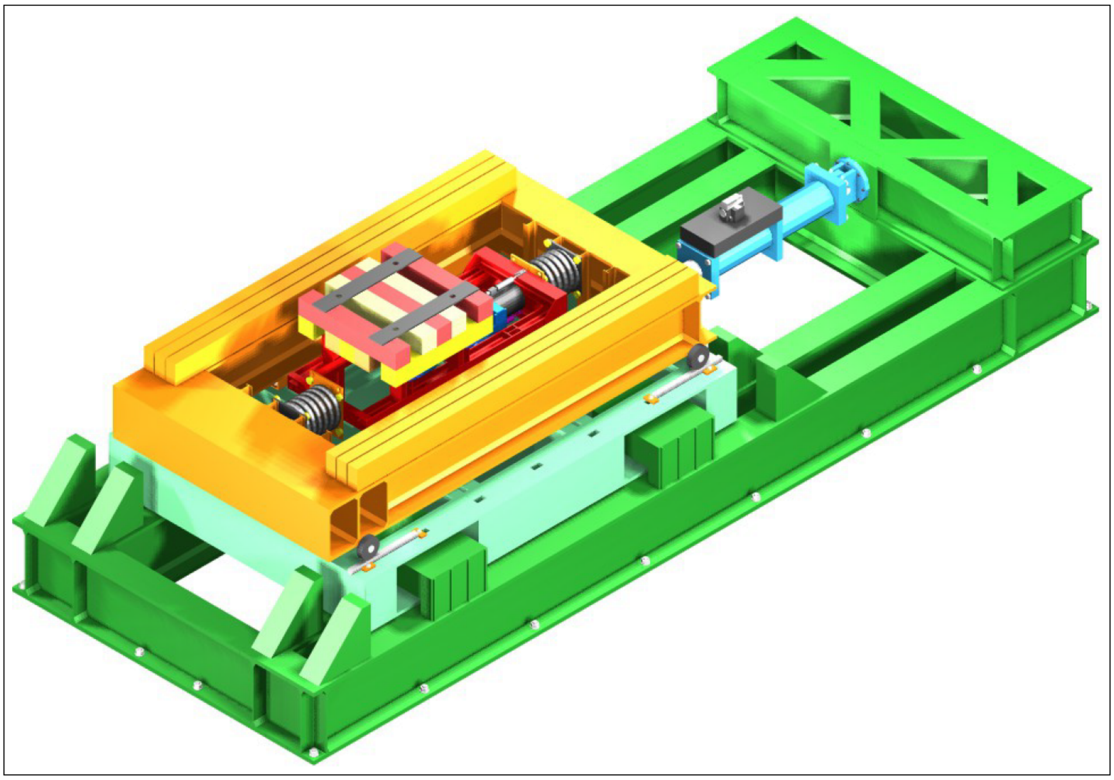
Controlo de Plataforma Sísmica

Projeto de Sistemas Mecatrónicos



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GitHub Repository & Overleaf Report

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Contents

1 Problem definition

The current seismic platform testing process at Laboratório Nacional de Engenharia Civil (LNEC) consists of synthesizing a drive signal, distinct from the reference signal, so that the platform replicates the response spectra of the reference signal, i.e. the earthquake. The system comprising the seismic platform and the structure to be tested uses a PI (Proportional-Integral) controller with fixed parameters.

During the seismic test, the structure is subjected to a series of tests with different earthquake amplitudes. Initially, the test is carried out with the earthquake at a reduced amplitude, assessing the subsequent damage. The procedure is then repeated with the same earthquake, but at a higher amplitude, again assessing the damage, and so on until a defined amplitude is reached, which usually corresponds to the original amplitude of the earthquake.

Before each test, a dynamic identification of the system is carried out, using a limited-band white noise signal, always with the same amplitude, to determine the system's transfer function. this function is then used in the command signal generation algorithm. throughout this process, the amplitude of the reference signal increases progressively, and it is expected that the structure will enter a non-linear regime, either due to the behaviour of some of its components or the damage accumulated during the various tests.

At the end of each test, the system's performance is evaluated by comparing the response spectrum of the reference signal with that of the signal measured on the platform. However, it is not always possible to achieve satisfactory performance with the command signal synthesized initially, and it may be necessary to generate more than one command signal and carry out additional tests at the same amplitude. This procedure, although necessary in some situations, should be avoided as it induces additional damage to the structure.

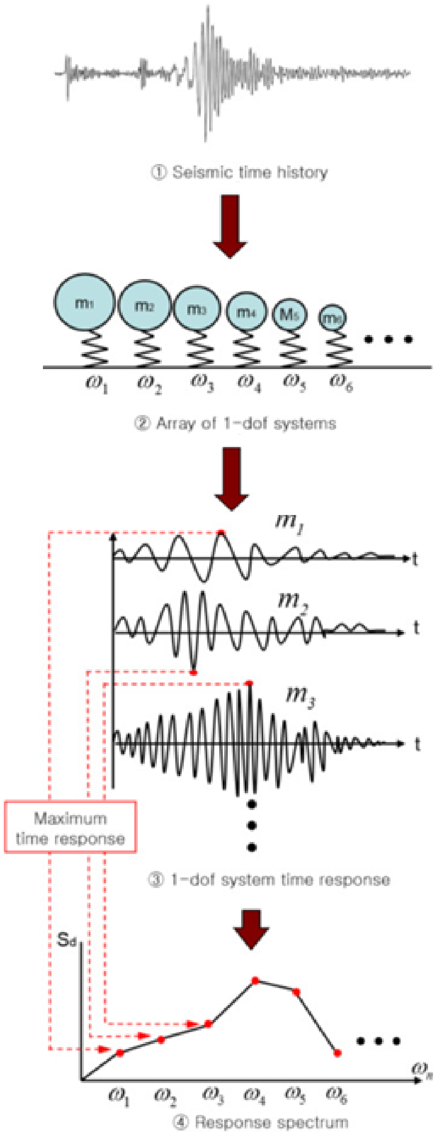
In addition, the system faces physical limitations inherent to the equipment, namely with regard to the finite field of displacement, velocity and acceleration, which must be duly considered during the tests.

2 Definition of Objectives

Implement the controller or strategy to ensure that the platform vibrations reproduce the test seismic signal (reference/earthquake) as accurately as possible, taking into account the following aspects:

- The amplitude of the earthquake increases progressively with each test during the experimental campaign;
- Before each test, a dynamic identification of the system is carried out at a reduced amplitude (to avoid damaging the model). One objective will be to assess the feasibility of using the earthquake response to identify, or complement the identified model, and cover higher amplitudes.
- The command signal, generated *offline*, is imposed on the seismic platform without prior evaluation by simulation as to its effectiveness;
- The seismic platform system with 1 degree of freedom (ST1D) is capable of testing models with a mass of up to 5 tons, and operates in a band of interest from 0 to 25 Hertz. It also has the following limitations (which should be confirmed in laboratory tests):
  - Maximum displacement, in absolute value, of 100 mm
  - Maximum speed, in absolute value, of 0.4 m/s
  - Maximum acceleration, in absolute value, of 25 m/s^2
- The model to be tested may initially exhibit linear behavior, but as it degrades, it inevitably becomes non-linear. In general, the structures tested have two vibration modes in the seismic platform's band of interest, whose initial characteristics (without damage) are:
  - ◇ $1.5 \le f_1(\text{Hz}) \le 4$
  - ◇ $2 \le \xi_1(\%) \le 5$
  - ◇ $6 \le f_2(\text{Hz}) \le 10$
  - ◇ $5 \le \xi_2(\%) \le 15$
  - ◇ Damping in damaged structures can reach:
    - ∗ $\xi_1 = 10\%$
    - ∗ $\xi_2 = 25\%$
- Performance will be evaluated by comparing the response spectrum of the measured signal with that of the reference signal.

3 Response Spectrum in Civil Engineering



The **response spectrum** is a fundamental concept in earthquake engineering and structural dynamics. It represents the maximum response (such as displacement, velocity, or acceleration) of a structure modeled as a **single-degree-of-freedom (SDOF) system** subjected to a ground motion.

1. **Ground Motion Dependency**
   - It is derived from an earthquake acceleration time history.
   - Different earthquakes produce different response spectra.
2. **Structure's Dynamic Properties**
   - The response depends on the structure's **natural frequency** and **damping ratio**.
   - Structures with different natural periods respond differently to the same ground motion.
3. **Spectral Parameters** The response spectrum can show maximum values of:
   - **Spectral Acceleration (Sa)** – Used for force-based design.
   - **Spectral Velocity (Sv)** – Important for energy-based considerations.
   - **Spectral Displacement (Sd)** – Relevant for displacement-based design.

Some of it's applications in Civil Engineering are:

- **Seismic Design of Buildings & Bridges**: Response spectra help in defining design forces.
- **Code-Based Seismic Analysis**: Building codes (e.g., *ASCE 7, Eurocode 8, IS 1893*) provide standard response spectra.
- **Performance-Based Seismic Design (PBSD)**: Uses response spectra to predict structural behavior.

4 Modelling Seismic Table Dynamics

In Gidewon G. Tekeste (2021) a model for the ST1D with a rigidly attached payload is devised by combining linearized analytical models of each of it's components (controller, servo valve, hydraulic actuator, platen mass, and total damping).

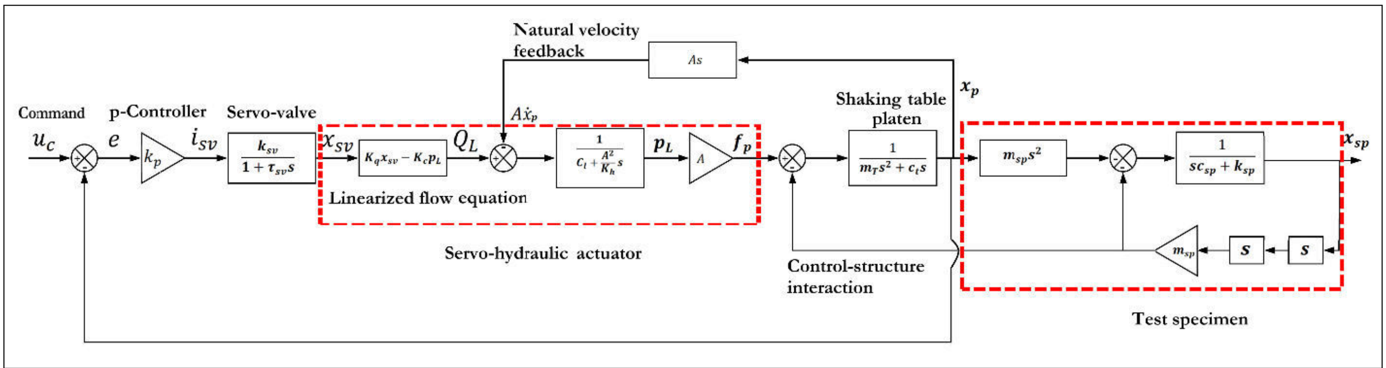


Figure 1: Schematic diagram of a shaking table system with payload rigidly attached (Tekeste, 2021)

In the previously mentioned publication, the parameters in table 1 were determined for the model in figure 1.

It's important to note that the servo valve and hydraulic actuators have since been updated. Until a new identification of the updated system has been performed, the parameters determined in Tekeste (2021) are the ones which will be used in all simulation studies.

Table 1: ST1D model parameters (Tekeste, 2021)

Symbol	Description	Value (Units)
k_p	Proportional gain of the controller	1.2993 V/cm
k_{sv}	Servo-valve gain	1934.50 $cm^3/s/V$
τ_{sv}	Time-delay parameter of the servo-valve transfer function	0.0246 s
k_q	Valve flow gain	1934.50 $cm^3/s/V$
k_c	Valve pressure-flow gain	8.37005×10^{-8} $m^3/s/kPa$
C_l	Total leakage coefficient of the piston	8.37005×10^{-8} $m^3/s/kPa$
A	Area of the fluid under compression in the actuator	0.012456 m^2
V_t	Total volume of the fluid under compression in the actuator	0.002659 m^3
β_e	Effective bulk modulus of the system	193716.28 kPa
K_h	Oil-column frequency of the actuator	4531.79 kPa/m
m_p	Mass of the platen	1.9751 ton
c_t	Combined damping force of the actuator and the platen	5.7800 kNs/m
k_{sp}	Stiffness of the SDOF structure	Assumed value
c_{sp}	Damping of the SDOF structure	Assumed value
m_t^*	Total mass considering the payload (shaking table)	Calculated value
H_{sp}	Transfer function relating the displacements of the platen and the SDOF structure	Function-defined

A *Simulink* model of the block diagram in Figure 1 was built in order to simulate the ST1D dynamics, however, it's implementation resulted in a build up of numerical errors leading to overflow, making this modelling approach unviable.

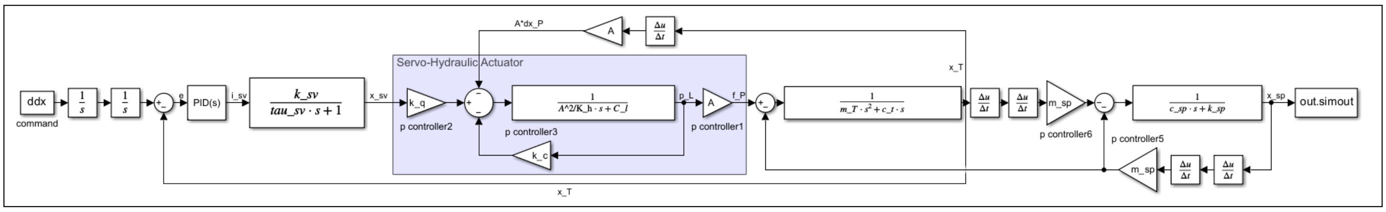


Figure 2: *Simulink* model of the ST1D

Given the previous results, an alternative approach was found in order to simulate the system, which consisted on obtaining the transfer function relating the desired platen position, x_{ref}, as input, and the force applied to the platen, F_P, as output.

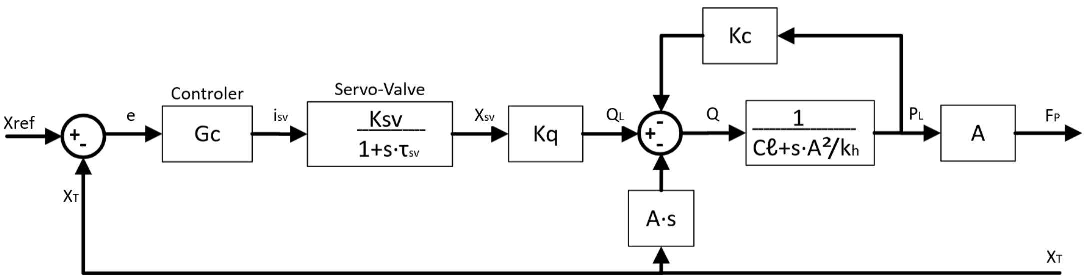


Figure 3: Block diagram of ST1D

From the block diagram in figure 3, the following equations were derived:

$$\begin{cases} G_C(s) = \dfrac{i_{sv}}{e} = \dfrac{i_{sv}}{x_{\text{ref}} - x_T} \\ \dfrac{Q_L}{x_{\text{ref}} - x_T} = \dfrac{Q_L}{e} = K_q \cdot \dfrac{K_{\text{sv}}}{1 + \tau_{\text{sv}} s} \cdot G_C(s) \end{cases} \Longrightarrow G_{csv}(s) = \frac{Q_L}{i_{sv}} = \frac{k_{sv} k_q G_c}{1 + \tau_{sv} s} \tag{1}$$

$$P_L = \frac{1}{C_l + \frac{A^2}{k_h} \cdot s} [Q_L - A \cdot S \cdot x_T - k_c \cdot P_L] \Longrightarrow \frac{F_P}{i_{sv}} = \frac{A \cdot \frac{k_{sv} k_q}{1 + \tau_{sv} s}}{k_{Pl} + \frac{A^2}{k_h} \cdot s + A^2 \cdot s \cdot G_{xT/Fp}} = G_{Fp/i_{sv}}(s) \quad \text{, where } k_{Pl} = k_c + k_l \tag{2}$$

To represent the dynamics of a typical structure on test(which have two vibration modes in the bandwidth of the seismic table), a 2 degree of freedom mass-spring-damper system is coupled to the platen, as depicted in figure 4:

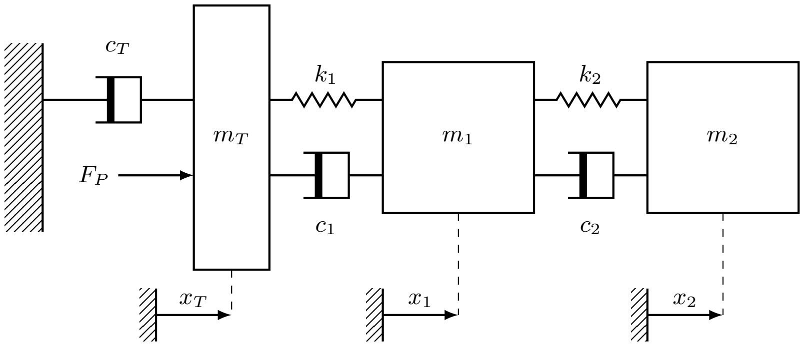


Figure 4: Schematic of the 2 degree of freedom mass-spring-damper system coupled to the platen

The mass m_i, stiffness k_i, and damping c_i, of each element will be determined such that it's natural frequency f_i and damping ratio ξ_i are similar to the structures in test:

$$k_i = m_i \cdot (2\pi f_i)^2 \quad (3) \qquad c_i = 2 \cdot \xi_i \cdot m_i \cdot (2\pi f_i) \quad (4)$$

For the system in figure 4 the following equations of motion are obtained:

$$\begin{cases} m_T\ddot{x}_T + C_1(\dot{x}_T - \dot{x}_1) + K_1(x_T - x_1) = F_p \\ m_1\ddot{x}_1 + C_1(\dot{x}_1 - \dot{x}_T) + C_2(\dot{x}_1 - \dot{x}_2) + K_1(x_1 - x_T) + K_2(x_1 - x_2) = 0 \\ m_2\ddot{x}_2 + C_2(\dot{x}_2 - \dot{x}_1) + K_2(x_2 - x_1) = 0 \end{cases} \iff \tag{5}$$

$$\iff \begin{cases} m_T\ddot{x}_T + (C_1 + C_2)\dot{x}_T + K_1 x_T - C_1\dot{x}_1 - K_1 x_1 = F_p \\ m_1\ddot{x}_1 + (C_1 + C_2)\dot{x}_1 + (K_1 + K_2)x_1 - C_1\dot{x}_T - C_2\dot{x}_2 - K_1 x_T - K_2 x_2 = 0 \\ m_2\ddot{x}_2 + C_2\dot{x}_2 + K_2 x_2 - C_2\dot{x}_1 - K_2 x_1 = 0 \end{cases} \iff$$

$$\iff \begin{bmatrix} m_T & 0 & 0 \\ 0 & m_1 & 0 \\ 0 & 0 & m_2 \end{bmatrix} \begin{bmatrix} \ddot{x}_T \\ \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix} + \begin{bmatrix} C_1 + C_2 & -C_1 & 0 \\ -C_1 & C_1 + C_2 & -C_2 \\ 0 & -C_2 & C_2 \end{bmatrix} \begin{bmatrix} \dot{x}_T \\ \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} + \begin{bmatrix} K_1 & -K_1 & 0 \\ -K_1 & K_1 + K_2 & -K_2 \\ 0 & -K_2 & K_2 \end{bmatrix} \begin{bmatrix} x_T \\ x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} F_p \\ 0 \\ 0 \end{bmatrix}$$

From the system of equations 5, the following transfer functions relating the displacements of the each mass to the displacements of an adjacent mass, or the force applied to the platen, are obtained:

$$\frac{x_T}{F_P} = \frac{G_1 G_2 - G_{21}^2}{G_T G_1 G_2 - G_T G_{21}^2 - G_2 G_{T1}^2} = G_{xT/Fp}(s) \tag{6}$$

$$\frac{x_1}{x_T} = \frac{G_{T1} G_2}{G_1 G_2 - G_{21}^2} = G_{x1/xT}(s) \tag{7}$$

$$\frac{x_2}{x_1} = \frac{G_{21}}{G_2} = G_{x2/x1}(s) \tag{8}$$

$$G_T(s) = m_T \cdot s^2 + (c_T + c_1) \cdot s + k_1 \tag{9}$$

$$G_1(s) = m_1 \cdot s^2 + (c_1 + c_2) \cdot s + k_1 + k_2 \tag{10}$$

$$G_2(s) = m_2 \cdot s^2 + c_2 \cdot s + k_2 \tag{11}$$

$$G_{T1}(s) = c_1 \cdot s + k_1 \tag{12}$$

$$G_{21}(s) = c_2 \cdot s + k_2 \tag{13}$$

$$G_{Fp/x_{ref}}(s) = \frac{G_{csv}}{\frac{k_{pl}}{A} + \frac{A \cdot s}{k_h} + G_{xT/Fp}(G_{csv} + A \cdot s)} \tag{14}$$

$$G_{xT/x_{ref}}(s) = G_{Fp/x_{ref}} \cdot G_{xT/Fp} \tag{15}$$

$$G_{x1/x_{ref}}(s) = G_{x1/xT} \cdot G_{xT/x_{ref}} \tag{16}$$

$$G_{x2/xT}(s) = G_{x2/x1} \cdot G_{x1/xT} \tag{17}$$

For a preliminary analysis of the mathematical model, some simulations were run using the seismic data from the 1940 El Centro earthquake. Table 2 contains the chosen parameters for the simulated 2DOF coupled structure (Figure 4).

Parameter	**1st Mode**	**2nd Mode**
Mass (m) [kg]	1000	1000
Frequency (f) [Hz]	2	10
Damping Ratio (ζ)	0.02	0.10
Stiffness (k) [N/m]	$1.58 \cdot 10^5$	$3.95 \cdot 10^6$
Damping Coefficient (c) [N·m/s]	502.65	12566.4

Table 2: Modal Parameters for the System

Initially the simulations were run with the controller set as $G_c(s) = 129.93$, which is the tune typically used at LNEC. Afterwards, a simulation was run with $G_c(s)$ as:

$$G_c(s) = K_p + \frac{K_i}{s} + \frac{K_d \cdot s}{T_f \cdot s + 1} \qquad \text{where: } Kp = 499, Ki = 308, Kd = 9.44, Tf = 0.00518 \tag{18}$$

Where the parameters K_p, K_i, K_d and T_f were obtained using MATLAB's *pidtune* function, with the tuning option *'DesignFocus'* set to *'reference-tracking'*. This results are labelled in the plots as "tuned".

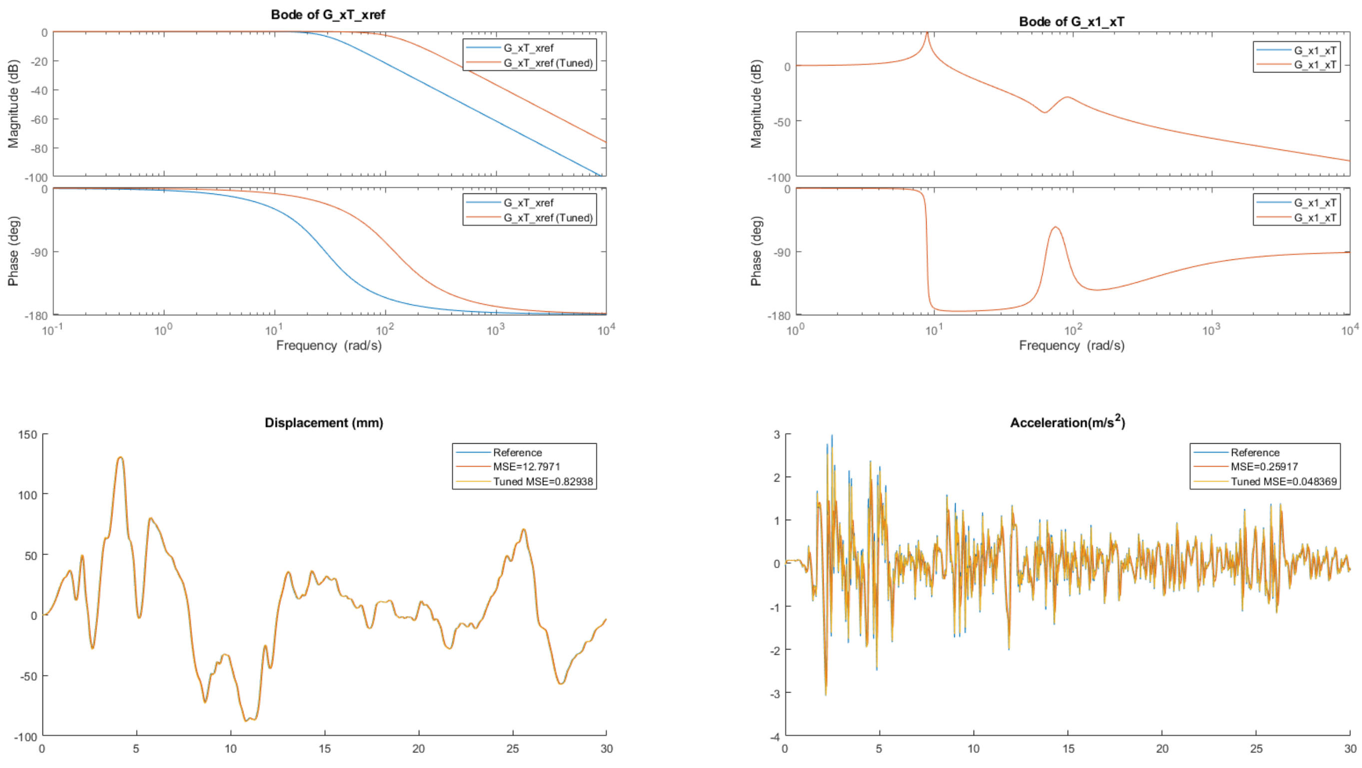


Figure 5: Bode plots of G_xT_x$_{\text{ref}}$ before and after tuning, as well as displacement and acceleration plots.

Both the displacement and acceleration tracking errors were significantly improved with the simple PIDF tune. A similar method could be quite simple to implement on the digital controller running on National Instruments hardware used at LNEC, and this may be an option worth exploring.

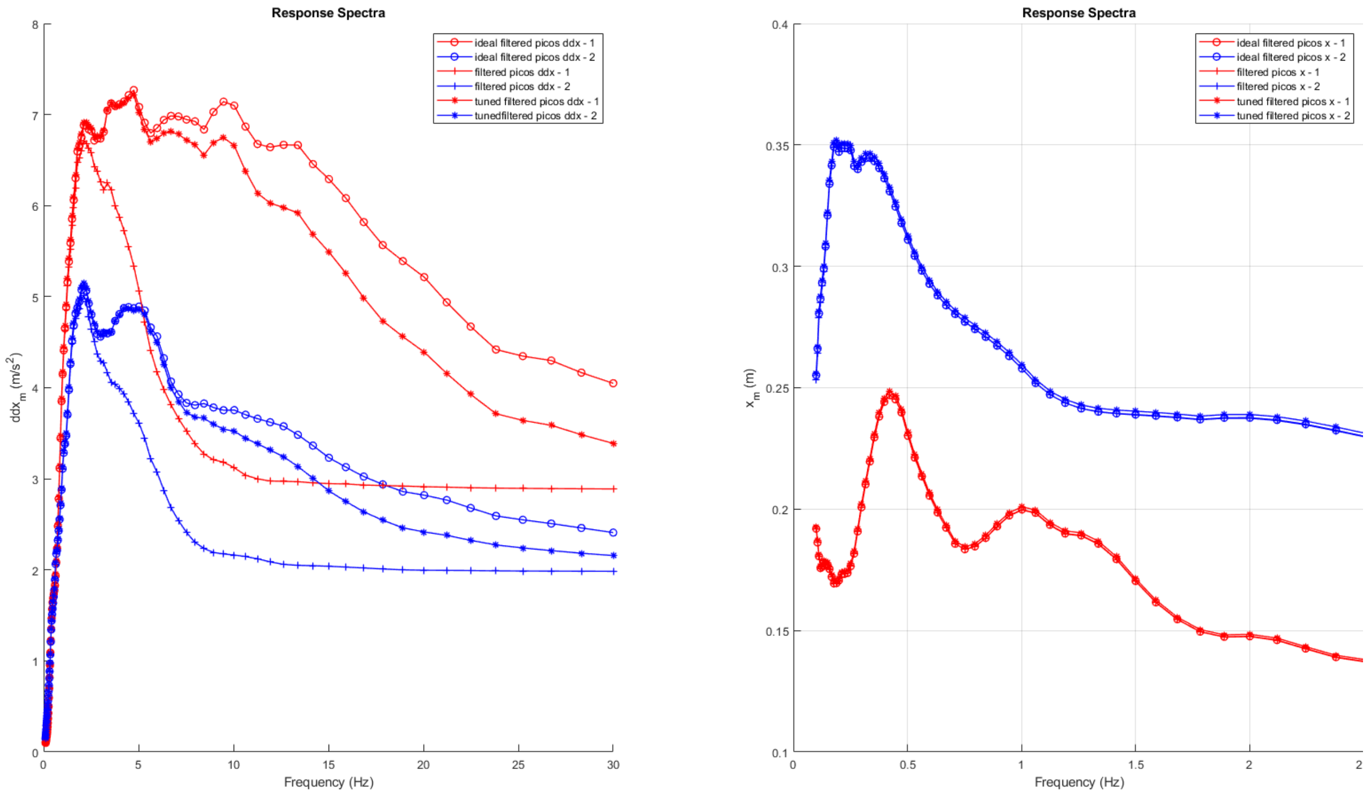


Figure 6: Response spectrum for fault normal(red) and fault parallel(blue) signals. The first pair corresponds to the response spectrum of the reference, the second pair, to the standard controller, and the third pair to the tuned controller.

In figure 6 it's clear that the standard controller, while capable of replicating the displacement response spectrum, falls significantly short when it comes to replicating the acceleration response spectrum, specially at frequencies above 5 Hz. This is markedly problematic due to the fact that the second mode of typical structures on test is between 5 and 10 Hz. The tuned controller fairs appreciably better up to the 10 Hz frequency.

5 Metodologia de Ensaios Sísmicos no LNEC

Compreender a metodologia de ensaios sísmicos utilizada no LNEC e desenvolver funções e modelos em Matlab/Simulink que reproduzam os ensaios em ambiente de simulação.

5.1 O modelo em anel fechado com controlador PID

Descrever e analisar o modelo do sistema em anel fechado utilizando um controlador PID.

5.2 Identificação dinâmica

Realizar a identificação dinâmica do sistema para caracterizar as suas propriedades dinâmicas.

5.3 Geração do sinal de comando

Desenvolver e avaliar algoritmos para a geração do sinal de comando.

5.4 Construção do espectro de resposta

Construir o espectro de resposta do sistema e utilizá-lo para análise de desempenho.

5.5 Análise do método como um todo

Realizar uma avaliação abrangente da metodologia adotada.

5.6 Análise do sistema com o modelo matemático construído

Utilizar métodos analíticos como Lugar das Raízes (LGR) ou diagramas de Bode para estudar o comportamento do sistema baseado no modelo matemático desenvolvido.

5.7 Avaliação do comportamento sob ações sísmicas

Examinar o desempenho do sistema perante ações sísmicas e identificar as suas vantagens e limitações.

5.8 Avaliação do método de geração do sinal de comando

Avaliar a eficácia e eficiência do método de geração do sinal de comando.

5.9 Resumo do Método de Ensaio no LNEC

Os ensaios realizados no LNEC visam avaliar a vulnerabilidade estrutural, verificando a evolução dos danos com o aumento da severidade sísmica. A metodologia consiste nos seguintes passos:

1. **Definição do sinal sísmico de referência:** Estabelecer o sinal de referência (deslocamento, velocidade e aceleração).
2. **Identificação do sistema:** Determinar a Função de Resposta em Frequência (FRF) do sistema plataforma + modelo.
3. **Geração do sinal de comando:** Criar o sinal de Drive utilizando o método *Online Iteration*, com base no sinal de referência e no modelo identificado.
4. **Execução do ensaio sísmico:** Aplicar o sinal de comando ao sistema em anel fechado.
5. **Avaliação do desempenho:** Comparar os espectros de resposta do sinal medido e do sinal de referência.
6. **Iteração ou término:** Repetir o procedimento para maior amplitude ou encerrar a campanha se o último nível for atingido.

6 Instalação Experimental

Concluir a instalação da plataforma sísmica ST1D, incluindo os sistemas hidráulico e de automação. Compreender o funcionamento do sistema de medição e controlo, que utiliza equipamento National Instruments e programação em LabView. Implementar e analisar o controlador PID em cascata com retroação de deslocamento e força.

7 Formação em LabView

Participar na formação organizada pelo LNEC para desenvolver competências em LabView, necessárias para a posterior implementação do controlador otimizado na plataforma ST1D.

8 Validação Experimental do Sistema

Realizar os ensaios experimentais para validar os modelos desenvolvidos e o funcionamento da plataforma sísmica ST1D.

8.1 Configuração dos Ensaios

Configurar a plataforma com base nos requisitos previamente definidos, incluindo a definição de parâmetros como amplitude, frequência e tipo de entrada para o controlador.

9 Definição da Instrumentação e Calibração do Sistema

Proceder à definição da instrumentação a utilizar nos ensaios, calibrar os sensores com recurso a padrões de referência metrológicos, e parametrizar curvas de calibração na aplicação para operação e controlo da plataforma sísmica;

9.1 Ensaios de Validação do Modelo 1-DOF

Realizar testes experimentais utilizando o modelo 1-DOF e comparar os resultados obtidos com os previstos pelos modelos matemáticos desenvolvidos em Matlab/Simulink.

9.2 Ensaios de Validação do Modelo 2-DOF

Reproduzir cenários dinâmicos mais complexos com o modelo 2-DOF e analisar o desempenho da plataforma e a precisão do modelo em prever a resposta estrutural.

9.3 Avaliação do Desempenho do Controlador PID

Estudar o comportamento do sistema com o controlador PID implementado, comparando as respostas esperadas e observadas em condições reais.

9.4 Testes com Diferentes Tipos de Sinais

Avaliar a resposta da plataforma com diferentes tipos de entradas, incluindo sinais harmónicos, aleatórios e sinais sísmicos reais.

9.5 Geração do Espectro de Resposta Experimental

Obter o espectro de resposta experimental e comparar com os resultados teóricos e de simulação, analisando discrepâncias e ajustando os modelos conforme necessário.

10 Relatório Final e Apresentação

Elaborar o relatório final e preparar a apresentação do trabalho desenvolvido.

10.1 Elaboração do Relatório Final

Preparar um documento detalhado que inclua:

- Descrição do trabalho realizado e do progresso alcançado;
- Modelos matemáticos desenvolvidos e resultados das simulações;
- Metodologia de ensaios sísmicos implementada;
- Validação experimental e análise de resultados;
- Identificação de limitações e propostas de trabalhos futuros.

10.2 Apresentação dos Resultados

Preparar uma apresentação que resuma o trabalho e destaque as principais conclusões, destinada a um público técnico e/ou académico.

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