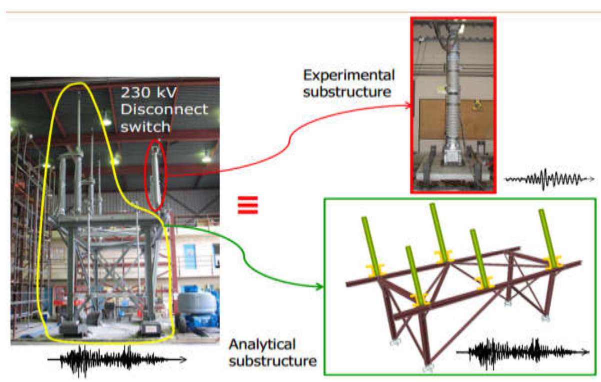
Hybrid simulation as a seismic testing technique

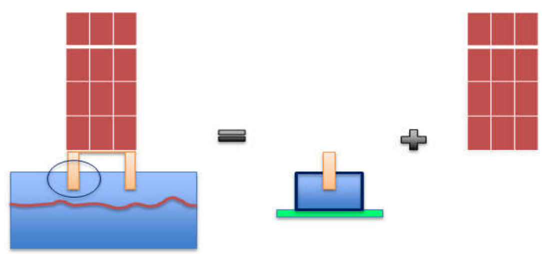
- Avoids scale effects
- Economically attractive and feasible for practical application
- Allows online numerical model-updating using experimental results
- Coupled response with other actions can be simulated numerically
- Geographically distributed testing is possible
- Allows physical testing of energy dissipation devices in a structure











Main issues in real-time hybrid simulation

1. Time-integration scheme

Integration scheme is preferred to be:

- ✓ Explicit – improves determinism of numerical solution
- ✓ Unconditionally stable – fulfills higher modes stability condition (small Δt)
- ✓ Controllable numerical damping – reduces the contribution of spurious modes

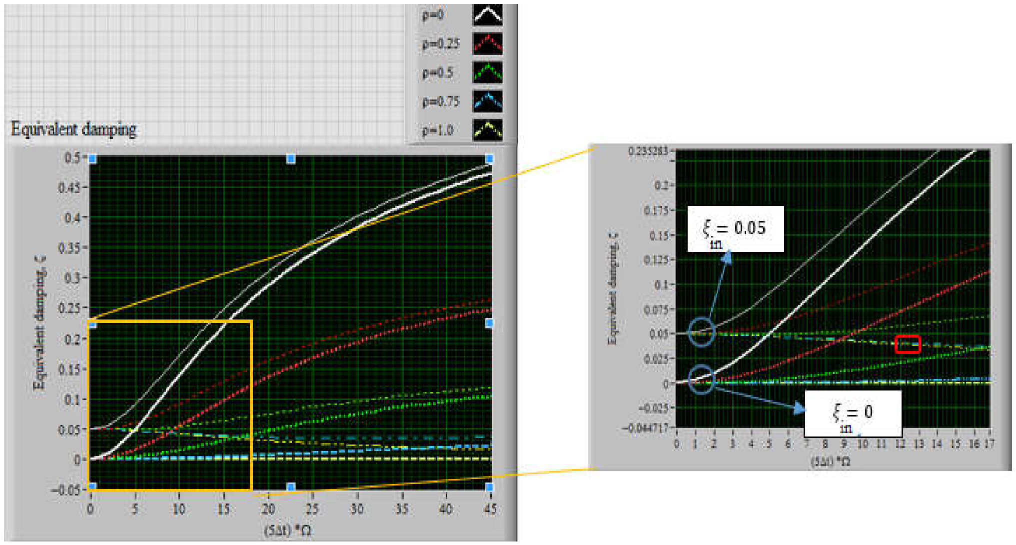
Attractive scheme: KR-α method (after Kolay and Ricles, 2014)

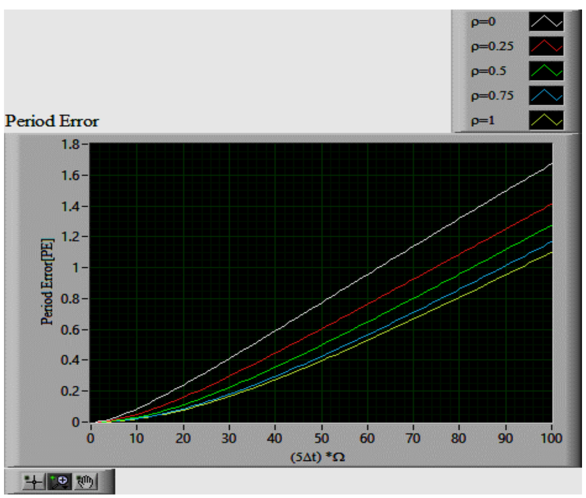
$$M_G \hat{\ddot{Y}}_{i+1} + C_G \dot{Y}_{i+1-\alpha_f} + K_G Y_{i+1-\alpha_f} = [\phi]^T P_{i+1-\alpha_f}$$
$$\dot{Y}_{i+1} = \dot{Y}_i + \Delta t \boldsymbol{\alpha}_1^* \ddot{Y}_i$$
$$Y_{i+1} = Y_i + \Delta t \dot{Y}_i + \Delta t^2 \boldsymbol{\alpha}_2^* \ddot{Y}_i$$
$$\hat{\ddot{Y}}_{i+1} = \boldsymbol{\alpha}_3^* \ddot{Y}_i + (\boldsymbol{I} - \boldsymbol{\alpha}_3^*) \ddot{Y}_{i+1}$$

- ❑ It is a one-parameter explicit method based on implicit generalized-α method
- ❑ Algorithmic damping controlled by spectral radius (ρ_∞)
- ❑ Good performance in terms of accuracy, negligible lower mode numerical damping and period elongation
- ❑ Unconditionally stable for linear elastic and non-linear softening systems

Main issues in real-time hybrid simulation

1. Time-integration scheme





Linear

$$A = \begin{bmatrix} 1 & 1 & \alpha_2 \\ 0 & 1 & \alpha_1 \\ \frac{\Omega^2}{b} & \frac{2\xi\Omega + a\Omega^2}{b} & \frac{\alpha_3 + 2a\alpha_1\xi + a\alpha_2\Omega^2}{b} \end{bmatrix}$$

$$where\ a = 1 - \alpha_f \,\&\, b = \alpha_3 - 1$$

Non-linear

$\frac{k_t}{k} = 1 + \frac{4}{\Omega^2}$ for $\rho_\infty = 1$

$\frac{k_t}{k} = \frac{4}{3}\left(1 + \frac{2\xi}{\Omega}\right) + \frac{4}{\Omega^2}$ for $\rho_\infty = 0$

- Accuracy analysis(using free-vibration response):

Integration scheme discrete transfer function:

$$\mathrm{H}(z) = \frac{X(z)}{F(z)} = \frac{\sum_{i=1}^{3} n_i z^i}{\sum_{i=1}^{3} d_i z^i}$$

✓ Energy dissipation - contributing modes are negligibly affected

✓ Numerical dispersion - negligible period error in lower modes

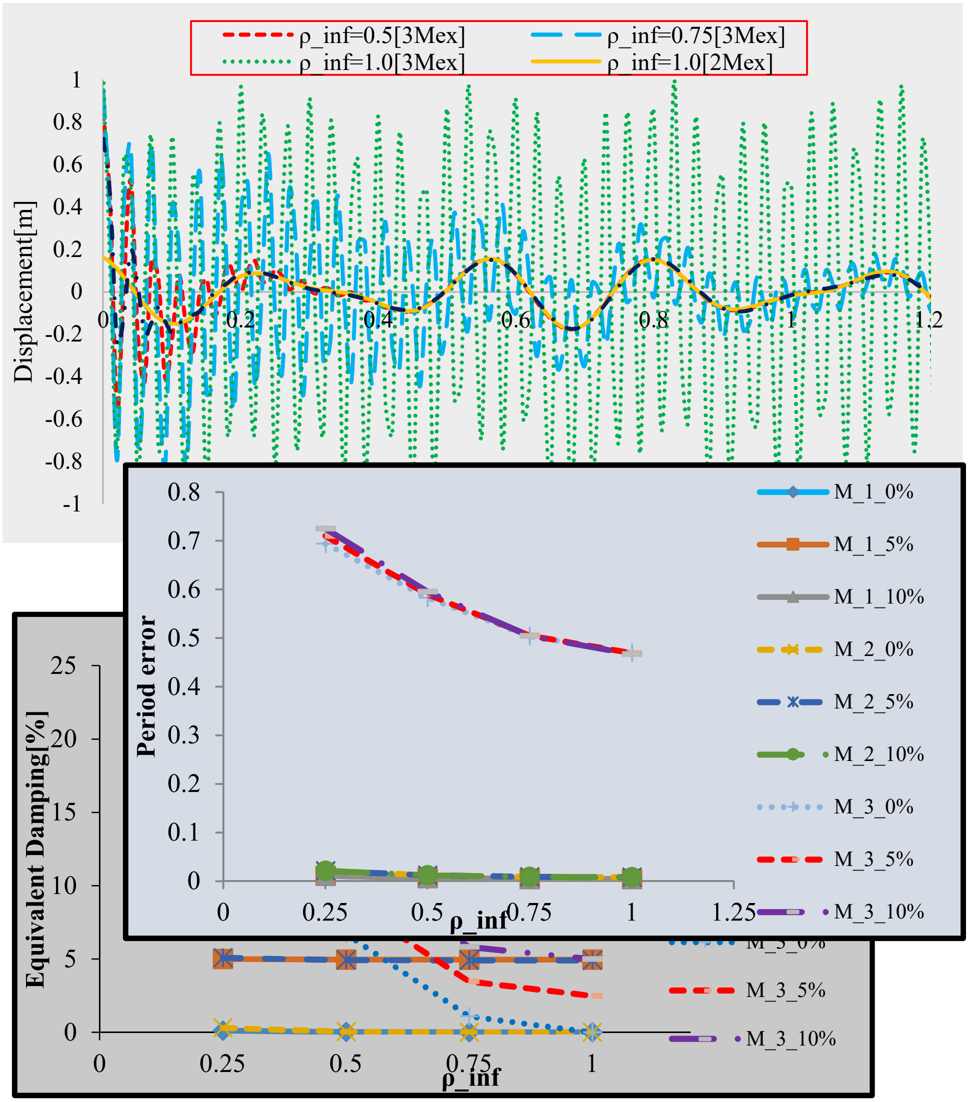
- Stability analysis:

✓ Increased stability limit for increased numerical damping for softening systems

Note: spectral radius near unity under significant inherent damping may lead to $\xi_{eq} < \xi_{in}$

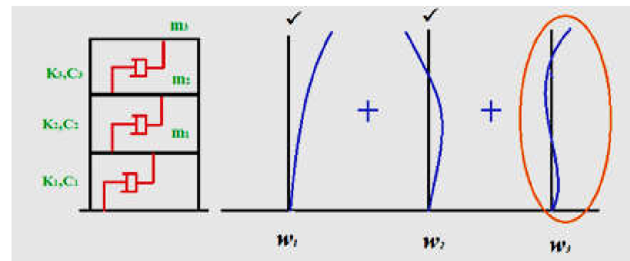
Main issues in real-time hybrid simulation

1. Time-integration scheme



Numerical analysis of a linear elastic 3DOF frame with a high-frequency third mode under free vibration (no inherent damping)

Modes=3.6Hz, 5.1Hz and 44.4Hz



Objective: demonstrate its efficiency in reducing third-mode contribution

$\xi_{eq}=\xi_N+\xi_{In}$ %	1st Mode Ω=0.08168	2nd Mode Ω=0.2324	3rd Mode Ω=2.60

$(T-T_n)/T_n$	1st Mode Ω=0.08168	2nd Mode Ω=0.2324	3rd Mode Ω=2.60
ρ∞=0.25	0.010887	0.02111	0.694013
ρ∞=0.50	0.006358	0.012544	0.583015
ρ∞=0.75	0.004647	0.009204	0.503956
ρ∞=1.00	0.004257	0.008434	0.469958

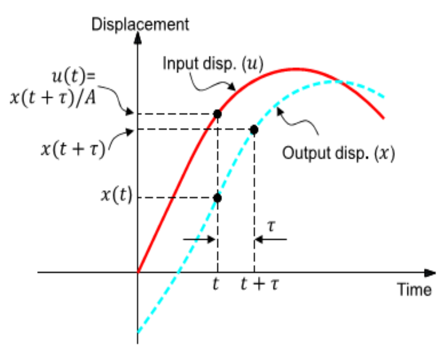
Main issues in real-time hybrid simulation

2. Restoring force error compensation

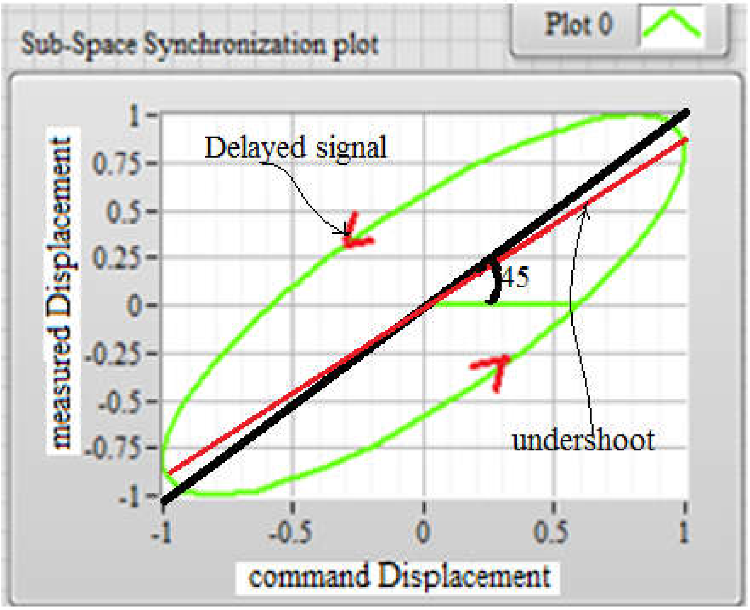
Components of error:

- Response delay of actuator (20-80ms)
- Communication delay (~1ms)
- Computational delay (unit time step)
- Gain error (λ, instrumentation etc.)

Delay

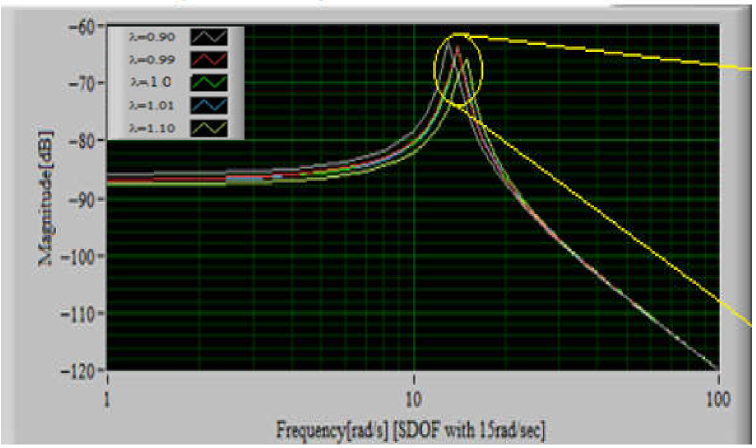


- **Effects of delay error:**
  - Inaccurate response
  - Stability problems due to negative damping introduced
- **Effects of gain error:**
  - Inaccurate response
    - Overshoot - add energy
    - Undershoot - remove energy



Inclination<45^0 - undershoot; CCW rotation - Delayed signal

Transfer function magnitude under amplitude Error



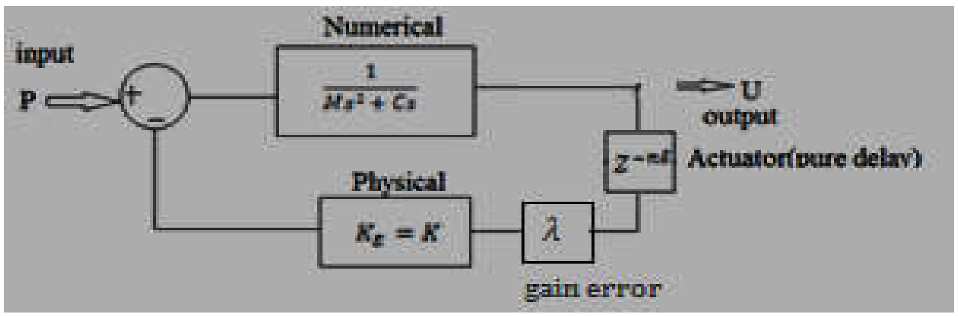
Main issues in real-time hybrid simulation

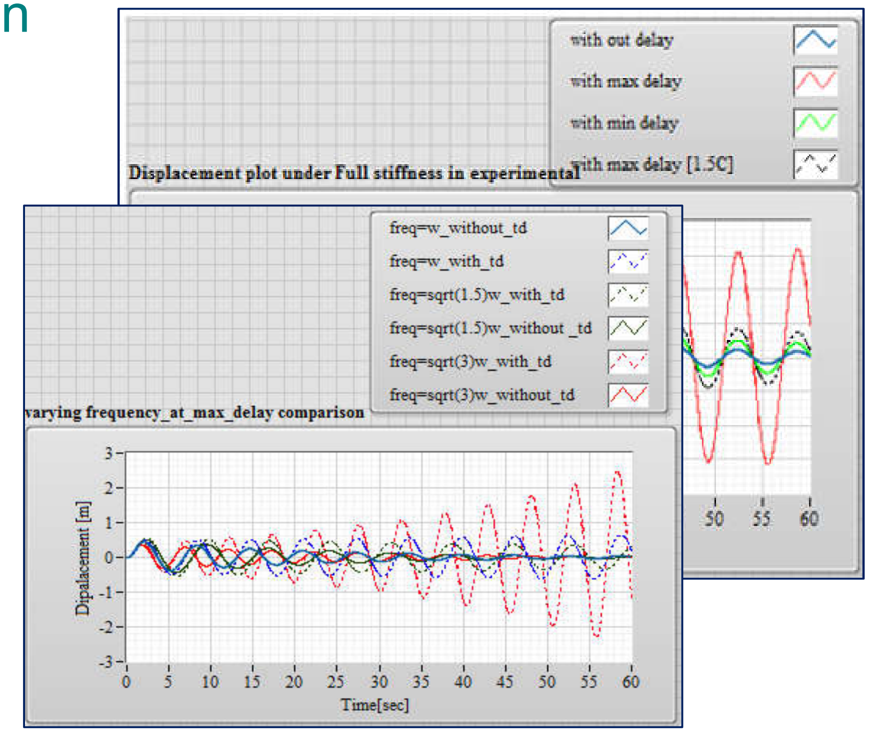
2. Restoring force error compensation

Precarious effects of delay:

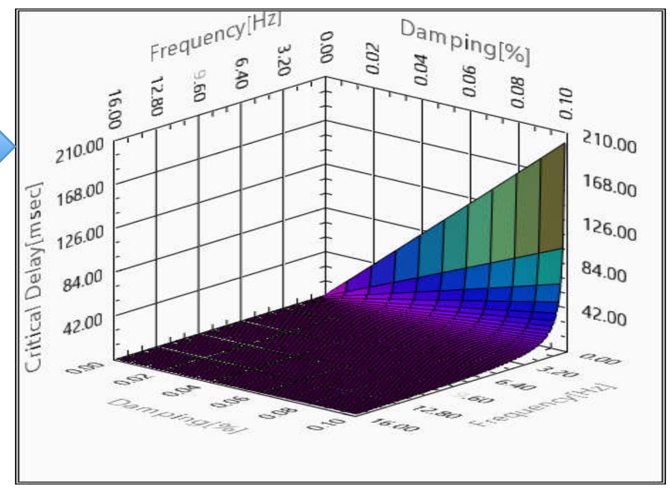
- Instability as the negative damping exceeds inherent damping

Instability analysis on linear elastic SDOF under no gain error with varying delay and damping for impulse response:





Comments: small delays lead to instability problems if system is lightly damped or element is stiff (e.g. squat wall)



- Critical delay investigation on SDOF with total stiffness modelled physically:

$$delay = e^{-s\tau} = (1 - sT)/1 + ST$$

Or

$$delay = e^{-s\tau} = \sum_{i=0}^{n} \frac{(-1)^i (s\tau)^i}{i!}$$

Main issues in real-time hybrid simulation

2. Restoring force error compensation

Error compensation techniques:

- ➢ Model based
  - ✓ Inverse compensation
  - ✓ Second-order compensation
- ➢ Adaptive method
  - ✓ Adaptive inverse compensation
  - ✓ Adaptive time series (ATS)

Attractive method: ATS

- ❑ Updates compensation parameters (A) at the rate of time integration clock speed using LS solution

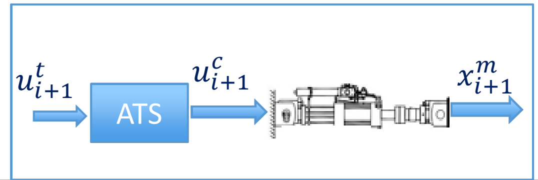
$$A = (X_m^T X)^{-1} X_m^T U_C \qquad u_{i+1}^c = [u_{i+1}^t \; \frac{d^1}{dt^1} u_{i+1}^t \; \frac{d^2}{dt^2} u_{i+1}^t][A]$$

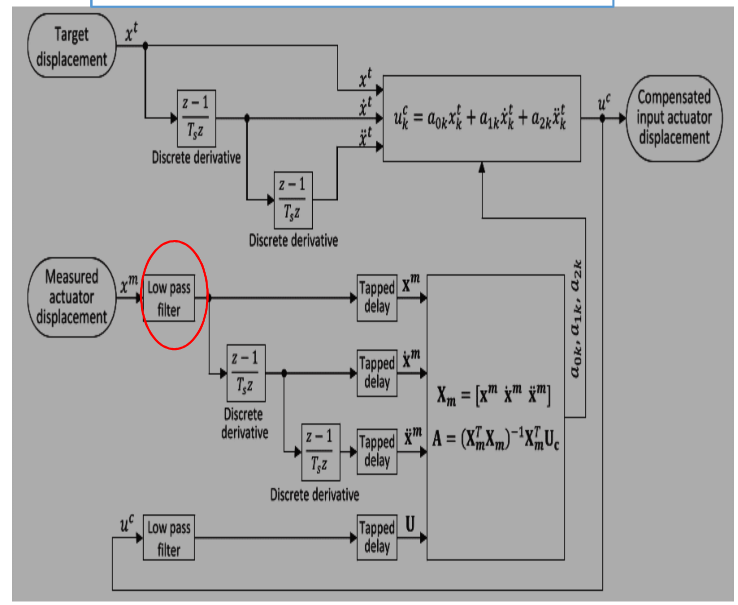
$$X_m = \begin{bmatrix} x_{k-1}^m & \cdots & \frac{d^2}{dt^2} x_{k-1}^m \\ \vdots & \ddots & \vdots \\ x_{k-q}^m & \cdots & \frac{d^2}{dt^2} x_{k-q}^m \end{bmatrix} \qquad U_c = [u_{k-1}^c, u_{k-2}^c, \dots \dots, u_{k-q}^c]^T$$

Where m and c represent previously measured and compensated parameters, respectively, and t represents a target value

Comparison of real time hybrid simulation using ATS on moment resisting frame by Chae and Ricles (2012):

- higher performance can be achieved in large amplitude ground motion
- triggering of ATS is found suitable to control signal to noise ratio





- LP Butterworth of higher order can be considered for filtering

Table V. Summary of real-time hybrid simulation results.

Earthquake name	Hazard level	Maximum measured actuator displacement amplitude (mm): Inverse compensation	Second-order compensator	ATS	NRMS error (%): Inverse Compensation	Second-order compensator	ATS
Imperial Valley	LDBE	17.1	15.6	15.9	3.6	2.0	1.9
	DBE	25.0	23.4	23.3	3.1	2.0	1.6
	MCE	41.9	37.0	37.4	2.8	2.0	1.4
Northridge	LDBE	23.3	22.4	23.6	2.5	2.0	1.9
	DBE	32.4	33.3	33.2	2.9	2.4	2.2
	MCE	49.7	49.1	48.7	3.7	3.6	2.5

NRMS, normalized root mean square; ATS, adaptive time series; LDBE, low-level design basis earthquake; DBE, design basis earthquake; MCE, maximum considered earthquake.

Main issues in real-time hybrid simulation

3. General hardware setup and framework for RTHS

Integrating existing shake table facility architecture for HS framework:

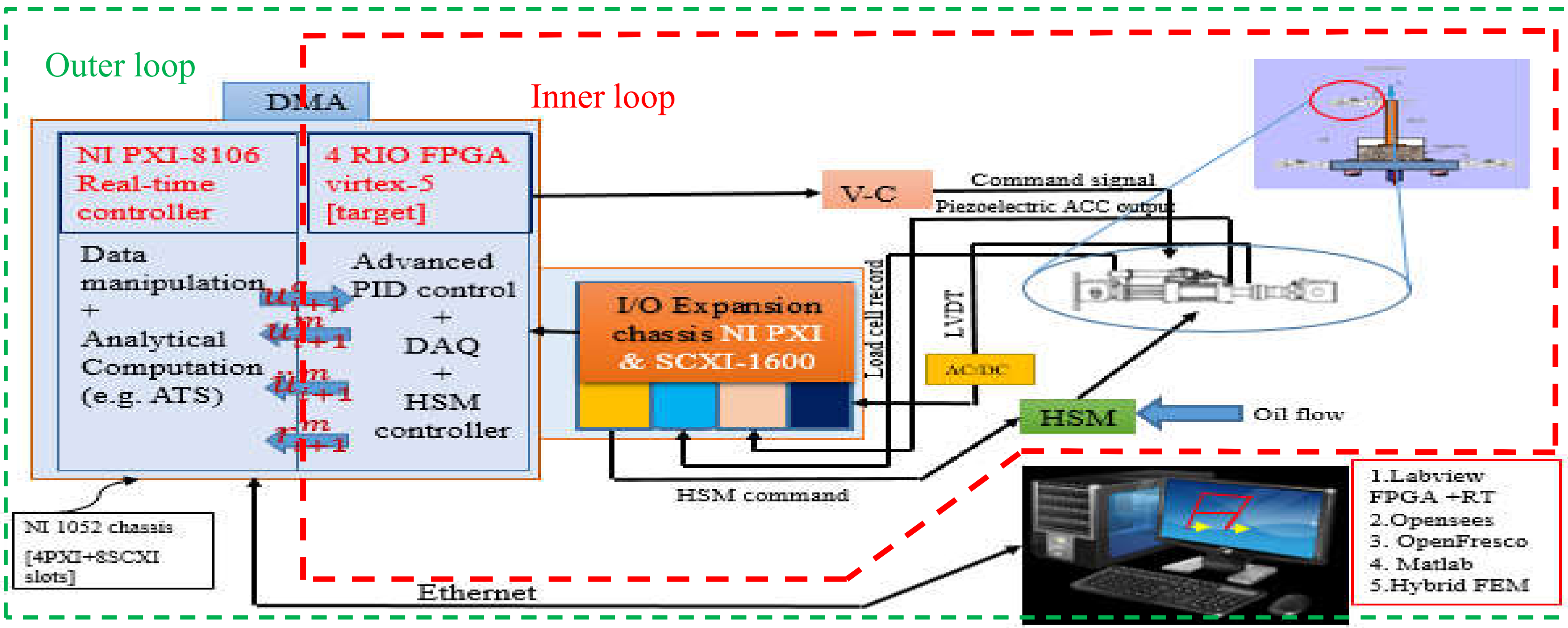
- NI Field Programmable Gate Array (FPGA) as target machine
- NI Real-Time controller
- NI SCXI data acquisition
- 3-stage servo-hydraulic actuator + 1-stage servo-valve(uniaxial shake table)
- Rectangular laminar box for soil

- PID control and HSM (hydraulic service manifold) operate in the inner loop with NI I/O modules(NI PXI +NI SCXI)
- Compensated displacement is sent to servo-valve and measured quantities are recorded and manipulated in NI RT

I.L

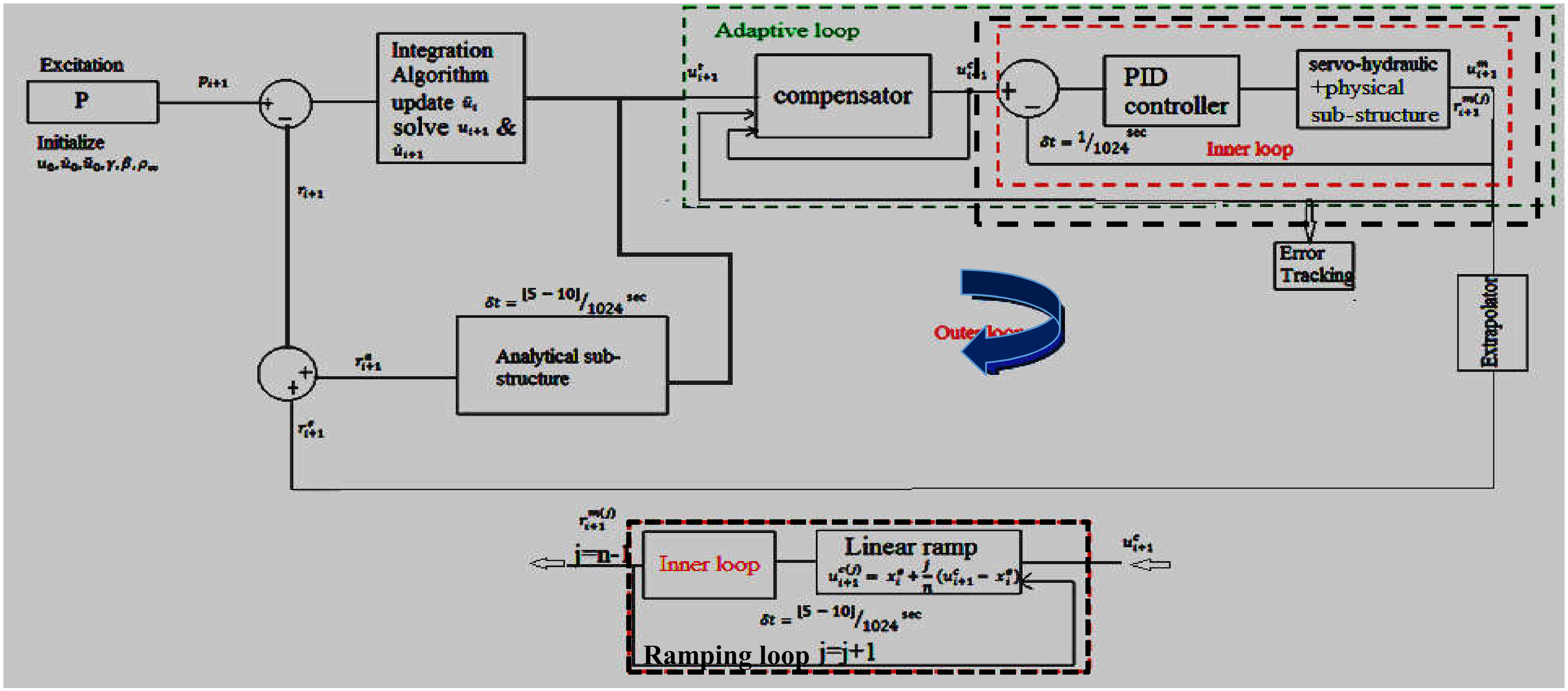
- DMA (direct memory access) allows small latency
- Error tracking using ATS parameters
- Computer solves equation of motion in the outer loop and deploys it to NI PXI

O.L



Main issues in real-time hybrid simulation

3. General hardware setup and framework for RTHS



- A four loop architecture using parallel execution of substructure counterparts
- Synchronization of physical and analytical parts through linear ramping and last sub-step extrapolation based on K_e and C_e
- Summing up restoring force in outer loop for KR-α to solve equation of motion followed by updating acceleration to compute next step target displacement and velocity
- Online error tracking allowing decision making (continue or abort test)

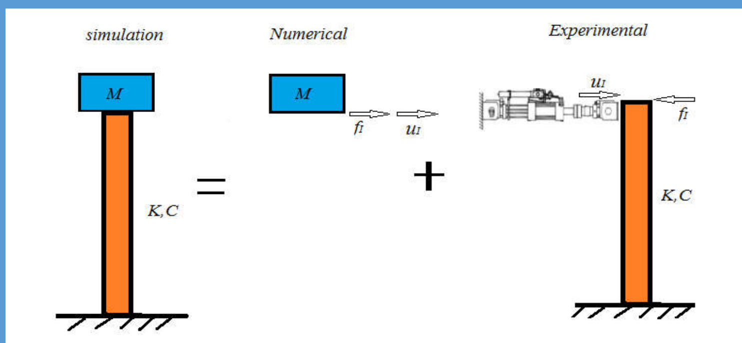
Plan of hybrid simulation tests at LNEC

1. Pseudo-dynamic tests

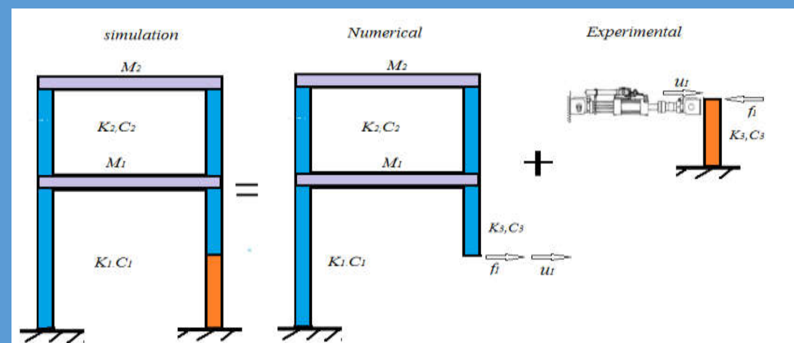
Objective: Gradual progress from slow to real-time tests, in order to perform:

- ✓ Assessment of existing integration schemes, error tracking methods and compensation techniques and possible improvements
- ✓ Assessment of challenges using existing shake table control and solutions

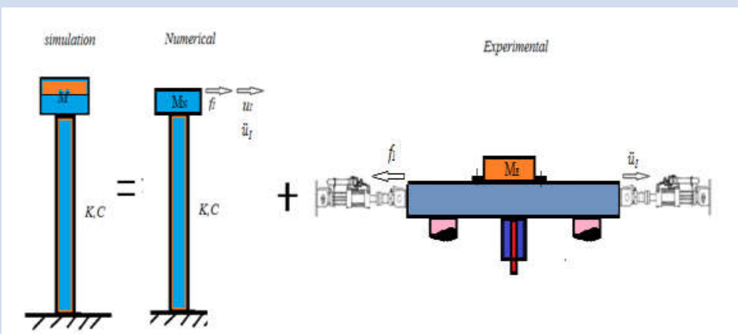
1. Cantilever (Actuator error and ATS) [**λ**=50-200]



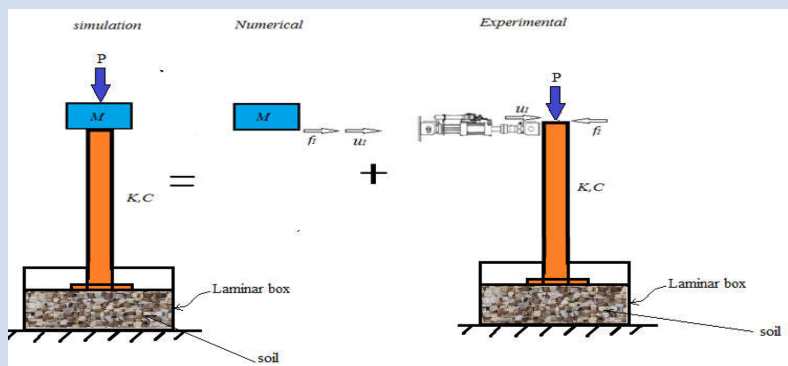
2. 2-Storey frame (KR-α and DOFs) [**λ**=50-200]



3. Shake table test (shake table errors + control issues) [λ=50-200]



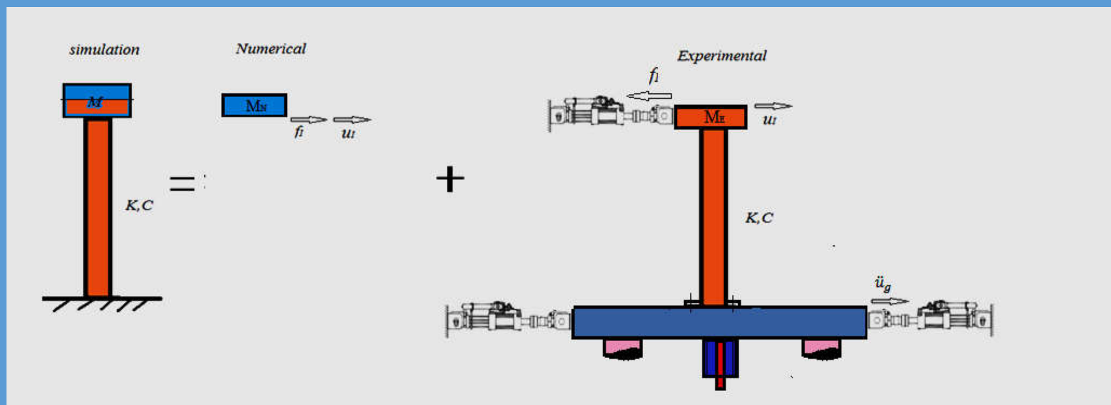
4. Test involving SSI (SSI issues)[λ=50-200/10-50]



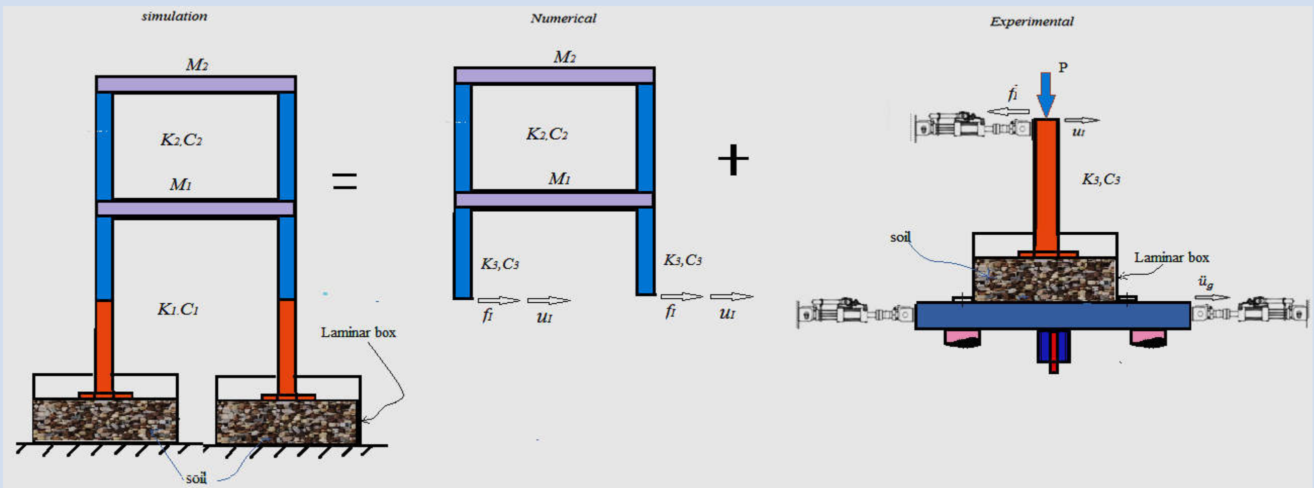
Plan of hybrid simulation tests at LNEC

2. Fast to real-time hybrid simulation tests

5. Shake table + actuator at interface (displacement control?)[**λ**=10-50/1-10]



6. SSI, near and/or at real-time (real-time challenges and summary)[λ=1-10]

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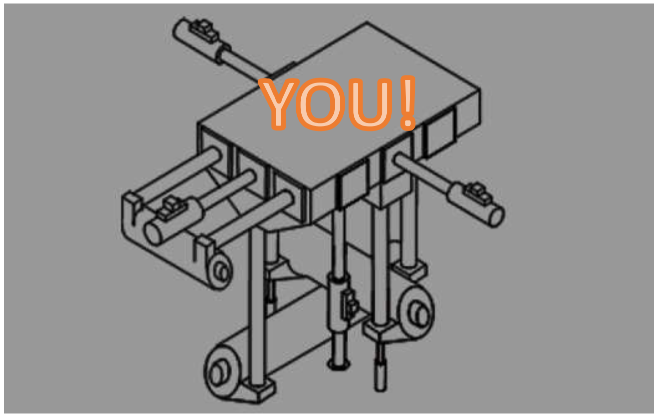
YOU!